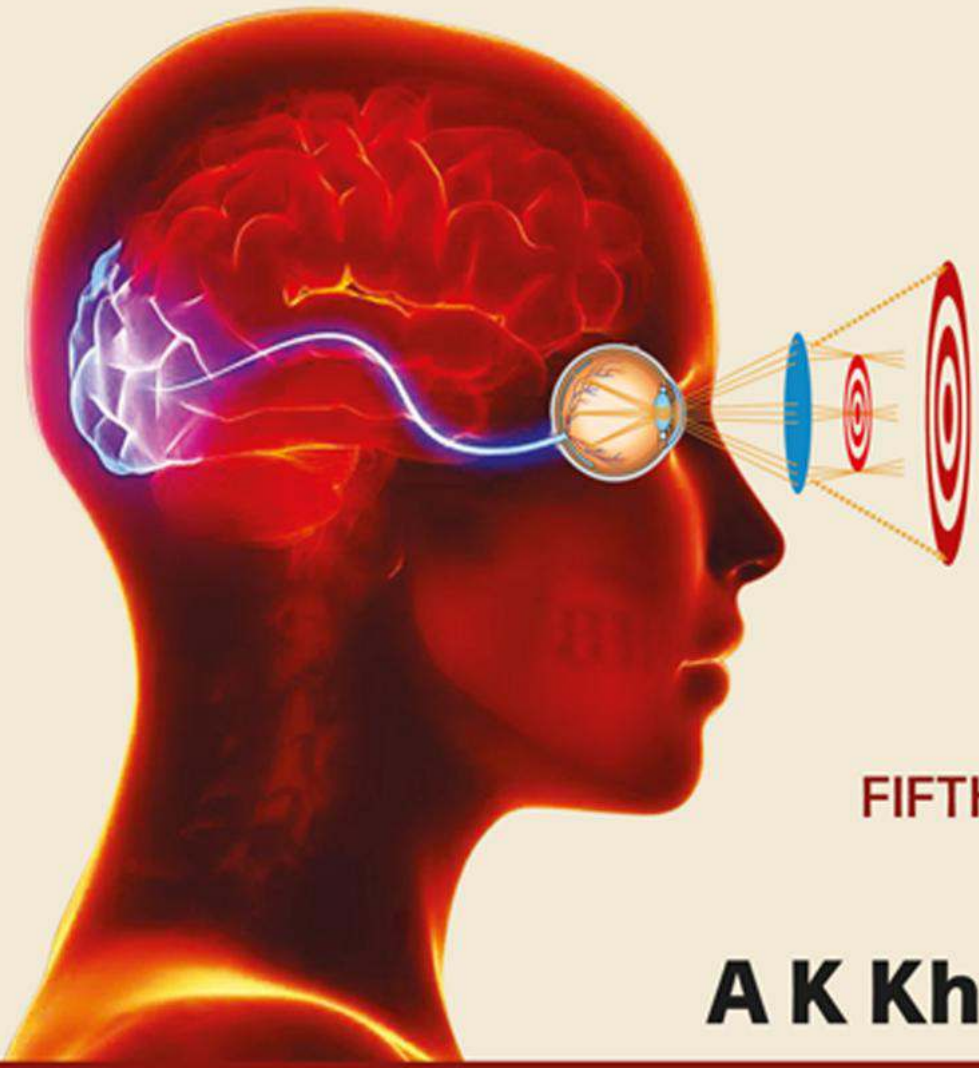
Modern System of Ophthalmology

MSO Series

Theory and Practice of OPTICS and REFRACTION



FIFTH EDITION

A K Khurana

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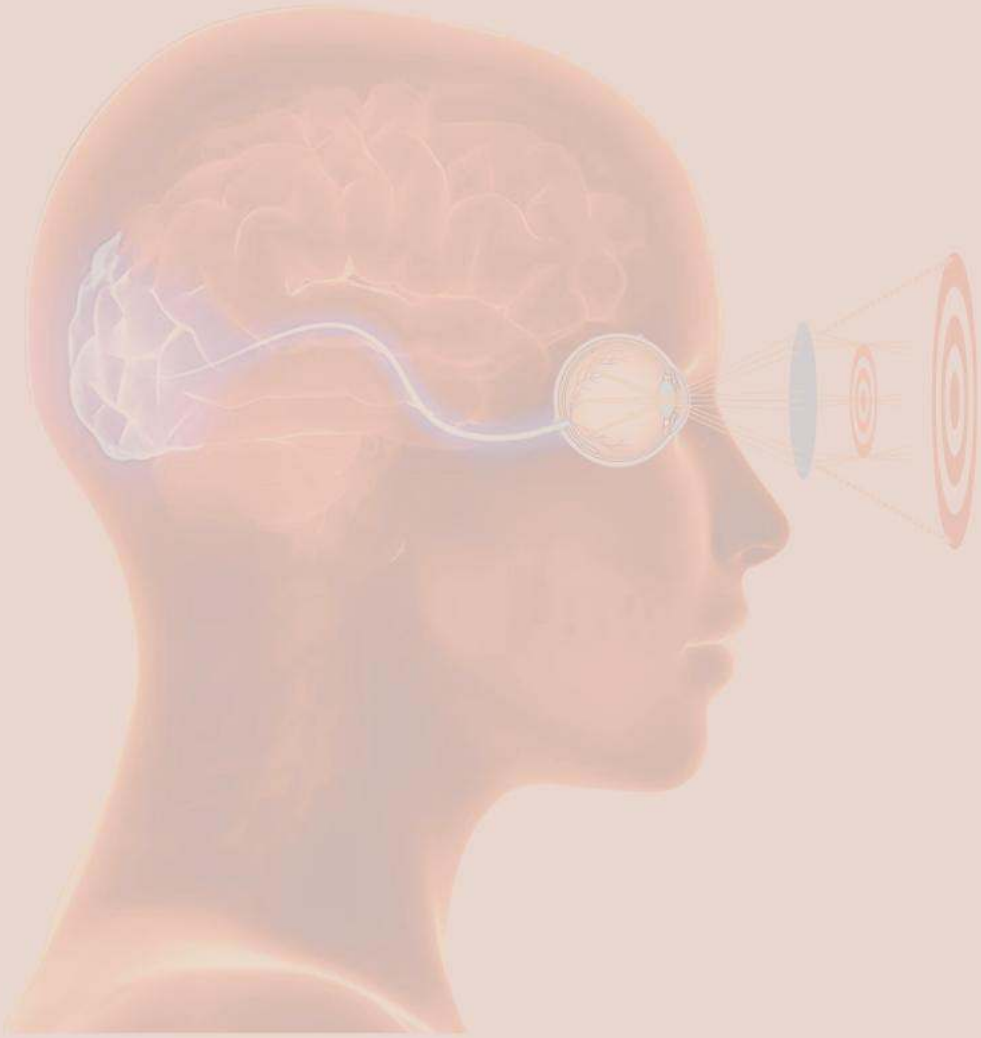

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Theory and Practice of OPTICS and REFRACTION

FIFTH EDITION

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Registered Office: 818, 8th Floor, Indraprakash Building, 8th Floor, 21, Barakhamba Road, New Delhi 110 001
Corporate Office: 14th Floor, Building No. 10B, DLF Cyber City, Phase II, Gurgaon-122 002, Haryana, India

Theory and Practice of Optics and Refraction, 5th Edition, AK Khurana

ISBN: 978-81-312-6371-6
eISBN: 978-81-312-6372-3

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Typeset by GW Tech

Printed in India by

Dedicated to

My parents and teachers for their blessings

My students for their encouragement

My children for their help

My grandchildren for their patience

And my wife Professor Indu Khurana, for her understanding

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Preface

Since the invention of eyeglasses, in Italy in the year 1289, efforts have been made to improve their profile as well as the technique of prescribing. Needless to say that still the refraction continues to form the bread and butter for ophthalmologists as well as the optometrists. So, the fifth edition of "Theory and Practice of Optics and Refraction" has been updated to provide basic principles and the recent advances in the field of optics and modalities of correcting refractive errors. In addition, the knowledge of basic principles of light and optics are essential to learn the art of refraction. So, An effort has been made to skillfully intermingle these two essential ingredients to the advantage of readers, and a detailed coverage has been given to the clinical refraction, i.e. determination of the errors of refraction. However, to keep this book primarily practically oriented, detailed theory and mathematical foundations and calculations have been purposely kept aside. The optical aspects of modalities of correcting the refractive errors, viz. spectacles, contact lenses, refractive surgery and intraocular lens implantation have been discussed at length. Management of low vision, which is a challenge, has also been included. Modern ophthalmic and optometric practice is virtually impossible without the use of sophisticated optical instruments. Description of such advances is beyond the scope of this basic book on optics and refraction. However, one separate chapter has been devoted to the description of optical instruments and procedures which form an essential part of the examination of the eye in modern ophthalmic practice.

Salient Features of Fifth Edition

- *Fifth edition* continuous to be a part of Modern System of Ophthalmology(MSO) Series
- *Chapter Layout* depicts list of contents and highlights the topics covered in the beginning of each chapter.
- *Text matter* is designed to meet the needs of students in ophthalmology and optometry, as well as practicing ophthalmologists and optometrists.
- *Text is arranged* in a user-friendly manner with various levels of headings, sub-headings, bold face and italics.
- *High quality coloured photographs and line diagrams,* provide vivid details and also profusely illustrate the text.
- *Revision of text* has been done in each chapter to include the recent advances.

Sincere efforts have been made to verify the correctness of the text. However, in spite of best efforts, ventures of this kind are not likely to be free from human errors, some inaccuracies, ambiguities and typographic mistakes. Users are, therefore, requested to send their feedback and suggestions. The importance of such views in improving the future editions of the book cannot be overemphasized. Feedbacks received will be highly appreciated and duly acknowledged.

A K Khurana

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Acknowledgements

Acknowledgement needs to be made to all those who have been instrumental in making this revised fifth edition a reality. Surely, I owe sincere thanks to them all. Those who need special mention; Prof JS Titiyal and Prof Namarata sharma from Dr RP Centre for Ophthalmic Sciences, AIIMS, New Delhi; Prof CS Dhull, WCMSR Jhajjar, Prof Sanjiv Mittal, AIIMS, Rishikesh, Prof Kirti Singh and Prof Subhash Dadeya, MAMC, New Delhi; Prof Harsh Bahadur and Prof Renu Dhasmana from HIMS, Jolly Grant, Dehradun; Prof Manisha Gupta, SGRRIHMS, Deharadun; Prof SP Singh and Prof Kamaljeet Singh from Allahabad; Prof Rupali Chopra and Prof Nitin Batra, CMC, Ludhiana; Prof BP Guliani, VMMC, New Delhi; Prof Gursatinder Singh, HoD, Deptt of Ophthalmology Adesh Medical College and Hospital, Shahbad; Dr RS Chauhan, Senior Prof and Head, RIO, PGIMS, Rohtak; Prof Anand Aggarwal, Head, Deptt of Ophthalmolgy, Govt Medical College, Patiala; Prof Prempal Kaur, Head, Deptt of Ophthalmolgy, Govt Medical College, Amritsar; Prof Manjeet Kaur from SHKM GMC Mewat, Dr Sumeet Khanduja, HOD Opthalmology, Kalpana Chawla Medical College, Karnal; Dr Mahipal S Sachdev, Medical Director, Centre for Sight, New Delhi and Mr Gagan Sahni, Contact Lens Specialist, New Delhi. Co-operation and help received from faculty and residents, especially Prof JP Chugh, Prof Neeraj Sharma, Dr Supriya, Dr Harvinder, Dr Harman and Dr Aman, of Department of Ophthalmology, SGT Medical College and Hospital, Gurugram is appreciated.

I am thankful to Prof Urmial Chawla, and Dr Chetan Chhikara from RIO, PGIMS, Rohtak for updating chapter on Optical Instruments and Techniques and Dr Ashwani Ghai, Lecturer, Optometry, SGT University for contributing text on, "Spectacle-related Asthenopia".

I want to put on record the remarkable hardwork put in by Dr Aruj K Khurana and Dr Bhawna P Khurana in completion of this edition. My task has been made untiring by the love and moral support, in addition to the editorial help, rendered by my daughter Dr Arushi and Son-in-Law Dr Gurukripa, Asst Professors of Medicine, Mayo Clinic College of Medicine and Science, Rochester, Minnesota, USA and my wife Dr Indu Khurana, Professor Emeritus, SGT University, and Former Prof of Physiology and Dean-cum Principal, World College of Medical Sciences and Research, Gurawar, Jhajjar, and Former Sr Prof and Head, Department of Physiology, PGIMS, Rohtak.

I also thank Sh Manmohan Singh Chawla, Managing Trustee, Mrs Madhupreet Chawla, Chairperson, Sh Ram Bahadur Rai, Chancellor, Prof Sham Lal Singla, Advisor, Prof OP Kalra, Vice-Chancellor, Prof Reena Naiyar, Executive Director, Prof Gen SPS Kochar, Dean FMHS, Mr GL Khanna, Head HR Dept, SGT University for providing atmosphere conducive to such academic activities.

The enthusiastic co-operation received from the team of Elsevier India esprecially Shabina Nasim, Head, Operations and Editorial, Anand K Jha, Content Project Manager is duly acknowledged.

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1 Elementary and Physiological Optics

Chapter Outline

ELEMENTARY OPTICS

Optics is the branch of physics that studies the behaviour and properties of light including its interaction with matter and the construction of instruments that use or detect it.

Elementary or Classical optics deals with the basic fundamentals of optics in the form of two models—physical and geometric optics. Elementary optics is thus concerned with:

- *Light*, its nature and properties,
- *Physical optics*, which takes into consideration the basic dual nature of light, and
- *Geometrical optics*, refers to ray optics, which uses the geometry of straight lines.

Before describing the geometrical and physical models of optics, it will be worthwhile to know about nature and properties of light.

LIGHT

Light is a form of energy whose interaction with retina gives the sensation of sight. Thus, light is

the visible portion of the electromagnetic radiation spectrum which ranges from short ionizing radiations (1×10^{-16}) to the longest radio waves (1×10^{16} meter) (Fig. 1.1). Light lies between the ultraviolet and infrared portions, from 400 nm at the violet end of the spectrum to 700 nm at the red end (Fig. 1.1 and Table 1.1). The white light consists of seven colours denoted by 'VIBGYOR' (violet, indigo, blue, green, yellow, orange and red).

NATURE OF LIGHT

To understand the nature of light, various theories have been put forward from time to time.

At present, it is universally accepted that like matter, light also has dual nature; i.e. it possesses the characters of both the wave and the particle. The two characters of its dual nature are complementary.

Electromagnetic Wave Nature of Light

Electromagnetic wave nature of the light implies that it is a portion of spectrum of electromagnetic radiations (400–700 nm). Light behaves as a wave as it passes through air, vacuum or other transparent media, including the transparent ocular tissues. Huygens in 1678 proposed that light moves in the form of waves from the luminous source. These waves consist of crests and troughs. At any instance, a trough (or a crest) is circular in shape. The locus of points in the same phase at a particular time is called a wavefront. The shape of the wavefront depends upon the nature of source. For waves from a point source in air, the wavefronts are spherical. If the source is a long slit, the wavefronts are cylindrical.

Table 1.1 *Wavelength of different rays*

S. no.	Types of rays	Wavelength (in nm)
1.	Cosmic rays	4×10^{25}
2.	Electronic rays	2.7×10^{24}
3.	Gamma rays	6×10^{25} to 0.14
4.	X-rays	0.14 to 13.6
5.	Ultraviolet rays	13.6 to 400
6.	Visible rays	400 to 700
	a. Violet	400 to 424
	b. Indigo	424 to 455
	c. Blue	455 to 492
	d. Green	492 to 575
	e. Yellow	575 to 585
	f. Orange	585 to 647
	g. Red	647 to 700
7.	Infrared rays	723 to 1×10^5
8.	Wireless rays (Hertzian rays)	1×10^5 to 3×10^{13}
	a. Short	1×10^5 to 1×10^{10}
	a. Long	1×10^{10} to 3×10^{13}
9.	Electromagnetic oscillations	Over 3×10^{13}

At long distances, they appear plane. An important characteristic of wave motion is that it transmits energy, not matter.

Phenomena explained by wave nature of light. Wave nature of the light explains the following phenomena:

- Propagation of light through vacuum,
- Reflection of light,

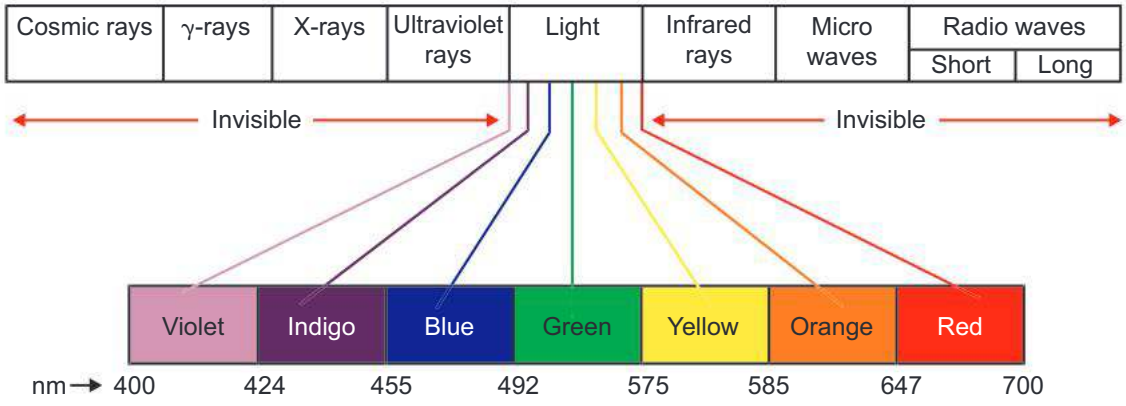


Fig. 1.1 *Spectrum of electromagnetic radiation. Note the very small portion occupied by visible light.*

- Refraction of light,
- Phenomenon of interference,
- Phenomenon of diffraction and
- Phenomenon of polarization.

Particle Nature of Light

Light exhibits some characteristics of particles (photons) when it is being absorbed or when it is being generated in a light source.

In order to explain the photoelectric effect of light, Einstein in 1905 proposed that light of a given frequency (ν) consists of quanta (photons) with the same energy ($E = h\nu$, where h is the Planck's constant). Thus, *quanta* or *photons* can be considered the units in which the energy of electromagnetic radiation is measured. The energy of an individual photon is directly proportional to the frequency and inversely proportional to the wavelength. Therefore, the energy of a photon at 400 nm is twice as great as that of a photon at 800 nm. For example, red light is innocuous, ultraviolet light produces burns and X-rays produce severe damage to the tissues.

Phenomena explained by particle nature of light. Particle nature of light explains the following phenomena successfully:

- Photoelectric effect of light,
- Scattering of light,
- Emission of light and
- Absorption of light.

Note. In fact, the photoelectric effect of light (explained by its particle nature) is responsible for seeing things. When a light photon is absorbed in one of the sensitive cells of the retina, the chemical change induces an electrical signal to the brain and one perceives the light.

PROPERTIES OF LIGHT

Some of the important properties of light are summarized as follows:

1. Light is propagated as electromagnetic waves; i.e. it does not require medium for its propagation.
2. Speed of light in free space (i.e. vacuum) is 3×10^8 m/s (186,000 miles/s).
3. It is transverse in nature and so can be polarized.
4. It is not deflected by electric and magnetic fields.
5. When light passes from one medium to the other, *velocity* and *wavelength* change, *amplitude* may decrease or remain constant, but *frequency* and *colour* of light do not change; i.e. colour of light is determined by its frequency and not by wavelength. For example, if red light passes from air to water (or glass), its velocity and wavelength in water (or glass) will be different from that in air, but frequency and colour remain the same.
6. Velocity of all wavelengths of light in free space is same and is equal to 3×10^8 m/s. However, in a medium, the speed of light is different for different wavelengths.
7. The speed of light in a medium is lesser than in vacuum. When the same light passes through different media, its speed will vary depending upon the density of medium (the denser the medium the lesser will be the speed of a given light).
8. Light of a single wavelength is called *monochromatic light*. White light is *heterochromatic*.
9. Light exhibits phenomena like reflection, refraction, absorption, diffraction, interference and polarization. These will be discussed later.

VISIBLE LIGHT AND THE EYE

- *The media of the eye are uniformly permeable* to the visible rays between 400 and 700 nm.
- *Cornea absorbs* rays shorter than 320 nm. Therefore, rays between 320 and 600 nm only can reach the crystalline lens.
- *The normal human eye is insensitive* to wavelengths between 350 and 400 nm (ultraviolet rays) because these are absorbed by the crystalline lens of the eye. In aphakic eyes, the light rays between 350 and 400 nm can also pass on to the retina. Therefore, the aphakic eyes are sensitive to those wavelengths which give rise to the sensation of blue or violet colour. Hence, the newly aphakic patients often complain that everything looks bluer than visualized before the operation.
- *The eye is most sensitive* to yellow-green light, i.e. light of wavelength 550 nm. The sensitivity of the eye decreases on both sides of this

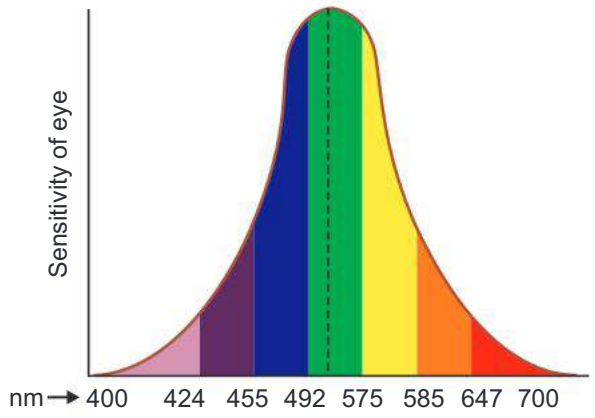


Fig. 1.2 *Sensitivity of eye to visible spectrum of light.*

wavelength, so it is minimum for violet and red light (Fig. 1.2).

- *Persistence of the eye* is 0.1 s; i.e. if the time interval between two successive light pulses is lesser than 0.1 s, eye cannot distinguish them separately.
- *Range of sensitivity*. The human eye can detect energies of a few photons per second up to bright sunlight, a difference of 10^{15} in sensitivity.
- *Fechner's law*. The relative sensation of an increase in sensitivity is proportional to the log of the change, and so by increasing the intensity of a lamp from 1 to 10 foot-candles, the same sensation of change as that from 10 to 100 foot-candles is given. This law applies for four orders of magnitude.
- *Weber's law*. The change of brightness necessary to be noticed is proportional to the original brightness; i.e. $\Delta L = KL$, where ΔL is the least amount of change of intensity noticeable, K is a constant and L is the brightness of the light. Therefore, the change necessary before a difference is noticed in a bright light source is larger than in a dim one.

MEASUREMENT OF LIGHT

The quantitative measurement of light is carried out in two different ways.

1. RADIOMETRY

Radiometry refers to the measurement of light in terms of its power generated/emitted/irradiated by a source of light. Its basic unit is watt. The power of light produced by a light source can be measured in the following terms:

- *Radiant flux*. It refers to the amount of light emitted from a source and is measured in *watts* or *joules per second*.
- *Radiant intensity*. It refers to the *intensity* of light emitted from a source and is measured in *watts per steradian*.
- *Irradiance*. It refers to the amount of light falling on a surface and is measured in *watts per square metre*.
- *Radiance*. It refers to the amount of light reflected from a surface and is measured in *watts per steradian per square metre*.

2. PHOTOMETRY

It is the measurement of light in units and is based on the response of the eye. Thus, photometry uses the eye as the comparison detector. Photometric measurement terms are as follows:

Luminous flux. It refers to the total flow of light in all directions from a source of light. The unit of measurement of luminous flux is called *lumen*.

Luminous intensity (old name: candlepower). It refers to the light emitted from a source in a given direction. The unit of light intensity is candela.

Candela is the modern unit of luminous intensity. It is mere precisely defined replacement for the old unit, the candle (which is based on a standard wave candle). The definition of candela is based on a standard electrical filament lamp.

1 candela = 1 lumen per steradian (the steradian is the measure of cone of light).
A point source with output of 1 candela emits a total of 4π (i.e. ~12.6) lumens.

Illumination (or illuminance on a surface). It refers to the light arriving at a surface, i.e. the number of lumens per square metre incident on that surface (lumen/m^2). The old names for this unit (lumen/m^2) were the metre-candle and lux. The illumination (E) of a given surface is as follows:

- Inversely proportional to the square of distance (d) of the surface from the light source.

- Directly proportional to the angle of incident light (i) on the surface, i.e. $E = I \cos i/d^2$, where I is the luminous intensity.

Luminance of a surface is the total amount of light reflected or emitted by the surface. Two sets of units are in use as measure of luminance:

- *Lambert.* One lambert is defined as the luminance of a perfect diffuser surface emitting 1 lumen/cm^2.
- *Footlambert* is more commonly used unit for luminance. It is defined as the luminance of a surface reflecting or emitting 1 lumen/ft^2. 1 footlambert = 1 candela ft^2.

If a source has a known output in watts, we can determine its output in lumens, provided we know the spectral properties of the lamp, i.e. power at each wavelength. The output at each wavelength is multiplied by the sensitivity of the eye at the wavelength and the results are summed to obtain the total response of the eye to light from that source. For example, if the source is monochromatic, with a wavelength at the peak of eye's photiopic sensitivity, 555 nm, the conversion factor is 685 lumens per watt. At other wavelengths, the factor is less, falling to approximately 0 at 400 and 700 nm.

Brightness is not a precisely defined term, but it refers in general to the sensation produced by a given illuminance on the retina.

Apostilb is defined as the luminance of a perfectly diffusing surface that is emitting or reflecting 1 lumen per square metre. It is encountered in perimetry, where the luminance of the background and the targets is often specified in apostilbs.

RADIOMETRIC VERSUS PHOTOMETRIC TERMS

The commonly used radiometric and photometric terms are summarized in Table 1.2.

APPLIED ASPECTS

The clinician should be familiar with frequently recommended levels of illumination employed by illumination engineers. It should be noted that the recommended foot-candles are a measure of the luminous power impinging on a surface, not that which is reflected into the eye. An ideal 100 W lamp bulb provides about 600 foot-candles of illumination 3 ft away and 150 foot-candles 6 ft away.

Table 1.2 *Principal types of light measurement and their relationships*

Description	Radiometric measure		Photometric measure	
	Type	Units	Type	Units
Quantity of light leaving a source or passing through a region of space	Radiant flux	Watts = joules/second	Luminous flux	Lumen (1 candle emits 4 p 1 m)
Light emitted per unit solid angle	Radiant intensity	Watts/steradian (1 sr = 1 unit of solid angle)	Luminous intensity (candlepower)	1 candela = 1 m/sr
Quantity of light per unit area incident on a surface or at an image	Irradiance	Watts/square metre	Illuminance	1 lux = 1 lumen/square metre
Light reflected or emitted by a surface, per unit area and per unit solid angle	Radiance	Watts/steradian/square metre	Luminance	1 foot-candle = 1 lumen/square foot 1 apostilb = (1/p) lumen/square metre/sr 1 footlambert = (1/p) lumen/square foot/sr
Illuminance at the retina, adjusted for pupil size			Retinal illuminance	Trolands (luminance of 1 candle/square metre viewed through 1 mm^2 pupil)

Recommended levels of illuminance (illumination) for some common purposes are as follows:

- Office, kitchen — 150 foot-candles
- Reading — 70 foot-candles
- Refracting lane
  - Wall chart — 25–50 foot-candles
  - Projector — 10 foot-candles
- Operating table — 2500 foot-candles

PHYSICAL OPTICS

Physical optics takes into consideration the basic dual nature of light; i.e. the light possesses the characteristics of both the waveform and the particle (photon or quantum). Therefore, the physical optics can be divided into two parts:

- wave optics and
- quantum optics.

WAVE OPTICS

Wave optics concerns with explanation of the observed phenomena such as *interference*, *diffraction* and *polarization*. In it, light is treated as a wave with the following characteristics:

- *Wavelength (L)* of a light wave is defined as the distance between two symmetrical parts of the wave motion (Fig. 1.3A).
- *Amplitude (A)* of a light wave is the maximum displacement of an imaginary particle on the wave from the base line (Fig. 1.3A).
- *Phase.* One complete oscillation of light waves is called a *cycle* (Fig. 1.3A). Any portion of the cycle is called a phase.

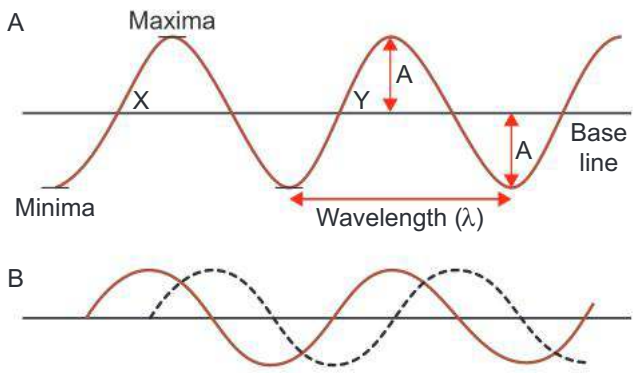


Fig. 1.3 *Light as a waveform depicting: A, basic characteristics; B, phase differences.*

- *Phase difference* refers to the fraction of a cycle or wavelength by which the two waves of equal wavelength travelling in the same direction are out of step with each other (Fig. 1.3B).
- *Coherent and incoherent light.* Light waves that are out of phase are called incoherent, while the light composed of waves exactly in phase is termed coherent.

Phenomena based on wave optics

- Interference,
- Diffraction and
- Polarization.

INTERFERENCE

When two or more wave trains of light of the same frequency travelling in almost same direction superimpose, the resultant intensity in the region of superimposition is in general different from the sum of the intensities due to individual waves. This modification in the distribution of intensity of light in the region of superimposition is called interference. Depending upon the way the waves superimpose, the interference is of two types:

1. *Constructive interference.* When the waves superimpose in such a way that their maxima and minima correspond with each other (full phase difference), the resultant intensity is greater than the sum of the intensities due to separate waves (Fig. 1.4A). This phenomenon is called constructive interference.

2. *Destructive interference.* When the waves superimpose in such a way that the maxima of one corresponds with the minima of other (half phase difference), the resultant intensity is lesser than the sum of the separate intensities. This phenomenon is termed as destructive interference (Fig. 1.4B).

Thus, due to the phenomenon of interference, we get *intensity maxima* (due to constructive interference) and *intensity minima* (due to destructive interference), which are called bright and dark fringes, respectively. The array of such fringes is labelled as *interference pattern* (Fig. 1.5).

It has been observed that to get interference effects, the waves must be coherent. The best condition for interference to occur is when the

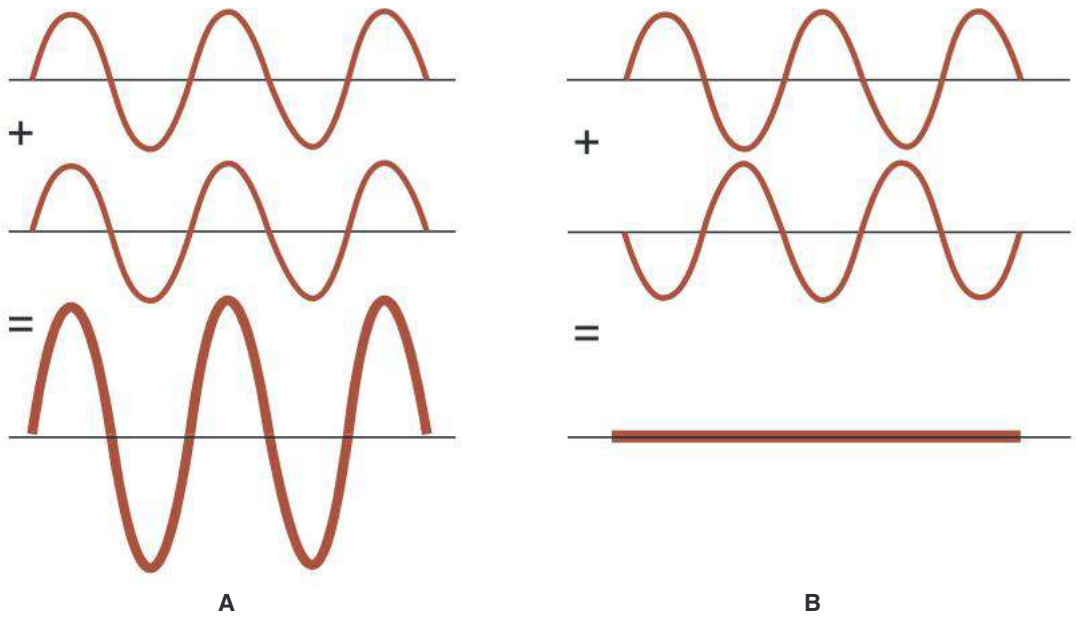


Fig. 1.4 *Phenomenon of interference: A, constructive interference; B, destructive interference (for explanation, see text).*

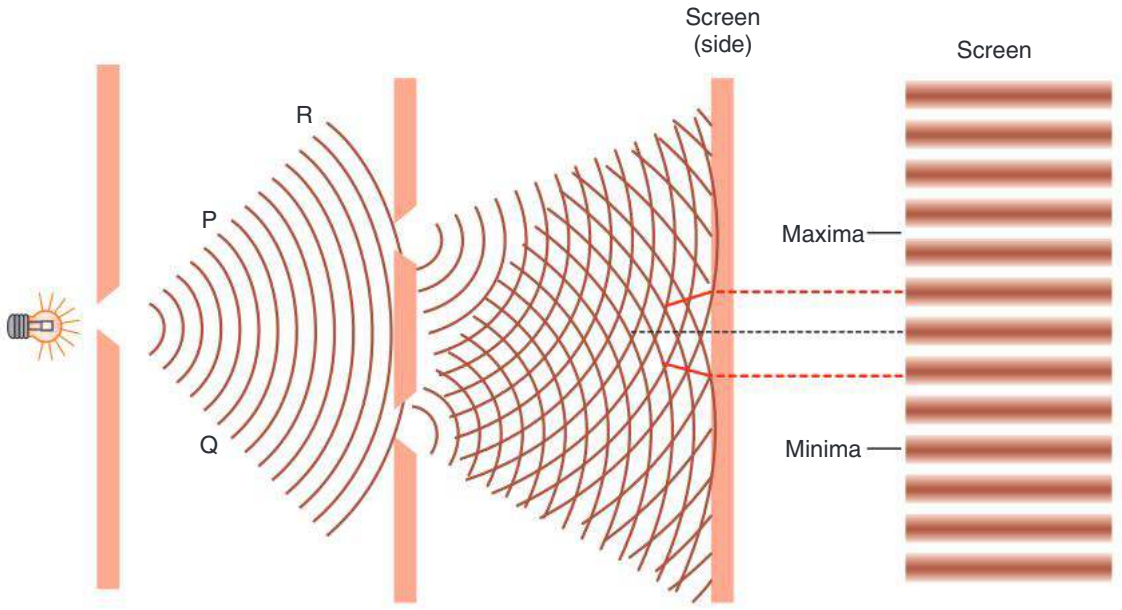


Fig. 1.5 *Interference pattern consisting of bright (due to intensity maxima) and dark (due to intensity minima) fringes.*

light is monochromatic, i.e. a narrow band of wavelengths. But interference can also be obtained with white light under optimum conditions.

Coherence is the measure of the ability of two light beams to produce interference. Coherence is of two types:

1. *Spatial coherence* refers to the ability of two separated portions of the wave (P and Q in Fig. 1.5) to produce interference.

2. *Temporal coherence* is a measure of the ability of a beam to interfere with another portion of itself (P and R in Fig. 1.5). Temporal coherence is improved by using a filter to select a narrow band of wavelength.

Clinical Significance of Interference

Destructive interference occurs within the stroma of the cornea. The collagen bundles of the stroma are so spaced that any light

deviated by them is eliminated by destructive interference.

Applications of Interference

Phenomenon of interference has a wide range of applications. A few important ones are as follows:

- *Holography* utilizes the phenomenon of interference to produce three-dimensional images.
- *Laser interferometry* is based on interference. With its use, it is possible to predict the visual potentials in patients with hazy media due to cataract.
- *Anti-reflection coating* on the spectacle glasses utilizes the principle of destructive interference.
- It is *used to determine* the refractive index or thickness of transparent sheets.
- *Excitation filter and the barrier filter* used in fluorescein angiography fundus camera are based on the phenomenon of interference.
- The so-called *cold mirror* has a multilayered coating (based on interference filter) that is designed to reflect the visible (cold) light and transmit the infrared wavelength.
- *Optical coherence tomography* (OCT) is the most recent innovative clinical application of interference. The OCT scanner is basically a Michelson interferometer (see page 523, Fig. 12.93).

DIFFRACTION

When an opaque obstacle or an aperture is placed between a source of light and a screen, in accordance with rectilinear propagation of light, usually a sharp shadow or an illuminated region is obtained on the screen, as shown in Figure 1.6A and B. When the size of aperture is larger than the wavelength of the light, there occurs rectilinear propagation of light (Fig. 1.6C). However, if the size of the obstacle or aperture is comparable with the wavelength of light, the light deviates from rectilinear propagation near the edge of the obstacle or aperture and enters the geometrical shadow (Fig. 1.6D). This flaring out or encroachment of light in the shadow zone as it passes around the obstacle or through small aperture is called diffraction (Fig. 1.6D).

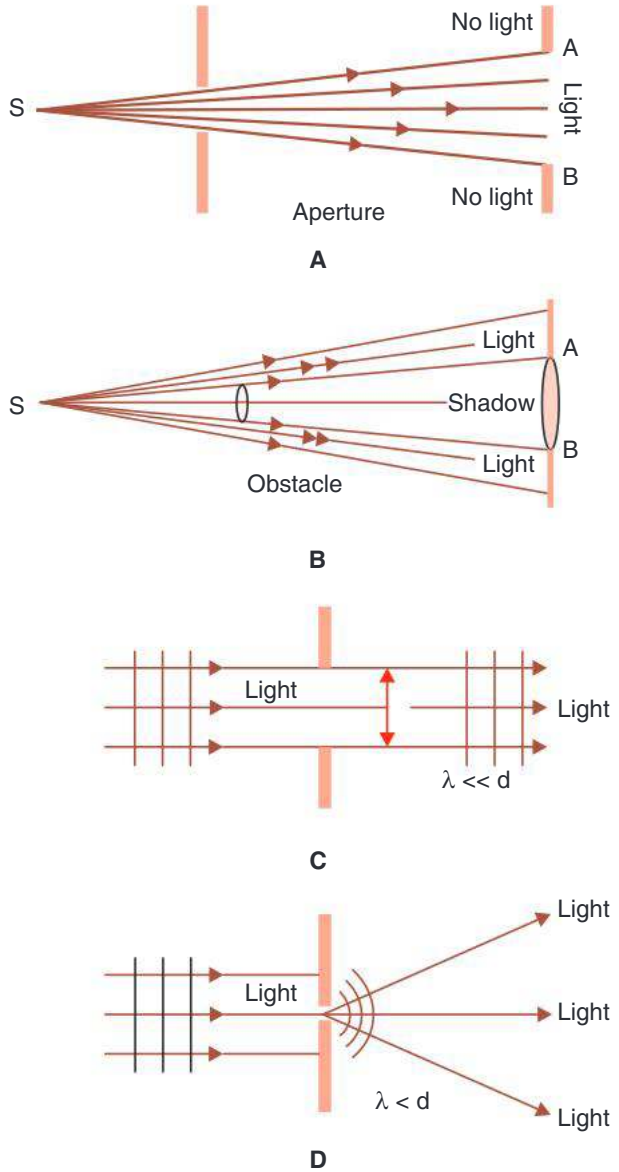


Fig. 1.6 *Phenomenon of rectilinear propagation: A, an illuminated area obtained on the screen due to light passing through an aperture; B, sharp shadow obtained due to an obstacle in the path of light; C, phenomenon of rectilinear propagation; and D, phenomenon of diffraction.*

Types of Diffraction

1. ***Fresnel diffraction.*** In this case, if source of light or screen or both are at a finite distance from the diffracting device (obstacle or aperture), the diffraction is called Fresnel type and the pattern is the shadow of diffracting device modified by diffracting effects (Fig. 1.7A). Examples:
   - Diffraction at a straight edge,
   - Diffraction at a narrow width and
   - Diffraction at a small opaque disc.

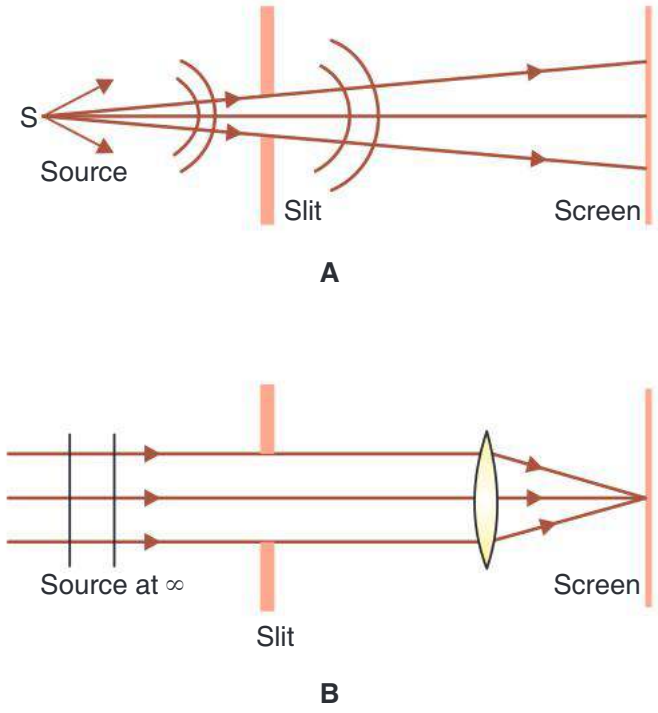


Fig. 1.7 *Types of diffraction: A, Fresnel diffraction; B, Fraunhofer diffraction.*

2. ***Fraunhofer diffraction.*** In this case, both the source of light and the screen are at infinite distance from the diffracting device and the pattern is the image of source modified by diffraction effects (Fig. 1.7B). Examples:

- Diffraction at single slit,
- Diffraction at double slit and
- Diffraction grating.

Applied Aspects of Diffraction

- Diffraction sets a limit on visual acuity when the pupil size is less than about 2.5 mm (for emmetropia). The image formed on the retina from a distant small source has the form of a blur circle, the Airy disc (Fig. 1.8).
  Thus, in the eye, the diffraction is a source of image imperfection when the pupil is small. However, the advantage of a large pupil in reducing the diffraction is outweighed by the increased effect of the aberrations of the refractive elements of eye.

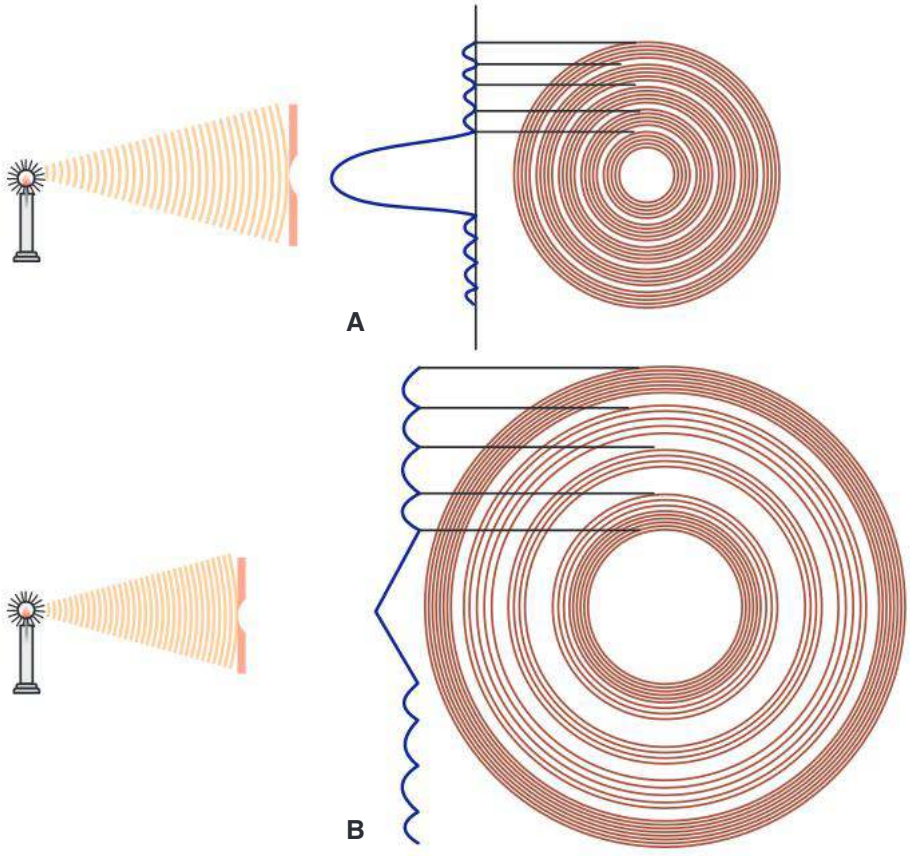


Fig. 1.8 *Airy disc pattern produced due to diffraction of light while passing through an aperture: A, larger aperture gives less edge effect and central disc is smaller, resulting in more accurate representation of point source; B, smaller aperture produces larger central disc.*

- The visual symptoms of glare and halos may be the result of diffraction.
- During pinhole test, when the aperture is very small, the visual acuity is decreased due to diffraction of light. The increased depth of focus is neutralized by the out of phase secondary wavefronts emanating from the aperture edges.
- Light with larger wavelength (red) diffracts more strongly than the light with shorter wavelength (blue) and, therefore, forms a larger diameter Airy disc.
- The best resolution obtainable from an optical instrument is limited by diffraction. The minimum resolvable distance is approximately equal to the radius of the Airy disc. Since diffraction sets a limit on the finest resolution that an optical system can achieve, there is a degree of perfection in the fabrication of optical component beyond which any improvement in the image is negligible.

POLARIZATION

An ordinary beam of light consists of a large number of waves emitted by the atom or molecule of light source. Each atom produces a wave with its own orientation of electric vector $\vec{E}$. However, because all directions of vibrations of $\vec{E}$ are equally probable, the resultant electromagnetic wave is a superimposition of waves produced by the individual atomic sources. This resultant wave is called unpolarized light and is symmetrical about the direction of wave propagation, as shown in Figure 1.9A. Thus, the unpolarized light consists of a random mixture of various plane-polarized beams. Partial polarization, as the name implies, is a mixture of unpolarized and polarized light (plane, circular or elliptical).

However, if somehow (say by using a polaroid or Nicol prism) we confine the vibrations of electric vector in one direction perpendicular to the direction of wave motion (Fig. 1.9B), the light is said to be *plane polarized* or *linearly polarized*. This phenomenon of confirming the vibrations of a wave in a specific direction perpendicular to the direction of wave motion is called polarization.

Production of Polarized Light

Polarization may be achieved in several ways:

- *Encounter with a polarizing substance* produces polarized light from the ordinary light. Polarizing substances, e.g. polaroid plastic, only transmits light waves which are vibrating in one particular plane. Thus, only a proportion of incident light is transmitted onwards and the emerging light is polarized.
- *Specular reflection from a plane surface* produces partial polarization of light. The direction of polarization is parallel to the reflecting surface. If light is reflected at a specific angle (*Brewster angle*), the reflected light is totally polarized.

In nature, light is polarized on reflection from a plane surface, such as water and snow, if the angle of incidence is equal to the polarizing

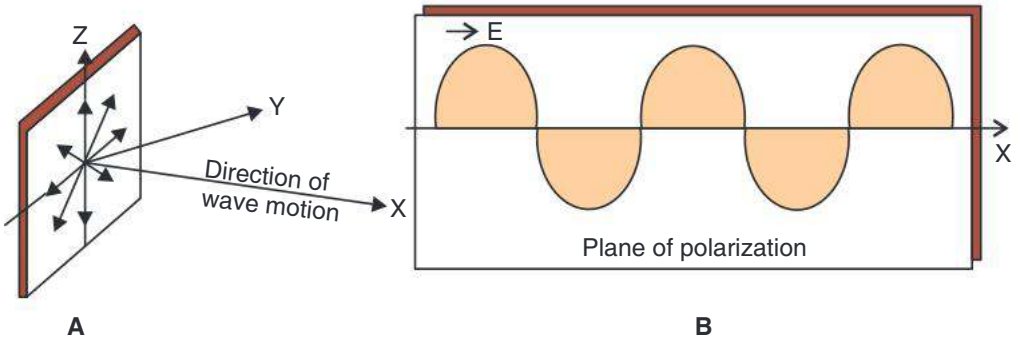


Fig. 1.9 *A, Unpolarized light propagating along x-axis; B, plane-polarized light.*

angle (Brewster angle) for the substance. The *polarizing angle* on glass is about 55 degrees and that on water is about 52 degrees.

The polarizing angle of a substance depends upon its refractive index. Some substances have different refractive indices, depending on the direction of polarization; they are called *birefringent* because they have two different refractive indices. Light incident on such birefringent substances travels in different directions, depending on its polarization. Such substances separate a beam of light into two beams, each linearly polarized at right angles to each other.

Applications of Polarized Light

- *Haidinger brush* phenomenon is based on polarized light.
- Ophthalmic instruments in which polarized light is used usually to control unwanted reflections (e.g. that from the front of cornea) include slit lamp and ophthalmoscope.
- *Polarizing projection charts* can be made to test one eye at a time while the patient is viewing binocularly through a pair of special polarizing glasses. This test is especially useful to detect malingering in patients complaining of unilateral visual lens. If the patient identifies all the letters on 6/6 line, the unilateral vision loss is factitious.
- *Three-dimensional pictures* are recorded and reproduced using polarized light.
- *Polaroid sunglasses* with vertical transmission axis reduce the glare that occurs due to horizontal polarization of light by reflection from ground or water.
- *Titmus fly test* used for testing stereopsis is based on polarization of light.
- *Measurement of thickness of retinal nerve fibre layer* (RNFL). Nerve fibres of the retina are birefringent. An instrument is now available for clinical use that measures birefringence in the RNFL as an indicator of thickness of that layer.
- *Detection of defects in the intraocular lenses* may be done by using the principle of birefringence.

QUANTUM OPTICS

Quantum optics treats light as a particle (localized energy pocket) called photon.

Phenomena based on the quantum optics include:

- Transmission and absorption,
- Scattering of light,
- Photoelectric effect,
- LASER
- Fluorescence and
- Raman effect.

TRANSMISSION AND ABSORPTION

When light falls upon an object, it may be transmitted, reflected, absorbed or, more usually, may undergo some combination of the above. If light of intensity I_0 falls upon a partially transparent plate, the intensity of the transmitted light would be $I = T \times I_0$, where T, called the transmittance, is a unitless number between 0 and 1. If several plates are stacked, the total transmittance of the stack is the product of the individual transmittances. It is sometimes more useful to add terms than to multiply them, so another term, called the density was invented:

$$D = \log \frac{1}{T} = 10^{-D}$$

where D is the density. Since numbers can be multiplied by adding their logarithms, the density of a series of plates is the sum of the densities of the individual plates.

Adsorbance refers to the quantity of light that is adsorbed by a matter on which it falls.

Absorbance is measured by absorption spectroscopy, the basis of which is the fact that the absorption spectrum comprises the absorption of light as a function of wavelength absorbed. A number of optical devices, such as light filters and sunglasses, make use of phenomenon of absorption.

Clinical Applications of Absorption

Absorption property of light may form basis of some other properties/effects of light as follows:

- *Thermal effect*. Absorbed light is usually converted into heat by the absorbing electrons.
- *Fluorescence*. Absorbed light may be used to excite an electron into a higher level and be re-radiated as in the case of fluorescence.
- *Polarization effect* may be produced by certain substances after absorption of light, e.g. dichroic substances like tourmaline are natural polarizers. They absorb and completely block transmission of those light waves through them which are not aligned along their molecular structure and thus transmit only the single beam of linear polarized light.
- *Vibrations in the medium* caused by the infrared rays after absorption.

SCATTERING OF LIGHT

When a parallel beam of light passes through a gas, a part of it appears in directions other than the incident direction. This phenomenon is called scattering of light. The phenomenon of scattering occurs due to the fact that when light is incident on atoms and molecules in the gas, the electrons absorb the incident light and re-radiate it in all directions (Fig. 1.10A). The

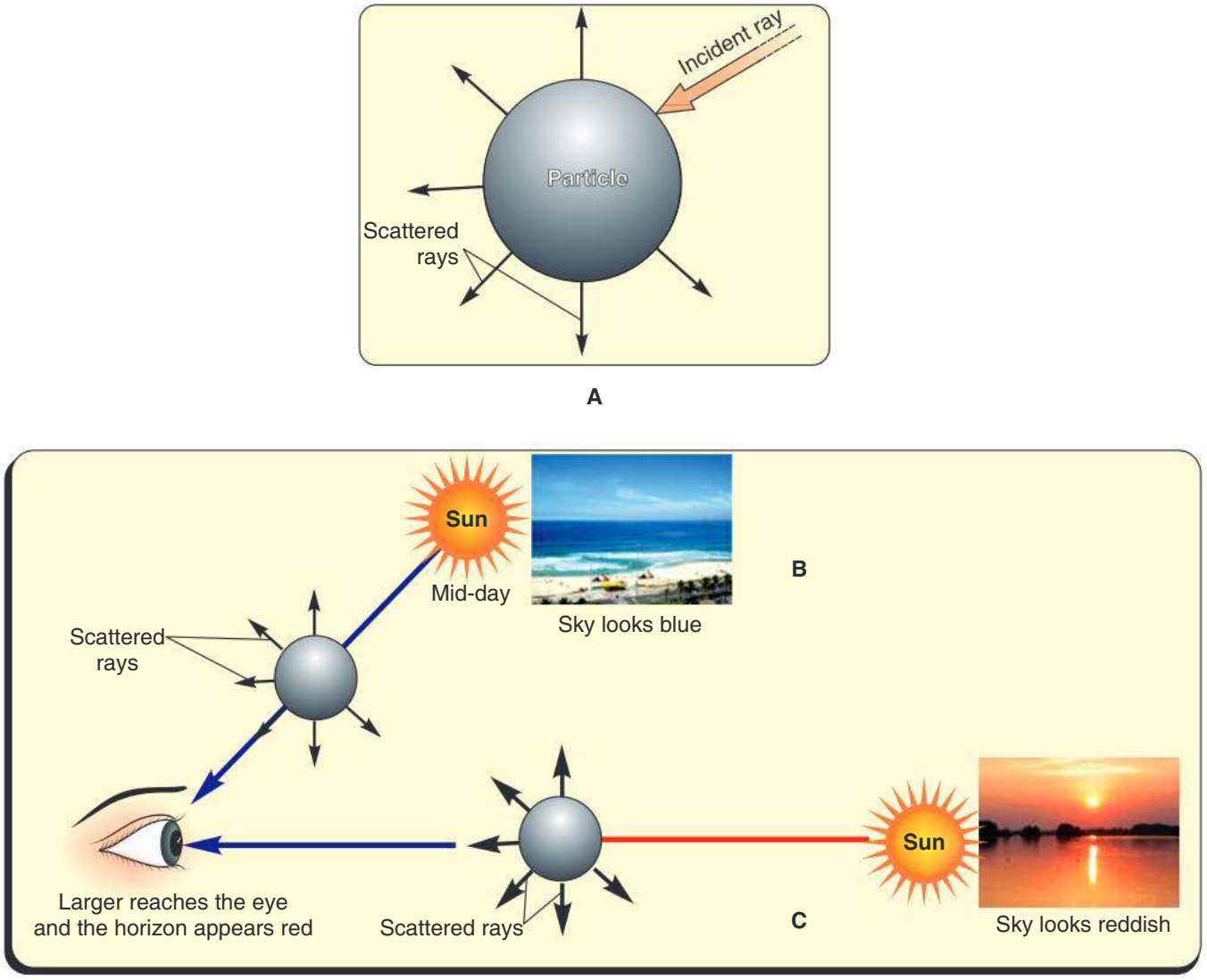


Fig. 1.10 *Phenomena of scattering of light (A) which explains why the sky looks blue in mid-day (B) and the sunset appears reddish (C). For explanation, see text.*

scattering of light occurs at irregularities in the light path, such as particles or inclusions in an otherwise homogeneous medium. When the size of particles in the medium is very large, all the components of white light are scattered. However, when the size of particles in the medium is small, specific wavelengths (those of violet, indigo and blue) may get scattered more than the others. The scattering from very small particles (e.g. from the molecules in the atmosphere) is called *Rayleigh scattering*.

Applied Aspects

1. ***Strength of scattering depends on the wavelength of the light*** besides the size of particles, which cause scattering. Thus, red light is scattered the least and violet light is scattered the most. This is why, red signals are used to indicate danger. Such a signal goes to large distances without an appreciable loss due to scattering.

2. ***Lights of short wavelengths (blue) are strongly scattered*** by the small air molecules and reach the observer (*Rayleigh scatter*). This explains why the sky looks blue in the mid-day because of the scattering of blue part of light (smaller wavelength) coming from the sun by very small particles in the atmosphere (Fig. 1.10B) and the sunset appears reddish because of dusk or dawn light has to travel a longer distance to reach the observer. In the process, all blue light is scattered and the left out red light is responsible for the sunset being reddish in colour (Fig. 1.10C).

3. ***Scattering of light in ocular tissues*** can result from a number of pathological conditions such as follows:

- *Corneal haze* in corneal oedema is caused by scattering of light.
- *Greyish appearance of an early cataract* is due to scattering by large molecules in the lens structure.
- *Flare in the anterior chamber* is caused by scattering of light by proteins in the aqueous humour.

4. ***Scattering material interferes with vision in two ways:***

i. *Glare effect*. When a light from a source, such as the sun or an oncoming headlight, reaches the eye, a fraction of the light scattered within the ocular media falls on the retina. That light which falls in the foveal area lowers the contrast in the image of interest and tends to obscure details in that image.

ii. *Light reduction effect*. When the scattering is very strong, there occurs a reduction in the light available to form the image on the retina. By this effect, scattering light causes decreased vision in patients with cataract and corneal opacities.

PHOTOELECTRIC EFFECT

It was discovered that electrons are emitted from certain metals when they are illuminated by light (particularly ultraviolet). This effect is called photoelectric effect.

In fact, the photoelectric effect of light (explained by its particle nature) is responsible for seeing things. When a light photon is absorbed in one of the sensitive cells of retina, the chemical change induces an electric signal to the brain and one perceives the light.

LASER

LASER is an acronym for light amplification by stimulated emission of radiation. It has got unique characteristics like:

- *Monochromaticity*, i.e. it consists of a narrow beam of a single wavelength and thus is always coloured and can never be white.
- *Coherence*, i.e. its each wave is in phase with the other near it.
- *Collimation*, i.e. all the rays are exactly parallel.

These properties make it the brightest existing light.

Production of Laser Beam

In the laser system, atomic environments of various types are stimulated to produce laser light. A laser system consists of a transparent crystal rod or a gas or liquid-filled cavity constructed with a fully reflective mirror at one end and a partially reflective mirror at the other end. Surrounding the rod or cavity is an optical or electrical source of energy that will raise the energy level of the atoms within the cavity or

rod to a high and unstable level. This phenomenon is called *population inversion.* From this level, the atoms spontaneously decay back to a lower energy level, releasing the excess energy in the form of light, which is amplified to an appropriate wavelength. Thus, laser is created mainly by two means: population inversion in active medium and amplification of appropriate wavelength of light.

In a laser, energy that has been stored in the laser material (e.g. ruby) is released as a narrow beam of light – either as a steady beam continuous wave or as an internal pulse. The beam remains narrow over a long distance and can be thought of as an ideal 'spot' light. A laser beam can be focused to a spot only a few microns in diameter. When all of the energy of the laser is concentrated in such a small area, the power per unit area (density) becomes very large. The total energy of a typical laser pulse used in medicine, which is measured in millijoules (mJ), can be delivered in less than a microsecond, and the resultant instantaneous power may be in megawatts. The output of a pulsed laser is usually measured by the heat produced in the detector (calorimetric method). The output of a low-power continuous wave laser is often measured with a photodetector such as a silicon photocell, often called a solar cell. Since in medicine, lasers are used primarily to deliver energy to tissue, the laser wavelength used should be strongly absorbed by tissues. The absorbance and reflectance curve for the skin varies for different individuals. Short wavelengths are always absorbed better than the long wavelengths.

FLUORESCENCE

Light may be absorbed by an electron in the ground state, raising the electron into an excited state. The excited electron may then decay to a lower level. If the electron decays to a state higher than the ground state, it will emit a photon that is less energetic than the absorbed photon, and therefore of a longer wavelength. This process is called fluorescence. Fluorescein, the chemical used in fundus fluorescein angiography, absorbs light at 490 nm in the blue region and re-radiates it at 530 nm in the green region. Other substances also fluoresce, absorbing and emitting light at different wavelengths from fluorescein.

GEOMETRICAL OPTICS

Geometrical model of optics describes the light propagation in terms of rays and so is also known as *ray optics* and is valid only if wavelength of light is much lesser than the size of obstacles, i.e., the structures with which light interacts.

The behaviour of light rays is determined by ray optics. *A light ray* is the straight-line path followed by light in travelling from one point to another. A group (or bundle) of adjacent divergent or convergent rays of light is termed a *pencil of light*. A bundle of light in which the rays are arranged in a parallel fashion is termed a *beam of light*.

The ray optics, therefore, uses the geometry of straight lines to account for the macroscopic phenomenon like *rectilinear propagation*, *reflection* and *refraction*. That is why the ray optics is also called geometrical optics.

Thus, the geometrical optics deals with the formation of images by using optical devices, such as lenses, prisms and mirrors, and with the laws governing the characteristics of these images, such as their size, shape, position and clarity.

The knowledge of geometrical optics is essential to understand the optics of eye, errors of refraction and their correction. Therefore, some of the important aspects of geometrical optics are described in the following text include:

- Rectilinear propagation of light,
- Reflection of light and
- Refraction of light.

RECTILINEAR PROPAGATION OF LIGHT

The rectilinear propagation of light in spite of its wave nature is attributed to its small wavelengths; i.e. due to its very small wavelength, it appears to travel in straight line (Fig. 1.11). Occurrence of eclipse is accounted from the facts that light propagates rectilinearly and

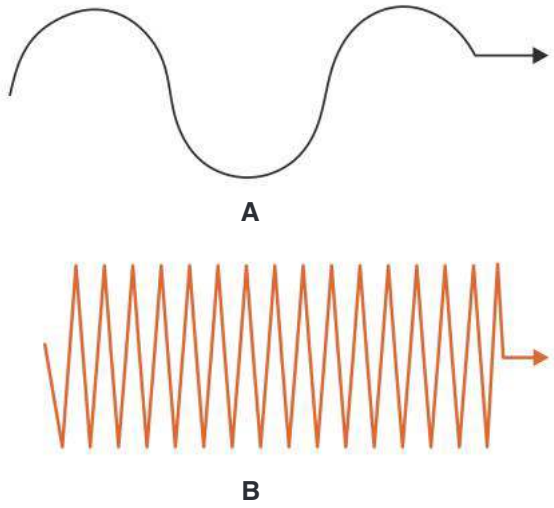


Fig. 1.11 *Rectilinear propagation of light: A, large wavelength; B, small wavelength.*

earth and moon are nonluminous and opaque celestial bodies, while the sun is self-luminous.

REFLECTION OF LIGHT

Reflection of light is a phenomenon of change in the path of light rays without any change in the medium (Fig. 1.12). The light rays falling on a reflecting surface are called *incident rays* and those reflected by it are called *reflected rays*. A line drawn at right angle to the surface is called the normal.

Reflection of light is of various types; two important ones to be considered are as follows:

- Specular reflection and
- Diffuse reflection.

Fig. 1.12 *Reflection of light.*

SPECULAR LIGHT REFLECTION

Specular light reflection occurs at regular surfaces such as plane mirrors or curved mirrors and forms images.

LAWS OF REFLECTION

The phenomenon of specular light reflection is governed by certain laws, called as '*laws of reflection*', which are as follows (Fig. 1.12):

1. The incident ray, the reflected ray and the normal at the point of incident ray all lie in the same plane.
2. The angle of incidence (i) is equal to the angle of reflection (r).
3. The light paths are reversible and sometimes result in a phenomenon called retroreflection.

MIRRORS: REFLECTION AT REGULAR SURFACES

A smooth and well-polished surface that reflects regularly most of the light falling on it is called a mirror.

Types of Mirrors

Mirrors can be plane or spherical.

1. ***Plane mirror.*** Plane mirror is a plane sheet of glass whose one side is silvered and the other side is polished. Plane mirror is also called looking mirror.
2. ***Spherical mirror.*** A spherical mirror (Fig. 1.13) is a part of a hollow sphere whose one side is silvered and the other side is polished. The two types of spherical mirrors are as follows:
   - *Concave mirror* (whose reflecting surface is towards the centre of the sphere) and
   - *Convex mirror* (whose reflecting surface is away from the centre of the sphere).

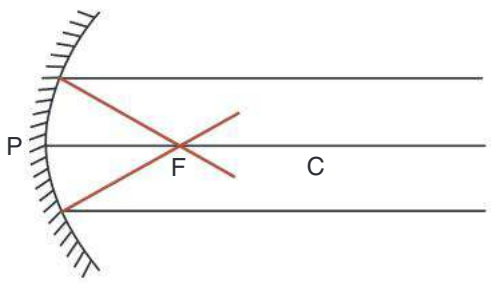


Fig. 1.13 *Cardinal points of a concave mirror.*

Cardinal Data of a Spherical Mirror

Cardinal data of a spherical mirror include (Fig. 1.13) following:

- *Centre of curvature* (C) and *radius of curvature* (r) of a spherical mirror are the centre and radius, respectively, of the sphere of which the mirror forms a part.
- *Normal* to the spherical mirror at any point is the line joining that point to the centre of curvature of the mirror.
- *Pole* (P) of the mirror is the centre of the reflecting surface.
- *Principal axis* of the mirror is the straight line joining the pole and centre of curvature of spherical mirror extended on both sides.
- *Principal focus* (F) of a spherical mirror is a point on the principal axis of the mirror at which rays incident on the mirror in a direction parallel to the principal axis actually meet (as in concave mirror) or appear to diverge (as in convex mirror) after reflection from the mirror.
- *Focal length* (f) of the mirror is the distance of principal focus from the pole of the spherical mirror.

Images Formed by Mirrors

Images Formed by a Plane Mirror

The features of an image formed by a plane mirror (Fig. 1.14):

- It is of the same size as the object.
- It lies at the same distance behind the mirror as the object is in front.
- It is laterally inverted.
- It is virtual in nature.

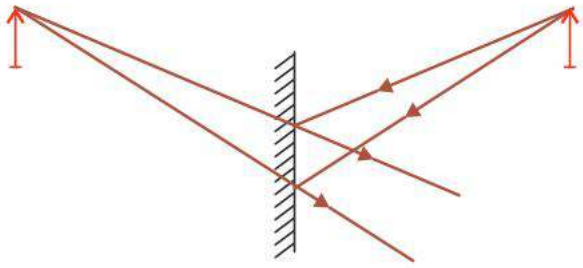


Fig. 1.14 *Image formation with a plane mirror.*

Images Formed by a Concave Mirror

As a summary, Table 1.3 gives the position, size and nature of images formed by a concave mirror for different positions of the object. Figure 1.15(I) illustrates various situations.

Images Formed by a Convex Mirror

The image formed by a convex mirror, as shown in Figure 1.15(II), is always virtual, erect and diminished in size irrespective of the place of object.

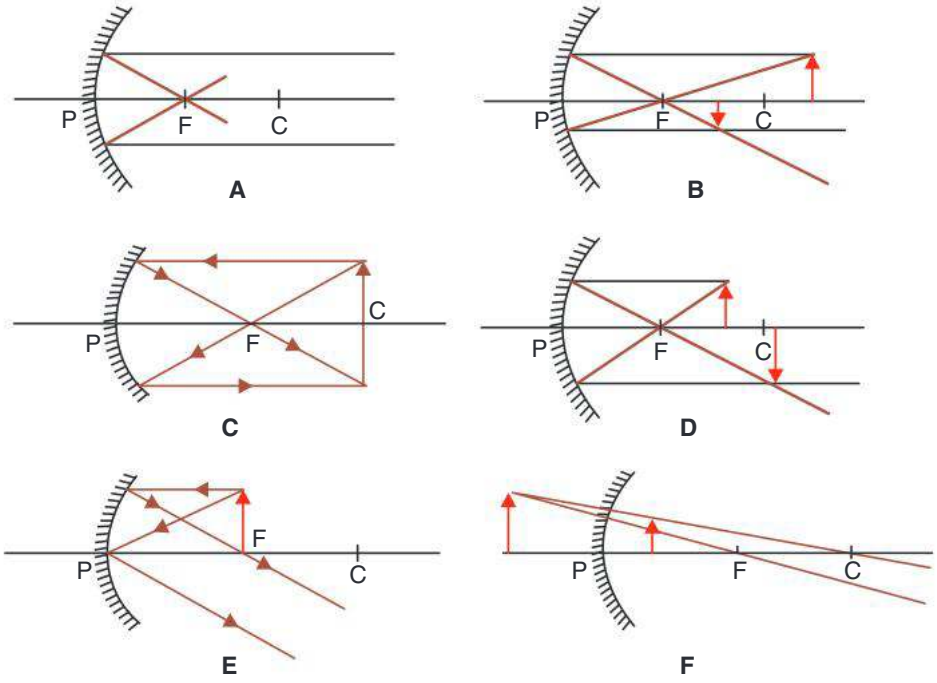
■ RETROREFLECTION

The term retroreflection is used when the reflected ray is returned in the same direction, i.e. parallel to the incident ray. This happens due to some structural peculiarities of the reflecting surface.

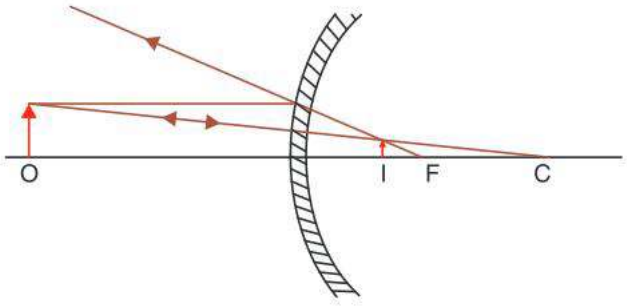
The phenomenon of retroreflection can be explained by the ray diagram of a corner reflector in which the two plane mirrors are placed perpendicular to each other in such a way that the incident ray of light (i), when reflected, becomes incident upon the other mirror surface and the reflected ray from the second mirror travels back in the same direction as the initial incident ray (Fig. 1.16A). This is the principle of retroreflection.

Table 1.3 *Images formed by a concave mirror for different positions of the object*

S. no.	Position of the object	Position of the image	Nature and size of the image	Ray diagram
1.	At infinity	At F	Real, very small and inverted	Fig. 1.15A
2.	Beyond the centre	Between F and C	Real, diminished in size and inverted	Fig. 1.15B
3.	At C	At C	Real, same size as object and inverted	Fig. 1.15C
4.	Between F and C	Beyond C	Real, enlarged and inverted	Fig. 1.15D
5.	At F	At infinity	Real, very large and inverted	Fig. 1.15E
6.	Between P and F	Behind the mirror	Virtual, enlarged and erect	Fig. 1.15F



I: Images formed by a concave mirror



II: Image formed by a convex mirror

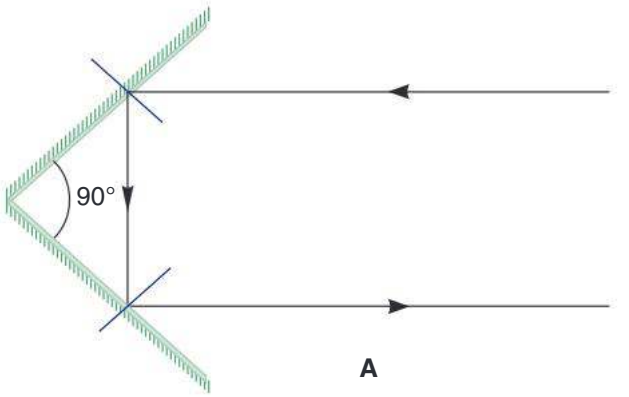
Fig. 1.15 *Images formed by a concave mirror (I) for different positions of the object: A, at infinity; B, between infinity and C; C, at C; D, between C and F; E, at F; F, between F and P; and by a convex mirror (II).*

Applications of Retroreflection

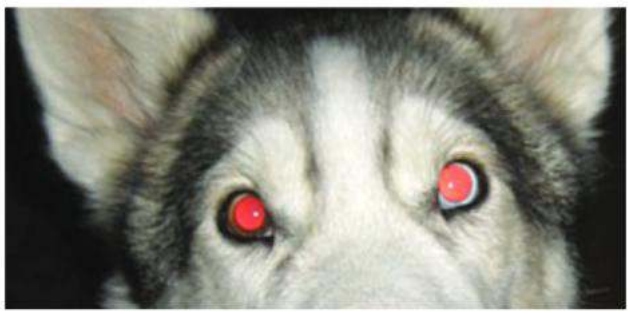
- *Cat's eye reflex* (glowing light) seen in the pupils of animals at night (Fig. 1.16B), occurs due to phenomenon of retroreflection.
- *Seeing a dewdrop on the grass* occurs due to retroreflection.
- *Bruckner's reflex* seen in patients with anisometropia and strabismus results due to retroreflection from the fundus (Fig. 1.16C).
- *Glowing signals on the roads* such as traffic signs, road markings and delineators are made on the basis of phenomenon of retroreflection and are thus visible as glowing signs when a headlight beam shines on them at night.
- *Glowing vests and clothes used by road maintenance workers* at night have bands of retroreflective material for their and pedestrian safety.

DIFFUSE REFLECTION (REFLECTION AT AN IRREGULAR SURFACE)

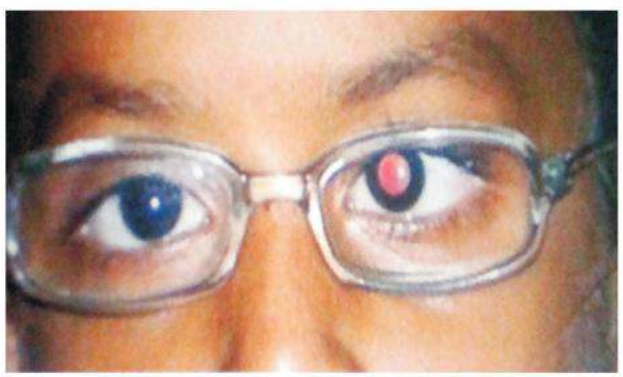
Reflection at an irregular surface is called *diffuse reflection*. In diffuse reflection, the parallel rays of light, after striking an irregular surface, are scattered in different directions (Fig. 1.17).



A



B



C

Fig. 1.16 *A, Principle of retroreflection (for explanation, see text); B, cat's eye reflex seen in animal's eyes due to retroreflection; and C, retroreflection from the fundus of a patient with strabismus (Bruckner's reflex).*

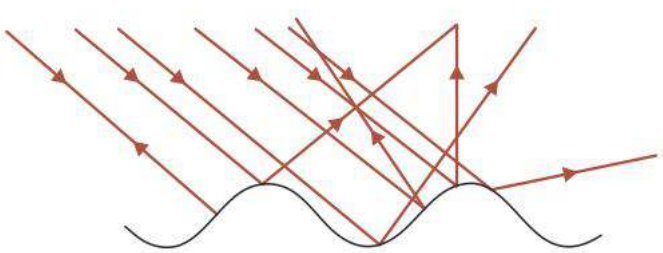


Fig. 1.17 *Reflection at an irregular surface (diffuse reflection).*

Applications of Diffuse Reflection

All the objects (except self-luminous ones) are seen because of diffuse reflection. In fact, some reflection occurs at all the surfaces, even when most of the light is transmitted or absorbed. For example, it is by small amount of reflected light that we see a glass door and thus avoid walking into it. We see buildings, furniture, vehicles, etc., because of diffuse reflection at the interfaces.

CALCULATION OF THE POSITION AND MAGNIFICATION OF THE IMAGE FORMED AFTER REFLECTION

Calculation of position of the image formed by a spherical mirror for any given position of the object is made by using the following formula:

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f} \text{ or } \frac{2}{r}$$

where:

- u is the distance of object from the mirror,
- v is the distance of image from the mirror,
- f is the focal length of the mirror and
- r is the radius of curvature of the mirror.

Calculation of the magnification of the image formed by a spherical mirror is made by using the following formula:

$$M = \frac{i}{o} = \frac{v}{u}$$

where:

- M is the magnification of image,
- i is the image size,
- o is the object size,
- u is the distance of object from the mirror and
- v is the distance of image from the mirror.

Sign convention to be used while using the above formulae is as follows (Fig. 1.18):

- All distances are to be measured from the pole of the mirror (or vertex of the lens) to the point in question.
- *Positive sign* is to be used for all the distances measured in the same direction as the incident light.

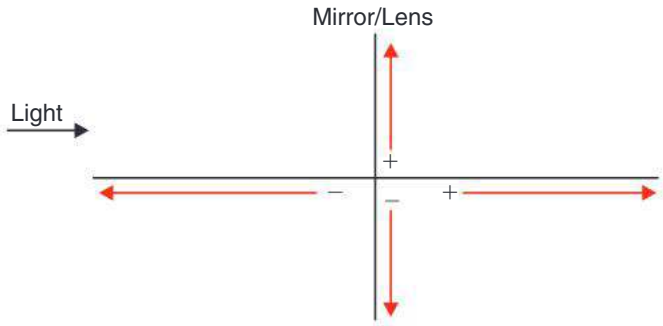


Fig. 1.18 *Sign convention for the formulae used to calculate position and size of the images formed after reflection and refraction.*

- *Negative sign* is to be used for all the distances measured against the direction of the incident light.
- *Image size is positive* for the erect images (formed above the principal axis).
- *Image size is negative* for all inverted images (formed below the principal axis).

REFRACTION OF LIGHT

Refraction of light is the phenomenon of change in the path of light, when it goes from one medium to another. The basic cause of refraction is change in the velocity of light when going from one medium to the other.

Before describing the refraction of light through different surfaces, it will be worthwhile to know about:

- Laws of refraction and
- Total internal refraction.

Laws of Refraction

Laws of refraction depicted in Figure 1.19 are given below:

1. The incident and refracted rays are on opposite sides of the normal and all the three are in the same plane.

2. The ratio of sine of angle of incidence to the sine of angle of refraction is constant for the part of media in contact. This constant is denoted by the letter n and is called *refractive index* of the medium 2 (in which the refracted ray lies) with respect to medium 1 (in which the incident ray lies), i.e. $\sin \iota / \sin r = {}^1n_2$. When the medium 1 is air (or vacuum), then n is called the refractive index of the medium 2. This law is also called *Snell's law of refraction.*

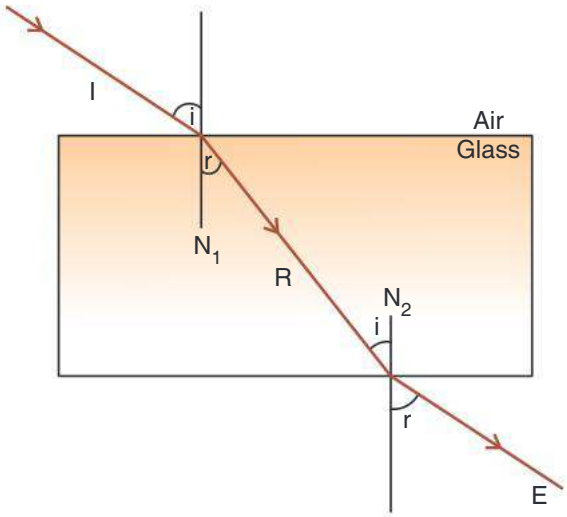


Fig. 1.19 *Laws of refraction. N_1 and N_2 (normals); I (incident ray); i (angle of incidence); R (refracted ray, bent towards normal); r (angle of refraction); E (emergent ray, bent away from the normal).*

Total Internal Reflection

When a ray of light travelling from an optically denser medium to an optically rarer medium is incident at an angle greater than the critical angle of the pair of media in contact, the ray is totally reflected back into the denser medium (Fig. 1.20). This phenomenon is called *total internal reflection.*

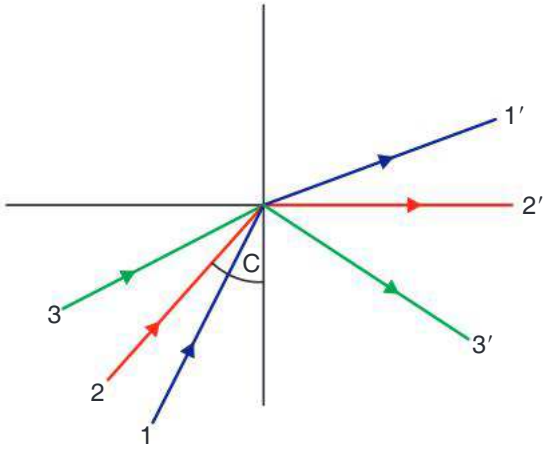


Fig. 1.20 *Refraction of light (1–1′); path of refracted ray at critical angle, C(2–2′); and total internal reflection (3–3′).*

Critical angle refers to the angle of incidence in the denser medium, corresponding to which the angle of refraction in the rarer medium is 90 degrees. It is represented by *C* and its value depends on the nature of media in contact.

Applications. The principle of total internal reflection is utilized in many optical equipment, such as fibre-optic lights, applanation tonometer and gonioscope.

REFRACTION THROUGH VARIOUS SURFACES

Occurrence of refraction of light need to be described under the following circumstances:

- Refraction through plane media,
- Refraction through prism,
- Refraction through curved surface,
- Refraction through spherical lenses and
- Refraction through cylindrical lenses.

REFRACTION THROUGH PLANE MEDIA

When refraction occurs through plane media, e.g. from air through a glass plate (Fig. 1.19), the incident ray (I), which interacts obliquely initially deflects towards the normal (towards N_1 in Fig. 1.19) within the glass. However, the emergent ray (E) back in the air gets deflected away from the normal (N_2 in Fig. 1.19). The shift of light ray towards normal in the denser medium (N_1 in Fig. 1.19) while coming from rarer is responsible for the phenomenon of objects appearing nearer than actually they are. For example, an object at the bottom of a water-filled bucket appears to be closer than what it really is (also see page 29, Fig. 1.43). Conversely, shift of light rays away from the normal while coming from denser to rarer medium accounts for the objects appearing farther than they actually are.

REFRACTION THROUGH PRISMS

A prism (Fig. 1.21) is a refracting medium, having two plane surfaces, inclined at an angle.

- *Refracting angle* or apical angle of a prism is the angle between two surfaces (x in Fig. 1.21). The greater the angle formed by two surfaces at the apex, the stronger the prismatic effect.

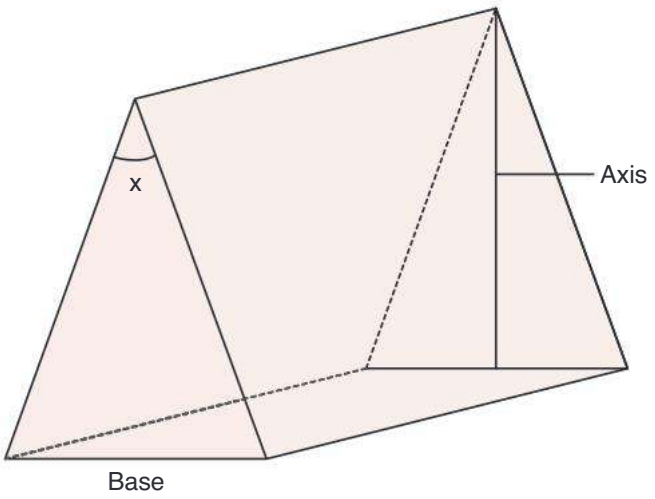


Fig. 1.21 *A prism; note its axis, base and the refracting angle.*

- *Axis of the prism* refers to the line bisecting the apical angle.
- *Base of prism* refers to the surface opposite to the apical angle. When prescribing a prism, the orientation is indicated by the position of the base, e.g. 'base-in' or 'base-out' or 'base-up'.

Refraction through a prism. Light ray passing through a prism obeys the Snell's law of refraction at each surface. The ray is deviated towards the base of the prism. The prism produces displacement of the objects seen through it towards apex (away from the base) (Fig. 1.22).

- *Angle of deviation* (D) refers to the net change in direction of the light ray passing through the prism. It is determined by three factors:
  - Refractive index of the prism material,
  - Refracting angle (λ) of prism and
  - Angle of incidence of the ray.

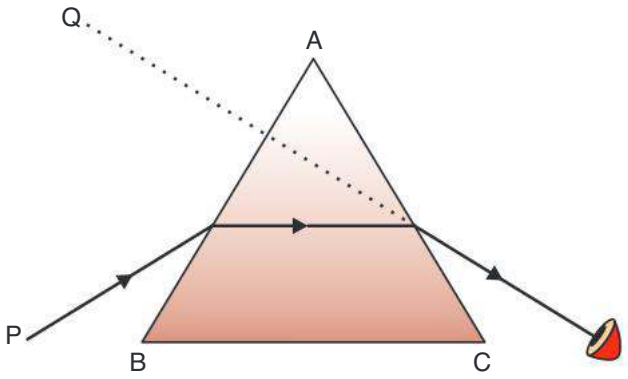


Fig. 1.22 *Refraction through a prism.*

By the rules of trigonometry:

Total deviation = Angle of incidence + Angle of emergence – Apical angle

- *Angle of minimum deviation* is produced when the angle of incidence equals the angle of emergence, i.e. when refraction is symmetrical.
- *Image formed by a prism* is erect, virtual and displaced towards the apex of the prism.
- *Power of a prism* is measured in prism dioptres. One prism dioptre (Δ) produces displacement of an object by 1 cm when kept at a distance of 1 m (Fig. 1.23). One prism dioptre of displacement is central or 0.57 degrees of arc.

Uses of Prisms in Ophthalmology

1. Diagnostic Uses

- Objective measurement of angle of deviation (prism cover test and Krimsky test).
- Subjective measurement of angle of deviation with Maddox rod.
- Measurement of fusional reserve.
- Diagnosis of microtropia (4 D prism test).
- To assess likelihood of diplopia after proposed squint surgery in adults.
- To diagnose malingering (simulated blindness).

Prisms used for diagnostic purposes are available as:

- Unmounted loose prisms,
- Mounted prisms from the trial lens set and
- Prism bars (horizontal and vertical, Fig. 1.24).

2. Therapeutic Uses of Prisms

- *To build up fusional reserve* in patients with convergence insufficiency (prisms are used base-out during exercise period only).
- *To relieve diplopia* in patients with decompensated phorias, small hypertropias and some patients of paralytic squint having diplopia in primary position.

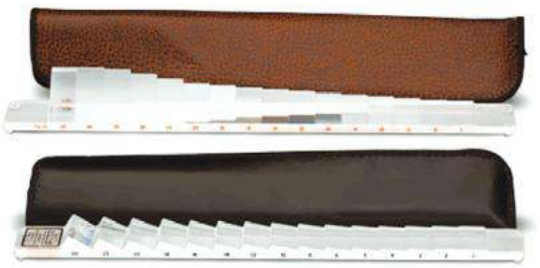


Fig. 1.24 *Prism bars: A, horizontal; B, vertical.*

Prisms used for therapeutic purposes

For temporary wear, the prisms used include:

- *Clip on spectacle prisms* and
- *Fresnel prisms*: These consist of a plastic sheet of parallel tiny prisms, which can be stuck on to the patient's glasses (Fig. 1.25).

For permanent wear, the prisms can be incorporated into the patient's spectacle by decentring the spherical lens prescribed to the patient.

Prentice's formula, used for determining the amount of prismatic effect (P) produced by decentration (d) of the lens of particular power (D), is as follows:

P = d (distance from optical centre in cm) × D (power of the lens in dioptre).

When patient does not need spherical correction, the prisms can be mounted in the spectacle.

Guidelines for prescription of prisms:

- Split the amount of correction equally between the two eyes.

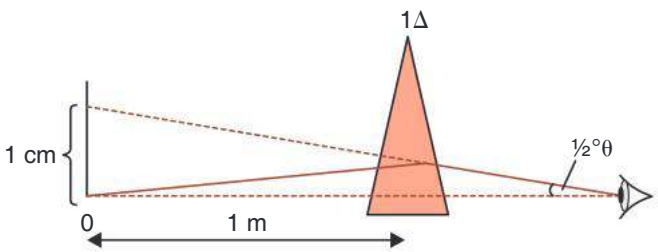


Fig. 1.23 *Refraction through a prism of one dioptre (Δ).*

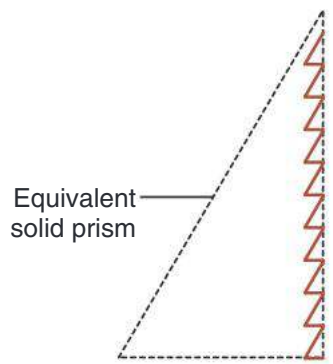


Fig. 1.25 *Diagrammatic depiction of Fresnel prism.*

- Base-out prisms are prescribed to correct esodeviations.
- Base-in prisms are prescribed to correct exodeviations.

Note. ATP (apex towards phoria, i.e. deviation) is the acronym to remember principle of prescribing prisms to correct deviations.

3. Use of Prisms in Optical Instruments

Prisms are commonly used as reflectors of light in ophthalmic instruments such as slit-lamp biomicroscope, gonioscope, keratometer and applanation tonometer.

■ REFRACTION AT A CURVED SURFACE

The study of refraction at curved surfaces is of practical importance in ophthalmology, since cornea is a convex curved surface. A ray of light that strikes a spherical surface separating two transparent media having different indices of refraction will be refracted as by Snell's law in plane surface refraction. The amount of refraction is dependent on the angle of incident light (or its vergence and the dioptric power of a spherical surface).

***Dioptric power* of a spherical reflecting surface** is equal to the difference in index of refraction of the two media divided by the radius of curvature of surface, $Ds = (n' - n)/r$, where n equals the index of refraction to the left of the surface, n′ equals the index of refraction to the right of the surface and r equals the radius of curvature (in metres) of the spherical surface: r is positive if to the right of the surface, and negative if to the left. For example (Fig. 1.26), a transparent medium (n = 1.5) is separated from air (n = 1) by a spherical surface of which the radius of curvature is 1 m. The refractive power at this surface $5(n' - n)/r = (1.5 - 1)/1 = 10.5$ D = Ds. Thus, +0.5 D of vergence is added to any ray of light incident at this surface. This ray of light, after entering the new optic medium, will now travel within that medium at a reduced velocity. If the ray of light now passes out of that medium back into air or a different medium, refraction is again said to occur at the new interface (Fig. 1.27).

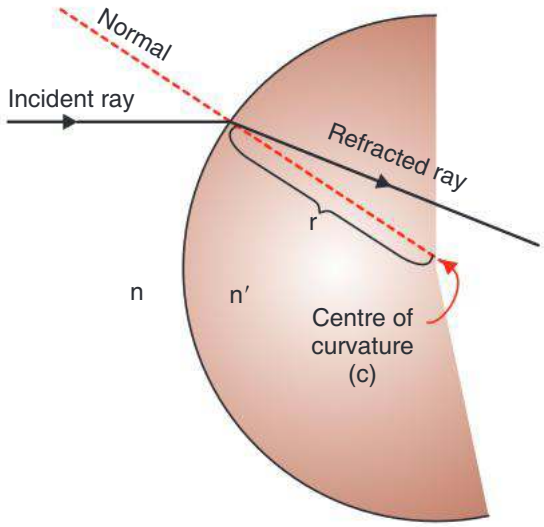


Fig. 1.26 *Curved surface refraction. n′ is greater than n; therefore, light is refracted towards the normal.*

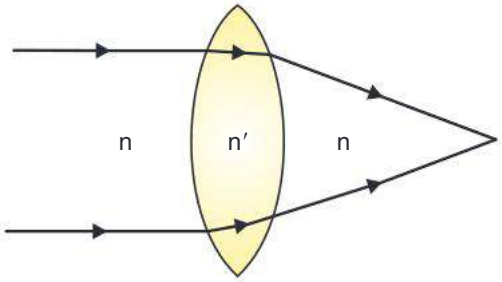


Fig. 1.27 *Refraction occurs at front and back surfaces of lens (n′ is greater than n).*

■ THE LENSES

The lenses represent curved surfaces. A lens is a transparent refracting medium, bounded by two surfaces that form a part of a sphere (spherical lens) or a cylinder (cylindrical or toric lens).

Types of lenses. Thus, lenses are of two types:

- Spherical lenses and
- Cylindrical (or toric or astigmatic) lenses.

■ CARDINAL DATA OF A LENS

1. ***Centre of curvature*** (C) of the spherical lens is the centre of the sphere of which the refracting lens surface is a part (Figs 1.26 and 1.28).

2. ***Radius of curvature*** (r) of the spherical lens is the radius of the sphere of which the refracting surface is a part (Fig. 1.26).

3. ***Principal axis*** (AB) of the lens is the line joining the centres of curvatures of its surfaces (Fig. 1.28).

4. ***Optical centre*** (N) of the lens corresponds to the nodal point (principal point) of a thick lens (Fig. 1.28). It is a point on the principal axis of the lens, the rays passing from where do not undergo deviation. In meniscus lenses, the optical centre lies outside the lens. At principal point, the principal axis and principal plane of the lens intersect.

5. ***Principal focus*** (F) of a lens is that point on the principal axis where parallel rays of light, after passing through the lens, converge (in convex lens) or appear to diverge (in concave lens).

Since the light ray can pass through a lens from either side, each lens has two principal foci, F_1 and F_2. As it is customary to always show the light travelling from left to right in all optical diagrams, the F_1 and F_2 can be defined as follows:

- *First principal focus* (F_1) is defined as a point on the principal axis on left side of the lens, the light rays originating from which after refraction by the lens become parallel to the principal axis (Fig. 1.29).
- *Second principal focus* (F_2) is defined as a point on the principal axis on the right side of the lens, where light rays parallel to principal axis after refraction through a lens converge (in convex lens) or appear to diverge (in concave lens) (Fig. 1.29).

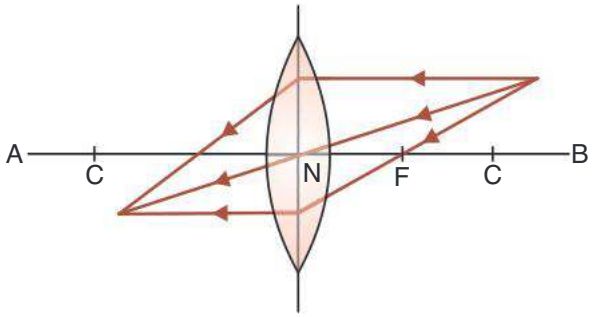


Fig. 1.28 *Cardinal points of a convex lens: optical centre (N); principal focus (F); centre of curvature (C); and principal axis (AB).*

6. ***Focal length*** (f) of a lens is the distance between the optical centre and the principal focus.

Since a lens has two principal foci, there are two focal lengths, f_1 and f_2, for each lens (Fig. 1.29).

- *First focal length* (f_1) is the distance between the principal point (N) and the first principal focus (F_1).
- *Second focal length* (f_2) is the distance between the principal point (N) and the second principal focus (F_2).

Note. When the medium on both sides of the lens is same, e.g. air, then $f_1 = f_2$. However, when the second medium differs from the first, e.g. as in the case of contact lens, then f_1 will not be equal to f_2.

7. ***Power of a lens*** (P) is defined as the ability of the lens to converge a beam of light falling on the lens. For a converging (convex) lens, the power is taken as positive and for a diverging (concave) lens, the power is taken as negative. It is measured as reciprocal of the second focal length in metres, i.e. $P = 1/f_2$. The unit of power is dioptre (D). One dioptre is the power of a lens with second focal length as 1 m.

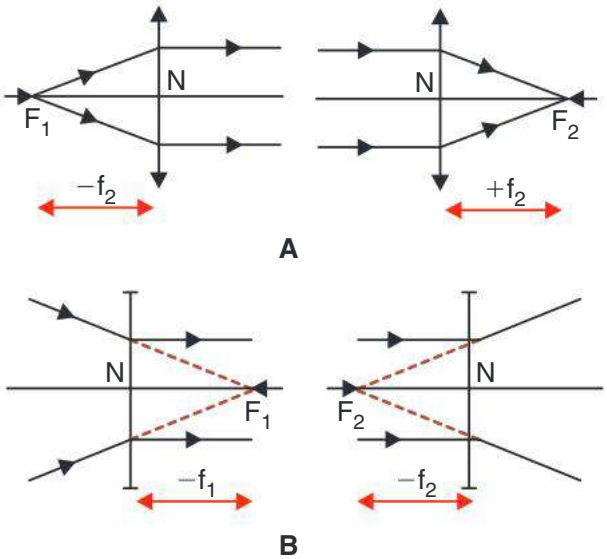


Fig. 1.29 *The principal foci F_1 and F_2 of convex lens (A) and concave lens (B).*

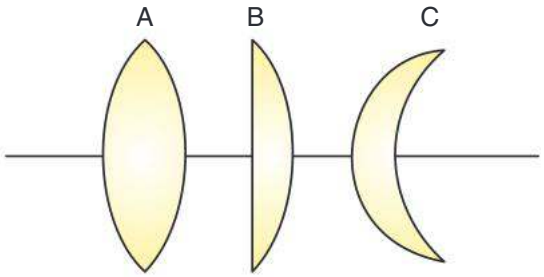


Fig. 1.30 *Basic forms of a convex lens: A, biconvex; B, plano-convex; C, concavo-convex.*

REFRACTION THROUGH SPHERICAL LENSES

Spherical lenses are bounded by two spherical surfaces and are mainly of two types: convex and concave.

1. Convex Lens

Convex lens or plus lens is a converging lens. It may be of biconvex, plano-convex or concavo-convex (meniscus) type (Fig. 1.30).

Identification of a convex lens. (i) The convex lens is thick in the centre and thin at the periphery. (ii) An object held close to the lens appears magnified. (iii) When a convex lens is held near the eye and is moved sideways, a distant object seen through it moves in the opposite direction to the lens.

Uses of convex lens. It is used (i) for correction of hypermetropia, aphakia and presbyopia, (ii) in oblique illumination (loupe and lens) examination and (iii) in indirect ophthalmoscopy, as a magnifying lens, and many other equipment.

Image formation by a convex lens. Table 1.4 and Figure 1.31 provide details about the position, size and the nature of the images formed by a convex lens.

2. Concave Lens

Concave lens or minus lens is a diverging lens. It is of three types: biconcave, plano-concave and convexo-concave (meniscus) (Fig. 1.32).

Identification of concave lens. (i) It is thin in the centre and thick at the periphery. (ii) An object seen through it appears minified. (iii) When the lens is moved, the object seen through it moves in the same direction as the lens.

Uses of concave lens. It is used (i) for correction of myopia and (ii) as Hruby lens for fundus examination with slit lamp.

Image formation by a concave lens. A concave lens always produces a virtual, erect and diminished image of an object (Fig. 1.33).

REFRACTION THROUGH A CYLINDRICAL LENS

A cylindrical lens acts only in one axis; i.e. power is incorporated in one axis, the other axis having zero power. A cylindrical lens may be convex (plus) or concave (minus). A convex cylindrical lens is a segment of a cylinder of glass cut parallel to its axis (Fig. 1.34A), whereas a lens cast in a convex cylindrical mould is called concave cylindrical lens (Fig. 1.34B). The axis of a cylindrical lens is parallel to that of the cylinder of which it is a segment. The cylindrical lens has a power only in the direction at right angle to the axis. Therefore, the parallel rays of light after passing through a cylindrical lens do not come to a point focus but form a focal line (Fig. 1.35).

Table 1.4 *Images formed by a convex lens for various positions of the object*

S. no.	Position of the object	Position of the image	Nature and size of the image	Ray diagram
1.	At infinity	At focus F_2	Real, very small and inverted	Fig. 1.31A
2.	Beyond $2F_1$	Between F_2 and $2F_2$	Real, diminished and inverted	Fig. 1.31B
3.	At $2F_1$	At $2F_2$	Real, same size and inverted	Fig. 1.31C
4.	Between F_1 and $2F_1$	Beyond $2F_2$	Real, enlarged and inverted	Fig. 1.31D
5.	At focus F_1	At infinity	Real, very large and inverted	Fig. 1.31E
6.	Between F_1 and the optical centre of the lens	On the same side of lens	Virtual, enlarged and erect	Fig. 1.31F

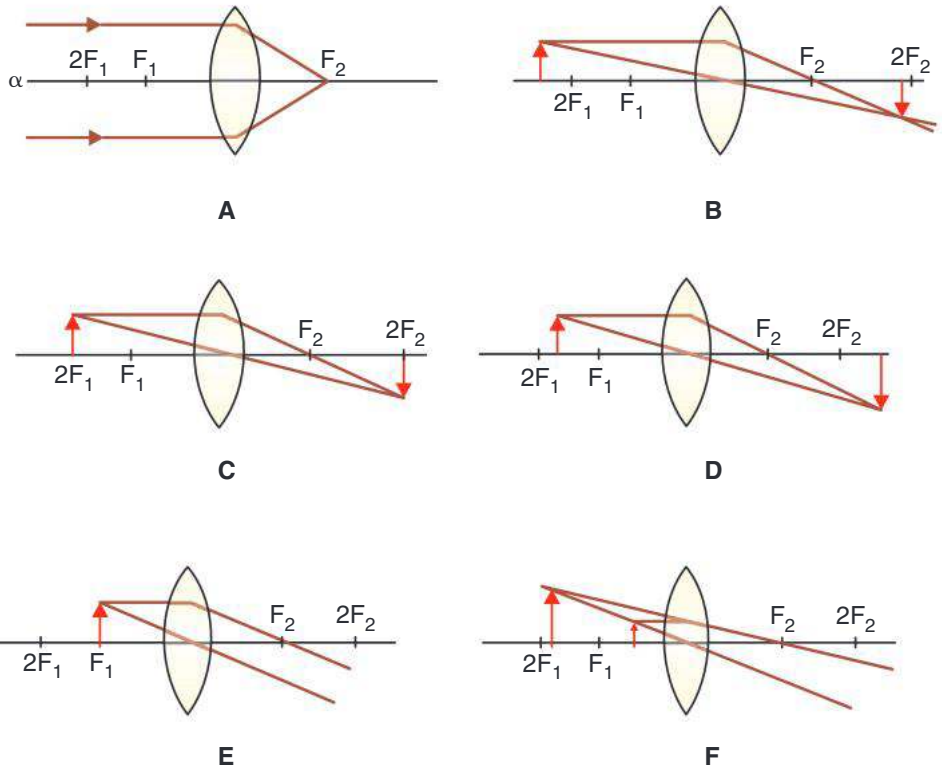


Fig. 1.31 *Images formed by a convex lens for different positions of the object: A, at infinity; B, beyond 2F; C, at $2F_1$; D, between F_1 and $2F_1$; E, at F_1; F, between F_1 and optical centre of lens.*

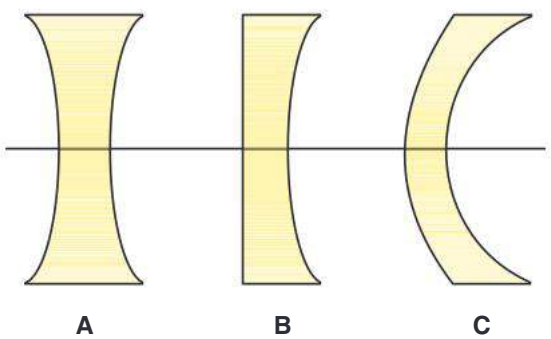


Fig. 1.32 *Basic forms of a concave lens: A, biconcave; B, plano-concave; and C, convexo-concave.*

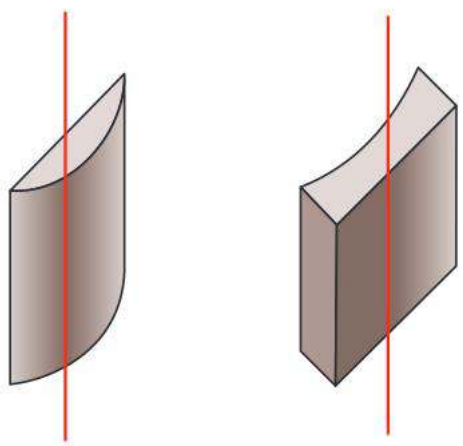


Fig. 1.34 *Cylindrical lenses: A, convex and B, concave.*

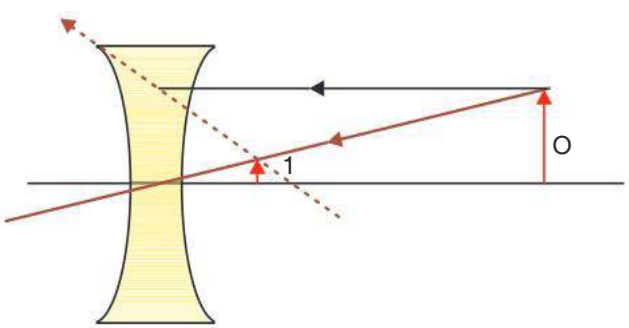


Fig. 1.33 *Image formation by a concave lens.*

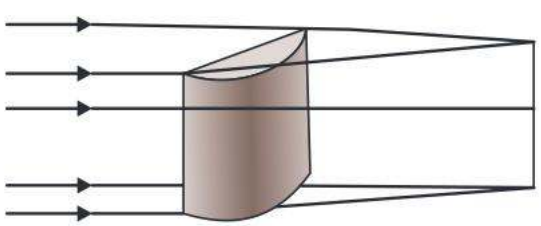


Fig. 1.35 *Refraction through a convex cylindrical lens.*

Identification of a cylindrical lens

- When the cylindrical lens is rotated around its optical axis, the object seen through it becomes distorted.
- The cylindrical lens acts in only one axis, so when it is moved up and down or sideways, the objects will move with the lens (in concave cylinder) or opposite to the lens (in convex cylinder) only in one direction.

Uses of cylindrical lenses

- Prescribed to correct astigmatism.
- As a cross cylinder used to check the refraction subjectively.
- Maddox rod consists of a series of powerful convex cylindrical lenses mounted together in a trial lens.

Images formed by cylindrical lenses

Cylindrical or astigmatic lens may be of three types:

- *Simple* (curved in one meridian only, either convex or concave).
- *Compound* (curved unequally in both the meridia, either convex or concave). The compound cylindrical lens is also called *spherocylinder*.
- *Mixed cylinder*, one meridian is convex and the other is concave.

The images formed by different types of cylindrical lenses are best understood by the study of Sturm's conoid.

Sturm's Conoid

As described above, in a toric surface, one principal meridian is more curved than the second principal meridian. The principal meridian with minimum curvature, and therefore with minimum power, is called *base curve* of a toric lens (Fig. 1.36).

The configuration of rays refracted through a toric surface is called the Sturm's conoid. The shape of bundle of the light rays at different levels in Sturm's conoid (Fig. 1.37) is as follows:

- *At point A*, the vertical rays (V) are converging more than the horizontal rays (H); so the section here is horizontal oval or an oblate ellipse.
- *At point B* (first focus), the vertical rays have come to a focus while the horizontal rays are still converging and so they form a horizontal line.

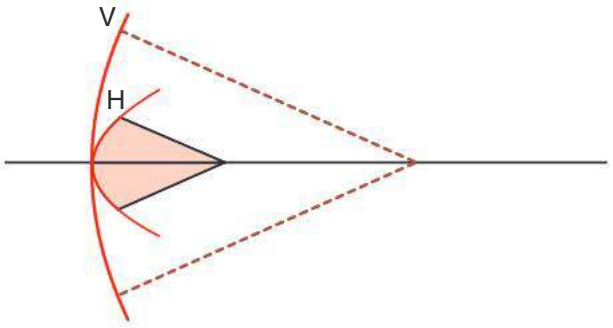


Fig. 1.36 *Principal meridia of a toric surface. (Dotted radii, vertical meridian V; shaded sector, horizontal meridian H.)*

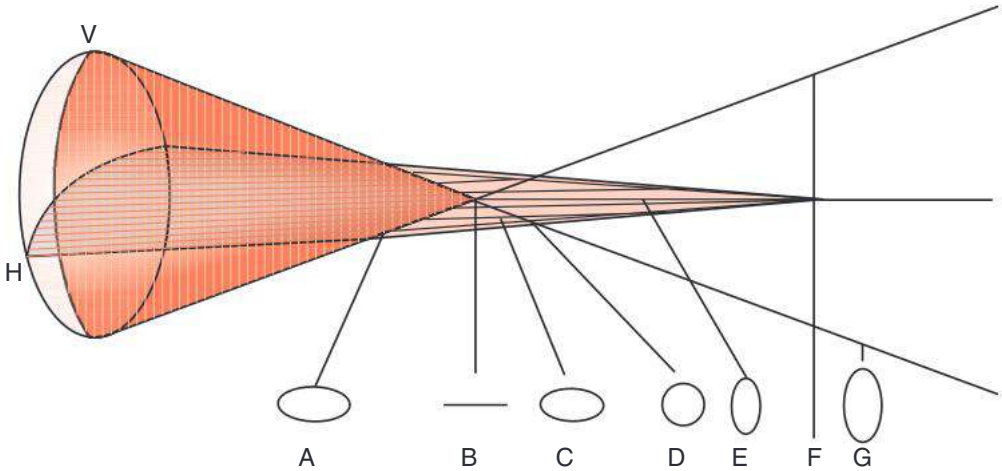


Fig. 1.37 *Sturm's conoid.*

- *At point C*, the vertical rays are diverging and their divergence is less than the convergence of the horizontal rays; so, a horizontal oval is formed here.
- *At point D*, the divergence of vertical rays is exactly equal to the convergence of the horizontal rays from the axis. So here, the section is a circle, which is called the *circle of least diffusion*.
- *At point E*, the divergence of vertical rays is more than the convergence of horizontal rays; so, the section here is a vertical oval.
- *At point F* (second focus), the horizontal rays have come to a focus while the vertical rays are divergent and so a vertical line is formed here.
- *Beyond F* (as at point G), both horizontal and vertical rays are diverging and so the section will always be a vertical oval or prolate ellipse.
- The distance between the two foci (B and F) is called the *focal interval of Sturm*.

COMBINATION OF LENSES AND GAUSS' THEOREM

The image produced by light rays passing through two or more lenses in succession can be determined by noting that the image produced by the first lens acts as an object to the second lens, the image produced by the second lens acts as an object for the third lens and so on. Thus, if an object is located 25 cm in front of the first lens of an optical system consisting of three lenses having powers of +2, +5 and –5 D and the separation between the first and the second lens is 50 cm and between the second and the third lens is 5 cm, the final image is located as follows (Fig. 1.38).

The image with respect to the first lens is found from $21/0.25 + 2 = V_1$, $–4 + 2 = –2 = V_1$ or 50 cm in front of first lens. This image is the object with respect to the second lens; it lies 1 m (50 cm + 50 cm) in front of the second lens.

The image produced by the second lens is found from $–1 + 5 = V_2 = 14$ D. The image is, therefore, located at $1/+4$ D = 25 cm behind the second lens. This image is the object with respect to the third lens; it lies 20 cm behind the third lens. The final image, that is the image produced by the third lens, is found from $+1/0.20 – 5 = +5 – 5 = V_3 = 0 = V_3 =$ infinity.

Such a mathematical calculation becomes very tedious when several such lenses are situated with their optical axes coinciding with each other. Gauss devised a simple alternative to the above-described tedious calculation, termed as *Gauss' theorem*. According to it, for a system of homocentric lenses, there exist three pairs of cardinal points, which are two principal foci, two principal points and two nodal

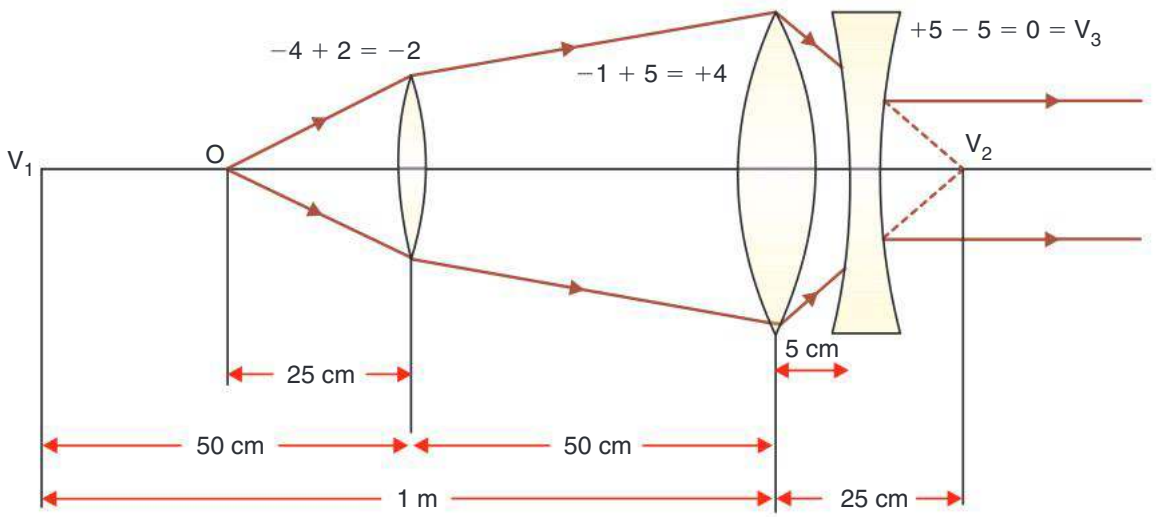


Fig. 1.38 *Pathway of light through multiple lenses. Rays from object point O pass through first lens to focus at V_1, which acts as object point for second lens and is conjugate with point V_2. Rays of light from V_2 are refracted by final lens to infinity.*

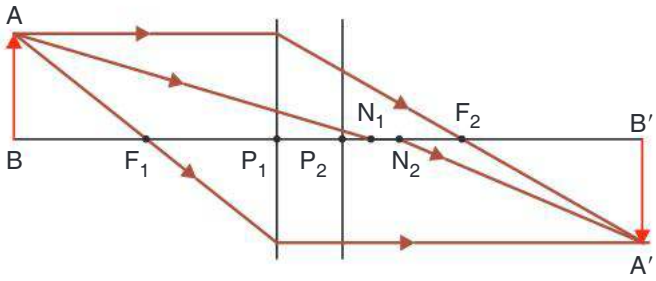


Fig. 1.39 *Cardinal points of combination of lenses according to Gauss' theorem.*

points, all situated on the principal axis of the system. These are as follows (Fig. 1.39):

- *The principal foci* (F_1 and F_2). The first principal focus (F_1) is the point on principal axis at which parallel rays emerging from the system intersect. The second principal focus (F_2) is the point on the principal axis at which parallel rays entering the system intersect.
- *The principal points* (P_1 and P_2). The principal points are such that an incident ray passing the first principal point (P_1) passes after refraction through the second principal point (P_2), but the incident and emergent rays are not necessarily parallel. The two principal points correspond to the conjugate foci of a simple lens.
- *The nodal points* (N_1 and N_2). The nodal points are such that every ray that before refraction is directed towards the first nodal point (N_1), after refraction, appears to come from the second nodal point (N_2) in a direction parallel to the incident ray.

CALCULATION OF THE POSITION AND MAGNIFICATION OF THE IMAGE FORMED BY LENSES

Calculation of the Position of Image Formed by a Lens

The position of the image formed by a lens for any given position of the object is calculated by using the formula:

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f_2}$$

where:

- v is the distance of the image from the principal point,
- u is the distance of the object from the principal point and
- f_2 is the second focal length of the lens.

Calculation of the Magnification of the Image Formed by a Lens

Linear magnification produced by a spherical lens can be calculated by the use of the following formula (Fig. 1.40):

$$LM = \frac{I}{O} = \frac{v}{u}$$

where:

- LM is the linear magnification,
- I is the image size,
- O is the object size,
- v is the distance of the image from the principal plane and
- u is the distance of the object from the principal plane.

Angular magnification. In the eye, the angle subtended by the object governs the retinal image size. Therefore, in ophthalmic practice, actual object and image size is of less importance than the angle subtended at the eye. As shown in Figure 1.41, the objects A, B, C and D all subtend angle θ at the eye and produce a retinal image xy. Therefore, all the objects are of the same apparent size. The apparent size is given by the ratio of the object (or image) size divided by its distance from the eye.

DIOPTRIC POWER OF LENSES (VERGENCE)

As mentioned earlier, the vergence power of a lens (positive for a convex converging lens and negative for a concave diverging lens) is reciprocal of the second focal length expressed in metres, i.e. $D = 1/f_2$. The unit of power is dioptre (D). One

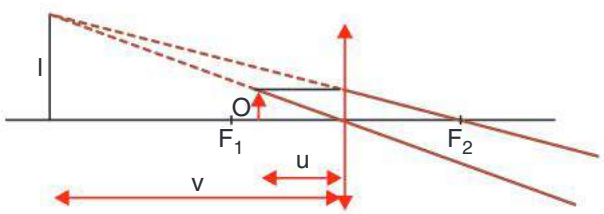


Fig. 1.40 *Calculation of linear magnification produced by a convex lens when the object is placed within focal length.*

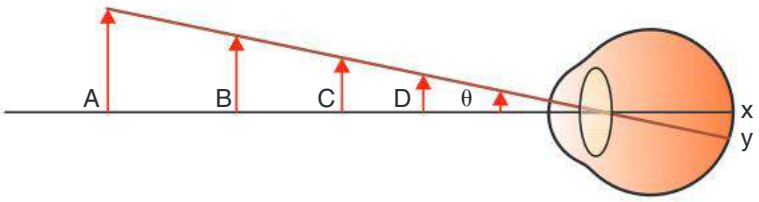


Fig. 1.41 *Apparent size and visual angle.*

dioptre is the power of a lens with second focal length as 1 m.

For example, a convex lens of second focal length 50 cm (0.5 m) has a power of:

$$D = \frac{1}{f_2} = \frac{1}{0.5} = 2$$

Theoretically, the total power (D_0) of a thin lens is equal to the sum of the powers at each of its two surfaces. Thus, $D_0 = D_1 + D_2$, where D_1 is the anterior surface power and D_2 the posterior surface power. Since a number of pairs of powers D_1 and D_2 may give the same D_0 (e.g. $D_0 = 12$ may result from values of $D_1 = +1, +2, +3$, paired, respectively, with values of $D_2 = +1, 0, -1$), the lens may be given any desirable shape (Fig. 1.42). Ophthalmic lenses prescribed for glasses are generally meniscus shaped; the front surface is convex and the back surface is concave.

Until now, we have said that the vergence of a ray of light from an object is equal to 1/u, where u is the distance of the object along the optic axis to the lens. Actually, the vergence of a ray of light is also directly related to the index of refraction of the optic medium in which it is travelling and equals n/u. Since the index of refraction (n) of air or vacuum equals 1, vergence in these media equals 1/u. In any other medium, however, the index of refraction must be taken into account when determining the vergence of light rays within that medium. This is termed the reduced vergence. This term is somewhat misleading because the reduced vergence produced by light rays located at any given point in an optically dense medium is always numerically greater than the vergence produced by another point similarly located in air or in vacuum. For example, an object O located 1 m under water (n = 1.33) has a vergence at the surface of water as 1.33/1 or 1.33 D. This produces a virtual image, 75 cm from the surface. Thus, to an observer in air, this object appears closer to the surface than it truly is (Fig. 1.43).

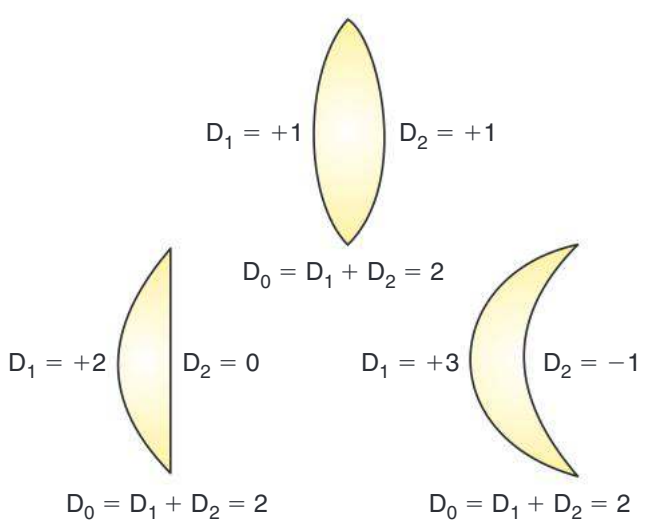


Fig. 1.42 *Various shaped +2 D lenses.*

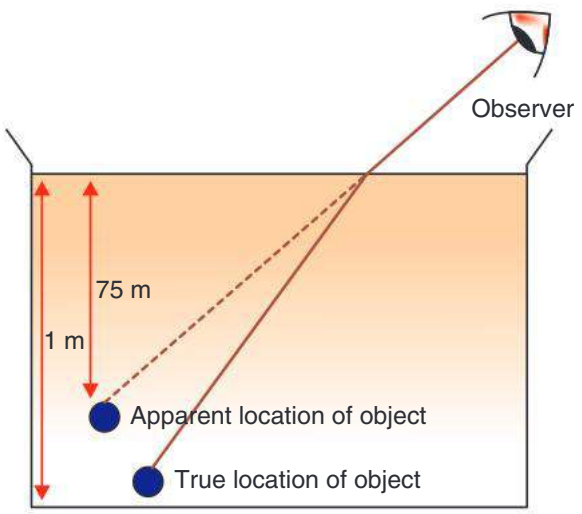


Fig. 1.43 *Object located 1 m under water appears to be only 75 cm from the surface.*

Thus, calculation of the vergence of a ray of light passing through a lens at its second surface is dependent not only on the distance from the first surface to the second (lens thickness = t) but also on the index of refraction, n, of the lens material, because of the concept of reduced vergence. The true or effective power of a real or thick lens is given by the formula $D_0 = \{D_1 + [1 - t/n(D_1)]\} + D_2$ or approximately, $D_0 = D_1 + D_2 + t/n(D_1)$. Since the power of a thin lens equals $D_1 + D_2$, the power of a thick lens differs approximately by the term $t/n(D_1)^2$. The value of this term $t/n(D_1)^2$ is usually small, but if the lens is rather thick and the front surface D_1 is highly curved, it must not be neglected. For example, if t = 5 mm and $D_1 = +11$ D, then $t/n(D_1)^2 = 0.005/1.5 \times 121 = 0.4$ D.

The Geneva lens measure is an ophthalmic device that measures the radius of curvature of a lens and converts this reading directly into dioptres on the instrument's dial (Fig. 1.44). This requires that the index of refraction (n′) equals 1.52 for the lens (ordinary crown glass). Thus, D = [n′ – n (air)/r] = [1.52 – 1/r]. The overall power of the lens being measured can then be calculated as that for a thin lens. For example, if the front surface of a minus lens measures +5 D and the rear surface of the lens measures –10 D, the overall power (neglecting its thickness) = +5 D – 10 D = –5 D.

Fig. 1.44 *Geneva lens measure.*

PHYSIOLOGICAL OPTICS (OPTICS OF THE EYE)

EYE AS AN OPTICAL INSTRUMENT

As an optical instrument, the eye can be compared with a camera as follows:

- *Eyelids* act as shutter of the camera.
- *Cornea and crystalline lens* act as focusing system of the camera with a total power of about + 60 D (cornea + 43D and lens + 17D).
- *Iris* acts as diaphragm which regulates the size of the aperture (*pupil*) and therefore the amount of light entering the eye.
- *Choroid* helps in forming the darkened interior of the camera.
- *Retina* acts as light-sensitive plate or film on which image is formed.

To be more precise, the functioning of the eye can be considered to be analogous to a closed-circuit colour TV system as depicted in Figure 1.45. The optic nerve and its connections convey the details of the image to the occipital region of the cerebral cortex, where they are processed before reaching consciousness.

COMPONENTS OF THE EYE'S OPTICAL SYSTEM

Broadly, the compound optical system of the eye may be divided into a *corneal portion*, including the tear layer that separates air from aqueous humour and a *lens portion* that separates aqueous humour from the vitreous humour. Thus, as a whole, the focusing system of eye is composed of cornea, aqueous humour, crystalline lens and vitreous humour.

These structures constitute a homocentric system of lenses, which when combined in action form a very strong system of short focal length. The total dioptric power of the eye is about +60 D, out of which about +43 D is contributed by the cornea and +17 D by the crystalline lens.

For practical purposes, the optical system of the eye is considered perfect, and it is assumed that the corneal and lenticular surfaces are spherical and their centres of curvatures lie

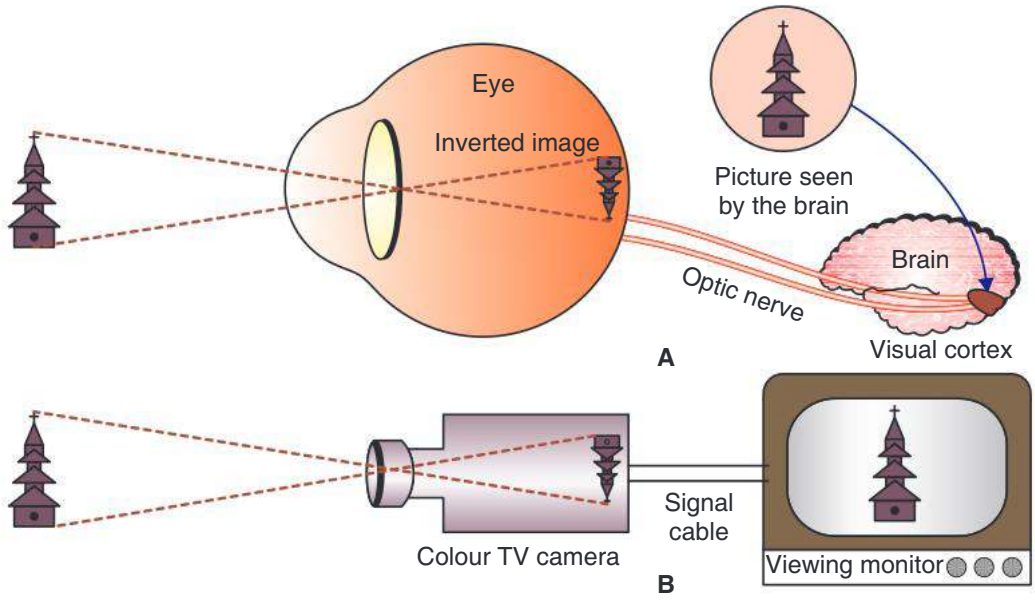


Fig. 1.45 *Functioning of eye as an optical system (A) is in many ways similar to a closed-circuit colour TV system (B).*

on a straight line – the optical axis. However, actually the optical system of the eye has got the following *imperfections*:

- The refractive surfaces tend to be aspherical.
- The crystalline lens is usually slightly decentred and tipped with respect to the axis of the cornea and with respect to the visual axis of the eye.
- The crystalline lens consists of non-homogeneous material.

With this introduction, we can now study the various components of the eye's optical system, first in sequence and then the system as a whole.

1. The Cornea

The cornea is a highly transparent structure of meniscus form, approximately 12 mm in diameter and slightly smaller vertically than horizontally. The centre thickness is usually between 0.5 and 0.6 mm.

A thin layer of lacrimal fluid normally covers the anterior surface, but it is too thin to affect the power appreciably and may be ignored in this context.

To a first approximation, both surfaces may be regarded as spherical, the radii of curvature having values approximately +7.7 mm (anterior) and +6.8 mm (posterior).

The refractive index of the corneal substance may be taken as 1.376 and that of the aqueous humour, in contact with the back surface of the cornea, as 1.336. By applying equation $F = (n' - n) R$ (where F = power of spherical refracting surface, R = reciprocal of radius of curvature in metres, n = refractive index of first medium and n′ = refractive index of second medium), the two surface powers of the cornea may be found as follows:

- *Anterior surface*

$$\text{Power} \quad F_1 = \frac{1000\,(1.376 - 1)}{+7.7} = +48.83\,\text{D}$$

- *Posterior surface*

$$\text{Power} \quad F_2 = \frac{1000\,(1.336 - 1.376)}{+6.8} = -5.88\,\text{D}$$

The power of the cornea as a whole is, therefore, about +43 D, over two-thirds of the total power of the eye.

The light entering the eye is refracted markedly at anterior corneal surface for two reasons: first, because of its curvature and second,

because of the big difference in refractive indices of air (1) and cornea (1.37). When the eyes are unprotected under water, the anterior surface of the cornea has its power greatly reduced, the retinal image then becoming inordinately blurred.

The aspherical shape of cornea's anterior surface is responsible for a baseline astigmatism of 0.25–0.5 D in almost every human eye. Further, a changing corneal surface's radius of curvature with distance from the centre of the pupil to the pupillary margin is responsible for a spherical aberration of 0.21–1.62 D (depending on the specific corneal form) in a normal human eye for a pupil of 4 mm in diameter.

2. The Anterior Chamber

From an optical point of view, the depth of the anterior chamber is important in as much as it affects the total power of the eye's optical system. If all other elements remain unchanged, a reduction of 1 mm in the depth of the anterior chamber (through a forward shift of the crystalline lens) would increase the eye's total power by about 1.4 D. The reverse effect would result from a shift in the opposite direction.

3. The Pupil

The amount of light admitted to the eye is regulated by the pupil, an approximately circular opening in the iris. The size of the blur circle on the retina generally increases with an increase in the size of the subject's pupil, particularly one who is ametropic.

With small pupil sizes, the 'depth of focus' of the eye increases and the objects remain in adequate focus even inside the actual near point of the eye. Therefore, an artificially close near point of accommodation is measured.

On the other hand, retinal image quality, as determined by diffraction, tends to improve with increasing pupil diameter (see page 09, Fig. 1.8). For most eyes, the best retinal images are obtained when the pupil diameter is about 2.4 mm, which is the diameter at which the effects of aberration and diffraction are balanced optimally. In fact, the pupil size tends to be adjusted automatically to give optimal visual acuity over a wide range of luminance.

4. The Crystalline Lens

The crystalline lens serves the double purpose of supplying the balance of the eye's refractive power and providing a mechanism for focusing at different distances. This latter facility is called accommodation.

Both anatomically and optically, the lens is a highly complex structure, composed of layers of fibres laid down in an essentially radial pattern that is regular enough to allow a symmetrical diffraction halo to be formed. The lens continues to grow in bulk throughout life by the formation of fresh layers of fibres on the exterior. As part of the normal process of ageing, it is susceptible to various changes impairing its flexibility and transparency. Its centre thickness is thereby increased, while the radii of curvature may become longer.

The lens has a diameter of approximately 9 mm and is biconvex in form, the radius of its anterior surface being about 1.7 times that of its posterior surface. When the lens is in its unaccommodated state, the centre thickness has traditionally been taken as 3.6 mm, a figure appropriate for a young adult. As accommodation is brought into play, both surfaces, but especially the anterior, assume a more steeply curved form. The central thickness thus increases and the vertex of the anterior surface moves forward, reducing the depth of the anterior diameter.

Because of its onion-like structure and the compression exerted on the innermost layers, the crystalline lens is far from being optically homogeneous. A slit-lamp section reveals several bands of discontinuity. In particular, it is possible to distinguish a central biconvex portion called the nucleus from the surrounding portion called the cortex. In the centre of the nucleus, the refractive index reaches its maximum value between 1.40 and 1.41 but diminishes from the centre outwards, being about 1.385 near the poles and about 1.375 near the equator, the mean value being about 1.39. Owing to the complexity of its architecture,

however, the entire lens has a refractive power higher than these figures indicates and would correspond to a uniform index of 1.42, if the crystalline lens was homogeneous. The total dioptric power of the crystalline lens in situ in relaxed state varies from 16 to 20 D.

The assumption that the lens surfaces are spherical is for convenience only. Careful observation reveals a marked degree of peripheral flattening, especially of the anterior surface in its accommodated state. Owing to this, and to the peripheral flattening of the cornea, the eye's spherical aberration is kept within reasonable limits. Further, the comparatively greater refractive strength of the nucleus of lens also diminishes the optical errors of spherical and chromatic aberration.

5. The Vitreous

The back surface of the crystalline lens is in contact with the vitreous humour, a transparent gel that fills the posterior segment of the globe. The vitreous humour has very nearly the same chemical composition as the aqueous and its refractive index may be taken as the same, i.e. 1.336.

6. The Retina

From an optical point of view, the retina could be described as the screen on which the image is formed. It can be regarded as part of a concave spherical surface with a radius of curvature approximately –12 mm.

In cameras and optical instruments, generally it is convenient to have images formed on plane surfaces, but the curvature of the retina has two positive advantages. In the first place, the images formed by optical systems tend to have curved surfaces. The curvature of the retina is of the right order from this point of view. Second, the steeply curved retina is able to cover a much wider field of view than would otherwise be possible.

Other retinal factors important to image formation:

- *Photoreceptors* (cones and rods) can be considered the pixel elements comprising a retinal image. It is the finite size of these photoreceptors that ultimately determine the eye's ability to resolve fine details.
- *Configuration of foveal pit and the tightly packed cones* in the foveal region contribute to finest resolution of retinal image in this area of retina.
- *Orientation of the retinal cones* is such that they function as 'light pipes' or 'fibre-optic', which is directed towards the second nodal point of the eye (Fig. 1.46). This orientation optimally receives the light that forms an image and partially prevents this light from being scattered to the neighbouring cones.
- *Yellow macular pigment* may be considered to act as a blue filter that limits chromatic aberration and also absorbs scattered light, which is predominantly of shorter wavelength (i.e. the blue end of the spectrum).

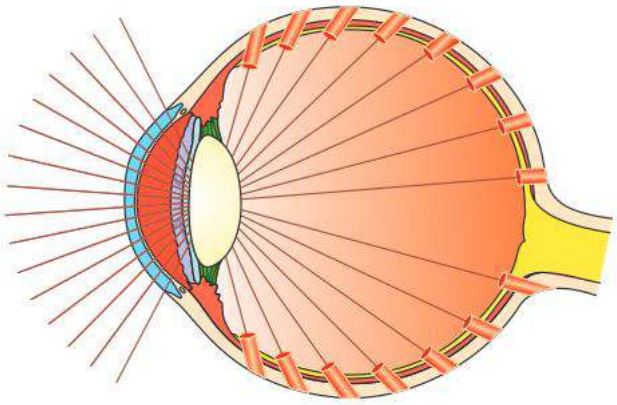


Fig. 1.46 *Orientation of the photoreceptors towards second nodal point of the eye helps them work as light pipes or fibre-optic.*

SCHEMATIC EYE

Listing and Gauss, while studying refraction by lens combinations, concluded that for a homocentric lenses' system, there exist three pairs of cardinal points, which are two principal foci, two principal points and two nodal points, all situated on the principal axis of the system. Therefore, the eye, forming a homocentric complex lens system, when analysed optically according to Gauss' concept can be resolved into six cardinal points (schematic eye). The models of schematic eyes developed by Listing, Tscherning and Helmholtz greatly advanced the understanding of the optics of the eye.

However, it was Gullstrand who developed the most authoritative model of the eye.

Cardinal Data of the Gullstrand's Schematic Eye

These are as follows (Fig. 1.47A):

- *Principal foci* F_1 and F_2 lie 15.7 mm in front of and 24.4 mm behind the cornea, respectively.
- *Principal points* P_1 and P_2 lie in the anterior chamber 1.35 mm and 1.60 mm behind the anterior surface of cornea, respectively.
- *Nodal points* N_1 and N_2 lie in the posterior part of the lens 7.08 mm and 7.33 mm behind the anterior surface of cornea, respectively.
- *Total dioptric power of this schematic eye is 58.64 D. Details of refracting power* data included in Gullstrand's schematic eye are as shown in Table 1.5.
- *Gullstrand's data on refractive indices* of the components of the optical system of eye are as follows:

Cornea	1.376
Aqueous	1.336
Lens cortex	1.386
Lens core	1.406
Vitreous	1.336

- *Gullstrand's data for radii of curvature* of the refractive surfaces are as follows:

Anterior surface of cornea	7.70 mm
Posterior surface of cornea	6.70 mm
Anterior surface of lens	10 mm
Posterior surface of lens	6 mm
Anterior surface of lens core	7.91 mm
Posterior surface of lens core	5.76 mm

- *Position of optical elements* in the eye is as follows:

Anterior surface of cornea	0 mm
Posterior surface of cornea	0.5 mm
Anterior surface of lens	3.6 mm
Posterior surface of lens	7.2 mm
Anterior surface of lens core	4.146 mm
Posterior surface of lens core	6.505 mm

THE REDUCED EYE

The optics of eye otherwise is very complex. The Gullstrand's model of schematic eye had definitely enhanced the understanding of the optics of eye, but the calculations were still cumbersome. Therefore, for understanding,

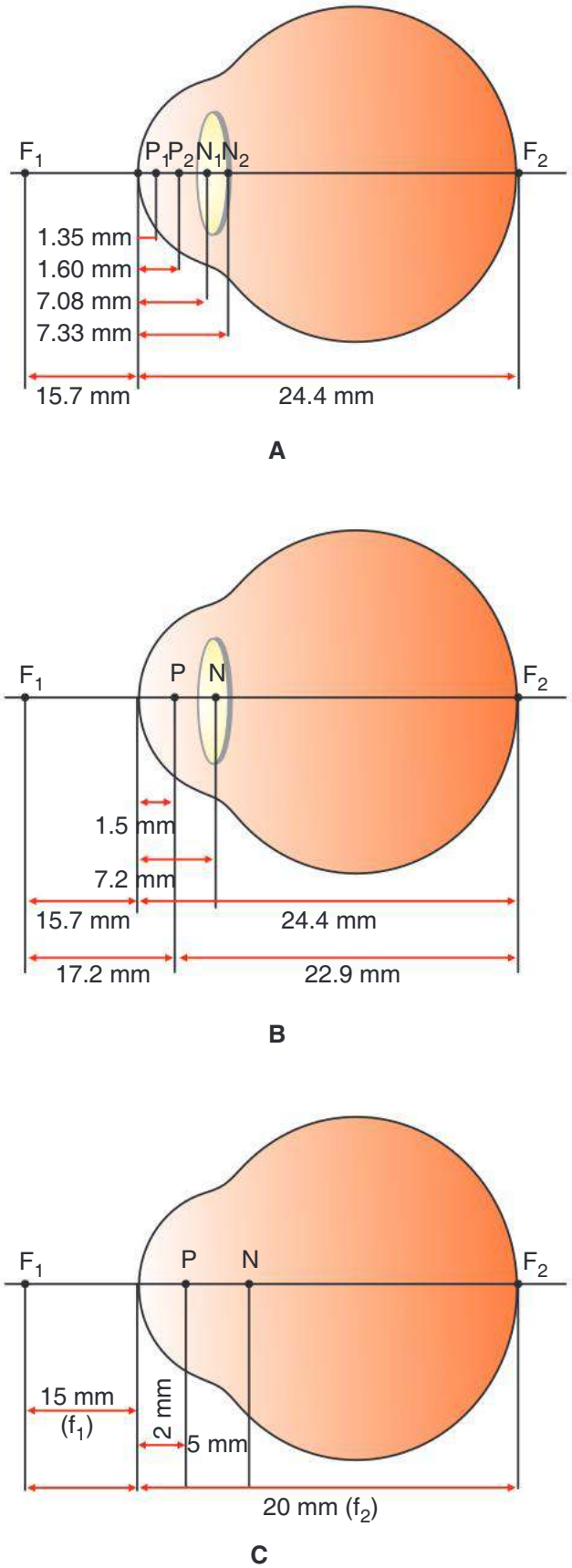


Fig. 1.47 *Cardinal points of Gullstrand's schematic eye (A); Listing's reduced eye (B); and Donders' reduced eye (C).*

Table 1.5 *Power data included in Gullstrand's schematic eye*

Optical system	Power (in D)	
	Accommodation relaxed	Accommodation maximum
Complete optical system of the eye	58.64	70.57
Corneal system	43.05	43.05
Lens system	19.11	33.06

Listing and then Donders introduced the concept of reduced eye.

Listing's Reduced Eye

Listing simplified the data by choosing single principal point and single nodal point lying midway between the two principal points and two nodal points, respectively. This is called ***Listing's reduced eye***. The simplified data of this eye (Fig. 1.47B) are as follows:

- *Principal point* (P) lies 1.5 mm behind the anterior surface of cornea and represents the vertex of a single refracting surface whose radius of curvature is 5.7 mm.
- *Nodal point* (N) is situated 7.2 mm behind the anterior surface of cornea, i.e. at the centre of curvature of single refracting surface (1.5 + 5.7 = 7.2).
- *Anterior focal point* is 15.7 mm in front of the anterior surface of cornea.
- *Posterior focal point* (on the retina) is 24.13 mm behind the anterior surface of cornea.
- *Anterior focal length* is 17.2 mm (15.7 + 1.5) and the posterior focal length is 22.63 mm (24.13 – 1.5).
- *Uniform refractive index* is 1.336.
- *Total dioptric power* is +58.20. The refractive power of the reduced eye is calculated by dividing refractive index by focal length.
  - Using the anterior focal length, the power of the eye is calculated as:

$$F = \frac{\text{Refractive index of air}}{\text{Anterior focal length in metres}}$$

$$\text{i.e. } F = \frac{1 \times 1000}{17.2} = 58.20 \text{ D}$$

  - Using the posterior focal length, the power of the eye is calculated as:

$$F = \frac{\text{Refractive index of viterous}}{\text{Posterior focal length in metres}}$$

$$\text{i.e. } F = \frac{1.336 \times 1000}{22.9} = 58.20 \text{ D}$$

Thus, the first focal length in air is optically equivalent to the second focal length inside the eye, and the fictional reduced eye is optically equivalent to Gullstrand's schematic eye, if liberties in rounding off numbers are taken.

Donders' Reduced Eye

Donders converted the cardinal data into round figures, so that they can be remembered easily. In his over simplified reduced eye, he treated the eye as a single curved surface with the following cardinal data (Fig. 1.47C):

- *Principal point* (P) lies 2 mm behind the cornea with a radius of curvature of 5 mm.
- *Nodal point* (N) is situated 5 mm behind the principal point (P).
- *Anterior focal length* (f_1) is 15 mm.
- *Posterior focal length* (f_2) is 20 mm.
- *Refractive index* is 1.336.
- *Total power* is +60 D.
- *Refractive index* 1.333.

Clinical Applications of Reduced Eye

- IOL power calculation
- Intraocular foreign body localization
- Used for designing of instruments
- Used for determining the size of retinal image since nodal point corresponds to the optical centre of convex lens.

RETINAL IMAGE SIZE

Retinal image size may be determined very easily, using the reduced eye model, because the nodal point is at the centre of curvature of the single anterior refracting surface. A ray from the top of an object directed towards the nodal point will go straight to the retina without bending; therefore, object and image subtend the same angle. The retinal image size is found by multiplying the distance from nodal point to the

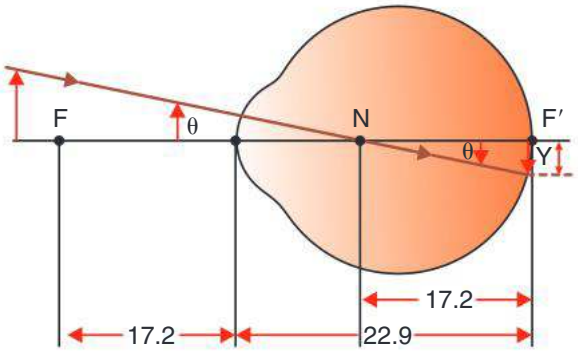


Fig. 1.48 *Retinal image size constructed by means of a ray through nodal point.*

retina (17.2 mm) by the angle, in radians, subtended by the object. For example, in Figure 1.48, if the ray coming from the top of an object subtends an angle ϑ (theta) of 0.1 radians at the nodal point, then the size of the retinal image will be 17.2 × 0.1 = 1.72 mm.

Image Size in Ametropia

Emmetropia prevails when the refractive power and axial length of the eye are properly matched. Clearly, there are any number of possible emmetropic combinations of power and length. The Gullstrand's schematic eye with a power of 58.64 D and an axial length of 24.13 mm represents a typical emmetropic eye. Consequently, it is convenient for illustrative purposes to consider axial ametropia, the condition in which the power of the eye is the normal 58.64 D, but the length of the eye is not 24.13 mm. Figure 1.49 illustrates the variation of axial length with ametropia. In order to indicate that the magnitude of the retinal image size changes due to axial ametropia, it is simplest to use the reduced eye model, which has a length of 22.9 mm and a power of approximately 58 D. It is evident in Figure 1.49 that for any given angular subtense of the object at the nodal point of the eye, the retinal image will be smallest in hyperopia and largest in myopia. The image size will be in direct proportion to the length of the eye.

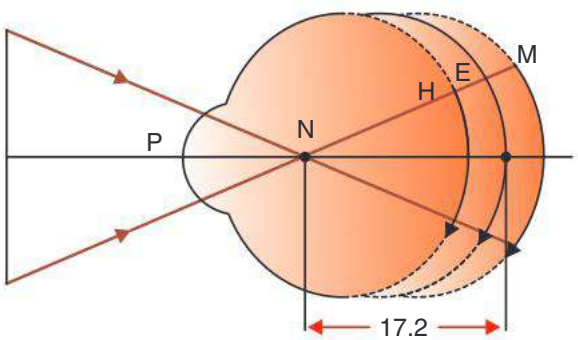


Fig. 1.49 *Visual angle and retinal image size in ametropia. The size of the retinal image corresponding to a given angular field of view (θ) varies with the elongation of the eye.*

CATOPTRIC IMAGES

It is important to note that each refracting interface of the eyeball also acts as reflecting surface and reflects some portion of the light incident upon it. Catoptric images, also known as Purkinje–Sanson images, refer to the images formed inside the eye as a result of reflection occurring from each refracting interface of the eye, which includes:

- Anterior surface of cornea,
- Posterior surface of cornea,
- Anterior surface of lens and
- Posterior surface of lens.

Features of Purkinje–Sanson images. As shown in Figure 1.50:

- *Images I, II* and *III* formed by the reflection from the anterior corneal, posterior corneal and anterior lens surface, respectively, are erect and virtual as they are formed from the convex reflecting surfaces.
- *Image IV*, formed by the reflection from concave posterior lens surface is real and inverted.

Clinical uses of Purkinje–Sanson images include:

- *Purkinje image test in cataract and aphakia*. Though not of much clinical significance, it is mentioned

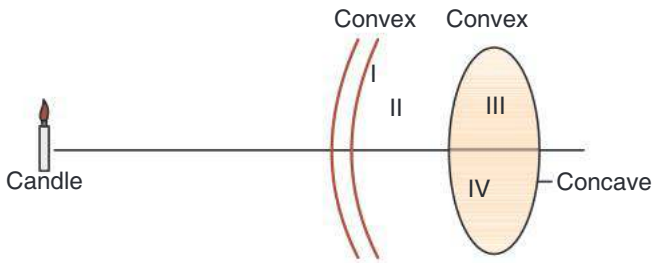


Fig. 1.50 *Purkinje–Sanson images.*

here as a tribute to original workers. In patients with mature senile cataract, instead of four, only three Purkinje images are seen, as the image IV formed by posterior lens surface is absent. In aphakia III as well as IV, Purkinje images (formed by anterior and posterior surface of lens) are absent; i.e. only two images are formed.

- *Keratometry*, i.e. measurement of curvature of cornea is based on the first Purkinje image (see page 36).
- *Hirschberg corneal reflex test* to diagnose strabismus also uses the first Purkinje image.
- *Changes in lens during accommodation* have been studied using the third and fourth Purkinje images.

AXES AND VISUAL ANGLES OF THE EYE

The eye has three principal axes and three visual angles (Fig. 1.51).

Axes of the Eye

1. *Optical axis* is the line passing through the centre of the cornea (P) and the centre of the lens (N) and meets the retina (R) on the nasal side of the fovea.

In practice, it is impossible to determine accurately the optic axis, since we cannot know the exact centre of cornea. However, it is much easier to estimate the centre of the pupil, e.g. by an image of light on the cornea. Therefore, in practice we substitute the optic axis by a line perpendicular to the cornea and the point coinciding to the centre of the pupil. This line is called *pupillary line*.

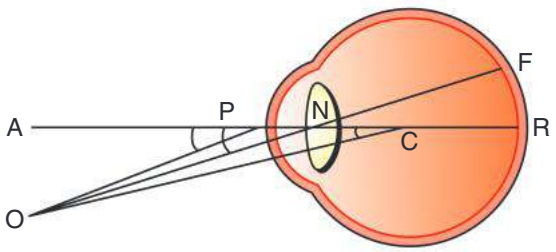


Fig. 1.51 *Axes of the eye: optical axis (AR); visual axis (OF); fixation axis (OC) and visual angles: angle alpha (ONA, between optical axis and visual axis at nodal point N); angle kappa (OPA, between optical axis and pupillary line OP) and angle gamma (OCA, between optical axis and fixation axis).*

2. *Visual axis* is the line joining the fixation point (O), nodal point (N) and the fovea (F).
3. *Fixation axis* is the line joining the fixation point (O) and the centre of rotation (C).

Visual Angles (Fig. 1.51)

1. *Angle alpha*. It is the angle (ONA) formed between the optical axis (AR) and the visual axis (OF) at the nodal point (N).
2. *Angle gamma*. It is the angle (OCA) between the optical axis (AR) and the fixation axis (OC) at the centre of rotation of the eyeball (C).
3. *Angle kappa*. It is the angle (OPA) formed between the visual axis (OF) and the pupillary line (AP). The point P on the centre of cornea is considered equivalent to the centre of pupil.

Note. Practically, only the angle kappa can be measured and is of clinical significance. A positive angle kappa results in pseudoexotropia and a negative angle kappa in pseudoesotropia.

OPTICAL ABERRATIONS OF THE NORMAL EYE

The eye, in common with many optical systems in practical use, is by no means optically perfect; the lapses from perfection are called aberrations. Fortunately, the eyes possess those defects to so small a degree that, for functional purposes, their presence is negligible.

Natural compensatory mechanisms to decrease aberrations in normal human eye include:

- Cutting off of the peripheral rays by iris,
- High refractive index of the core of nucleus of the lens than that of the peripheral cortex,
- Low sensitivity of the peripheral retina and
- Stiles–Crawford effect, i.e. more sensitivity of the retina to perpendicular rays than the oblique rays. It has been said that despite imperfections, the overall performance of the eye is little short of astonishing.

Physiological optical defects in a normal eye are described below briefly:

1. Diffraction of Light

Diffraction is a bending of light caused by the edge of an aperture or the rim of a lens. Even a perfect lens, free from aberrations, will not

focus light to a point due to diffraction. The actual pattern of a diffracted image point produced by a lens with a circular aperture or pupil is a series of concentric bright and dark rings (Fig. 1.52). At the centre of the pattern is a bright spot, known as the Airy disc, after Sir George Airy who was the first to report it. In the eye, with a pupil of 2 mm diameter, the diameter of the spot of concentric rings is about 0.01 mm. As a practical result of the interaction of diffraction, spherical aberrations and retinal illumination, optimum visual acuity occurs over an intermediate range of pupil diameter, viz. 3–4 mm. Diffraction blur increases with the small size of the pupil.

2. Spherical Aberrations

Spherical aberrations occur because a spherical lens refracts peripheral rays more strongly than paraxial rays, which in the case of a convex lens brings the more peripheral rays to focus closer to the lens (Fig. 1.53).

Fig. 1.52 *The diffraction of light. Light brought to a focus does not come to a point, but gives rise to a blurred disc of light surrounded by several dark and light bands (the 'Airy disc').*

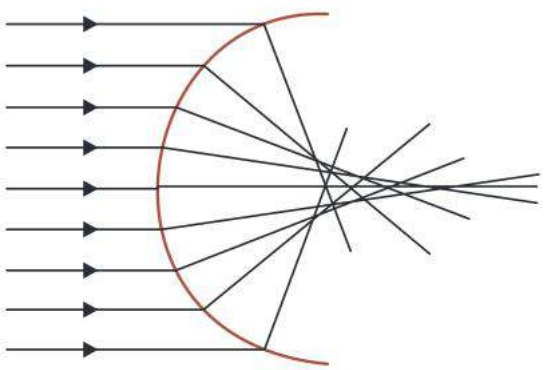


Fig. 1.53 *Spherical aberration. Since there is greater refraction at periphery of spherical lens than near centre, incoming rays of light do not truly come to a point focus.*

The human eye, having a power of about 160 D, was long thought to suffer from various amounts of spherical aberrations. However, results from aberroscopy have revealed that the dominant aberration of the human eye is not spherical aberration but rather a coma-like aberration.

Factors that contribute in diminishing the spherical aberrations of human eye:

- Peculiar curvature of the cornea, i.e. flatter periphery than the centre.
- Peculiar structure of the crystalline lens, wherein the central portions have a greater density and are arranged in layers of greater curvature than the peripheral portion.
- Iris blocks the peripheral rays to enter the eye and thus in ordinary circumstances, refraction of only paraxial rays of light takes place.

3. Chromatic Aberrations

Chromatic aberrations result because the index of refraction of any transparent medium varies with the wavelength of the incident light. In human eye, which optically acts as a convex lens, blue light is focused slightly in front of the red (Fig. 1.54). In other words, the emmetropic eye is in fact slightly hypermetropic for red rays and myopic for blue and green rays. This fact forms the basis of bichrome test, used in subjective refraction.

However, in reality, the effect of this chromatic aberration is minimized by the rather narrow spectral sensitivity bands of the long and mid-wavelength cones and the fact that the fovea is largely lacking in blue cones. Moreover, the effect is to a certain extent neutralized by

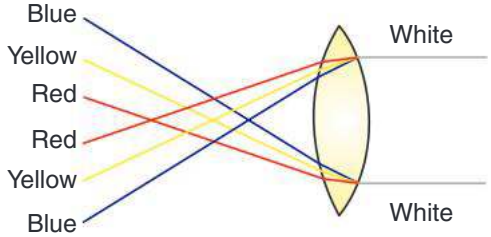


Fig. 1.54 *Chromatic aberration. The dioptric system of the eye is represented by a simple lens. The yellow light is focused on the retina, and the eye is myopic for blue and hypermetropic for red.*

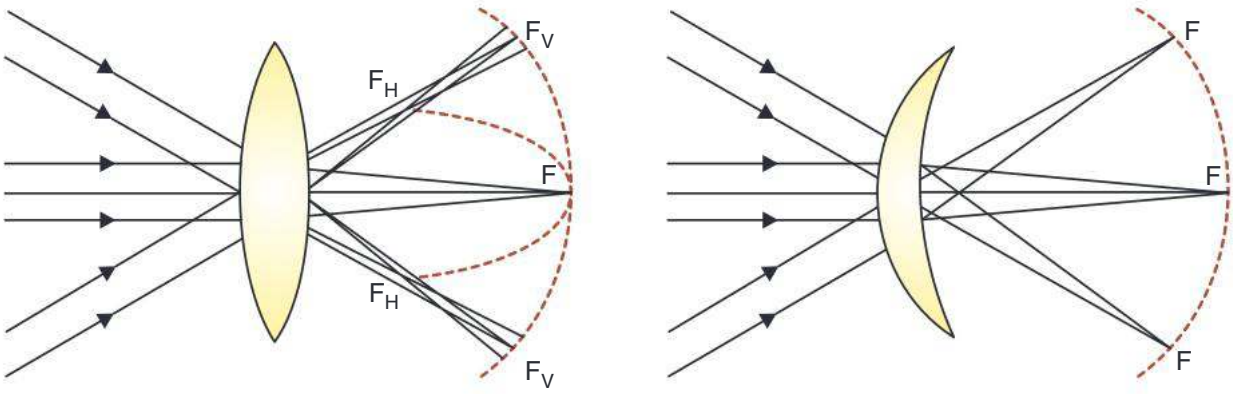


Fig. 1.55 *A, Oblique astigmatic effect occurs from the formation of Sturm's conoid for light incident to the biconvex (poor optical form) lens. This results in double image formation (F_H and F_V). B, Best form lens (meniscus type) forms a single image.*

the fact that the eye is normally focused, and so the rays of greatest intensity (the yellow) form the most sharply defined image, while the colours of longer and shorter foci form circles of relatively low intensity compared with this, and their images are, therefore, neglected. So effective are all these factors that human visual acuity is not materially improved by achromatizing lenses.

4. Decentring

The cornea and lens surfaces alter the direction of incident light rays, causing them to focus on the retina. Actually, these surfaces are not centred on a common axis. The crystalline lens is usually slightly decentred and tipped with respect to the axis of the cornea and with respect to the visual axis of the eye. It has been reported that the centre of curvature of cornea is situated about 0.25 mm below the axis of the lens. However, the effects of deviation are usually so small that they are functionally neglected.

5. Oblique Aberration

Objects in the peripheral field are seen by virtue of obliquely incident narrow pencil of rays, which are limited by the pupil. Because of this, the refracted pencil shows oblique astigmatism. As shown in Figure 1.55A, the peripheral portion of the lens will form Sturm's conoid, and therefore in any peripheral oblique axis, two line foci will be formed. Likewise, the emergent pencils from the peripheral retina are also affected with oblique astigmatism. However, there is no doubt that the curvature of the retina is admirably adapted to the eye's optical system, and so the efficiency of the peripheral vision is not jeopardized in reality.

Oblique astigmatism is much more evident when biconvex or biconcave lenses are used and is considerably reduced by the use of best form of lenses such as 'periscopic' or other meniscus (Fig. 1.55B).

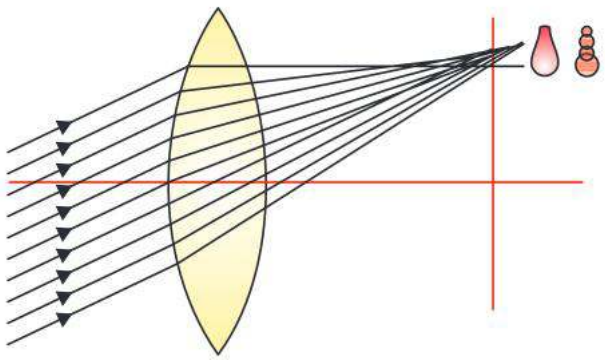


Fig. 1.56 *Aberrations – coma.*

6. Coma

Different areas of the lens will form foci in planes other than the chief focus. This produces in the image plane a 'coma effect' from a point source of light. As with spherical aberration, the limitation of rays to the axial areas of the lens can reduce this effect (Fig. 1.56).

2 Visual Acuity, Contrast Sensitivity and Tests for Potential Vision

Chapter Outline

VISUAL ACUITY

GENERAL CONSIDERATIONS

The vision or visual perception is a complex integration of light sense, form sense, contrast sense and colour sense. ***Visual acuity*** is considered a measure of form sense, so it refers to the spatial limit of visual discrimination. Technically speaking, visual acuity measurement involves the determination of a threshold. In terms of visual angle, the visual acuity is defined as the reciprocal of the minimum resolvable visual angle measured in minutes of arc for a standard test pattern. Therefore, to understand visual acuity, the knowledge about visual angle is essential.

VISUAL ANGLE

Visual angle is the angle subtended at the nodal point of the eye by the physical dimensions of an object in the visual field (Fig. 2.1). Visual angle is a useful and convenient mode of specifying the spatial extent of objects or elements in the visual field.

It has been observed that the two adjacent points can be seen clearly and discretely only when these two points (say A and B in Fig. 2.1) produce a visual angle not less than 1 min. The

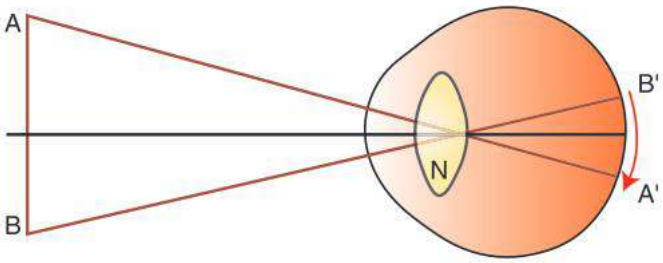


Fig. 2.1 *Visual angle (ANB) subtended at the nodal point by the physical dimensions (AB) of the object.*

dimensions of the visual angle depend upon the size of the object as well as its distance from the eye. Therefore, to be seen clearly, either the object should be large enough or it should be placed near the eye (at an appropriate distance).

In terms of the length of the retinal image, it has been seen that the two points (A and B) will be seen clearly when their image size (A′B′) is more than 4.5 μ. This is so because the diameter of individual cone stimulated by the image points A′ and B′ is 1.5 μ each and at least one cone in between (of 1.5 μ diameter) must be unstimulated. The retinal image size for a given visual angle may vary slightly with changes in viewing distance and associated changes in accommodation of the lens, but this effect is relatively small.

COMPONENTS OF VISUAL ACUITY

In clinical practice, measurement of the threshold of discrimination of two spatially separated targets (a function of the fovea centralis) is termed visual acuity. However, in theory, visual acuity is a highly complex function that consists of the following components:

- Minimum visible,
- Resolution,
- Recognition and
- Minimum discriminable.

MINIMUM VISIBLE

The ability to determine whether or not an object is present in an otherwise empty visual field is termed *visibility* or *detection.* This kind of task is referred to as the *minimum visible* or *minimum detectable function.* The limit of visibility reflects the absolute threshold of vision. The minimum visible spatial threshold level will depend upon the specification of stimulus such as size, shape and illumination. A few observations made about the *minimal visible* threshold are as follows:

- A black dot against a white background can be detected, if its diameter is of the order of 30 s of arc or more.
- A black square can be discriminated against a light background when the length of a diagonal is 30 s.
- An extended line (e.g. visualization of a thin telegraph wire against a uniform sky) with a thickness of as little as one-half second of arc may be discriminable. The ability to discriminate such a fine line when its image is of sufficient extent implies dependence upon some kind of process that involves the convergence of subthreshold signals from a number of individual retinal elements along the extent of retinal image at a common point. The addition of these subthreshold signals yields a discriminable suprathreshold level of activity.
- Detection of an illuminated object against a dark background solely depends upon its intensity and not on its size.

RESOLUTION (ORDINARY VISUAL ACUITY)

- Discrimination of two spatially separated targets is termed resolution. The minimum separation between the two points, which can be discriminated, is known as *minimum resolvable.* Measurement of the threshold of discrimination is essentially an assessment of the function of the fovea centralis and is termed *ordinary visual acuity.* The distance between the two targets is specified by the angle subtended at the nodal point of the eye. The normal angular threshold of discrimination for resolution measures approximately 30–60 s of an arc; it is usually called the minimum angle of resolution (MAR).
- If the minimum separation between the two light bars is considered, the threshold value

becomes increasingly smaller as the width of the bars increases, reaching a limiting condition of approximately one-half second of arc when the light bars have become so broad that the overall presentation is indiscriminable from a dark line against a large homogeneous light background.

- The minimum separation, which can be discriminated between the two dark bars, will become infinitesimal as the bars become wider and the stimulus is seen as a light line against a dark background.
- The clinical tests determining visual acuity measure the form sense or reading ability of the eye. Thus, broadly, resolution refers to the ability to identify the spatial characteristics of a test figure. The test targets in these tests may either consist of letters (Snellen's chart) or broken circles (Landolt's ring). More complex targets include gratings and checkerboard patterns.

RECOGNITION

It is that faculty by virtue of which an individual not only discriminates the spatial characteristics of the test pattern but also identifies the patterns with which one has had some experience. Recognition is thus a task involving cognitive components in addition to spatial resolution. For recognition, the individual should be familiar with the set of test figures employed in addition to being able to resolve them. The most common example of recognition phenomenon is identification of faces. An average adult can recognize thousands of faces.

MINIMUM DISCRIMINABLE OR HYPERACUITY

Minimum discriminable refers to spatial distinction by an observer when the threshold is much lower than the ordinary acuity. The best example of minimum discriminable is *vernier acuity*, which refers to the ability to determine whether or not two parallel and straight lines are aligned in the frontal plane. The threshold values of vernier acuity (Fig. 2.2) are in the range of only a few seconds (2–10 s) of arc. Hyperacuity should not be confused with the threshold for the minimum visible, where

Fig. 2.2 *Typical target configuration for detecting vernier acuity.*

merely the presence or absence of a target is being judged. The mechanism subserving hyperacuity is not clearly known, but so much is clear; no contradiction is involved with the optical and receptor mosaic factors that limit ordinary visual acuity.

FACTORS AFFECTING VISUAL ACUITY

As discussed earlier, resolution part of the spatial discrimination is considered synonymous with the ordinary visual acuity. And we know that where an observer exhibits the so-called normal visual acuity, all the elements (optical, anatomical and physiological) concerned with the vision are near their peak performance. In general, the factors that influence the spatial resolution can be classified into physical and physiological.

- ***Physical factors*** include those which influence the light characteristics of the distribution and hence influence the nature of retinal image.
- ***Physiological factors*** are those which influence the processing of the stimulus and are thus mainly observer-related factors. However, there is some overlap between physical and physiological groups. For example, the lens is a physical factor, but the related accommodation process is physiological. Similarly, the size of pupil that controls the amount

of light entering the eye is a physical factor, but the reflexes controlling its size are physiological processes.

Therefore, these factors have been classified into stimulus-related and observer-related factors. Further, the list of such factors is exhaustive, but only the important ones are mentioned here briefly.

STIMULUS-RELATED FACTORS

- Luminance of test object
- Geometrical configuration of the stimulus
- Contrast of the stimulus from the surround
- Influence of wavelength of stimulus light
- Exposure duration of stimulus
- Interaction effects of the two targets

OBSERVER-RELATED FACTORS

- Retinal locus of stimulation
- Pupil size
- Accommodation
- Effect of eye movements
- Meridional variation in acuity
- Optical elements of the eye
- Developmental aspects

MEASUREMENT OF VISUAL ACUITY

As discussed earlier, the visual acuity is a highly complex function that consists of the following:

1. *Minimum visible*, i.e. detection of presence or absence of stimulus,
2. *Minimum separable*, i.e. judgement of location of a visual target relative to another element of the same target and
3. *Minimum resolvable* (ordinary visual acuity), i.e. the ability to distinguish between more than one identifying feature in a visible target.

In clinical practice, the measurement of visual acuity is considered synonymous with the measurement of 'minimum resolvable'. (However, in theory, it is not so, as it is clear from the above.) The threshold of the minimum resolvable is between 30 s and 1 min of arc. Therefore, all the clinical tests employed to measure the visual acuity are designed, taking into consideration the threshold of the one minimum resolvable. Based on this basic principle, many visual acuity charts have been developed.

MILESTONES IN DEVELOPMENT OF VISION

Before discussing the various methods of visual assessment in infants, children and adults, it will be worthwhile to have a quick look on the visual development. Important milestones in development of vision are summarized in Table 2.1

TESTS FOR VISUAL ACUITY ASSESSMENT

Various visual acuity tests available can be grouped as follows:

I. ***Detection acuity tests.*** These assess the ability to *detect* the smallest stimulus without recognizing correctly. Following are the common detection acuity tests:

1. Dot visual acuity test,
2. Catford drum test,
3. Boek candy bead test,
4. STYCAR graded balls test and
5. Schwarting metronome test.

II. ***Recognition acuity tests.*** These are designed to assess the ability to recognize the stimulus or to distinguish it from other competing stimuli. These include the following:

(A) *Direction identification tests*

1. Snellen's E-chart test,
2. Landolt's C-chart test,
3. Sjögren's hand test and
4. Arrows test.

(B) *Letter identification tests*

1. Snellen's letter chart test,
2. Sheridan's letter test,
3. Flook's symbol test and
4. Lipman's HOTV test.

(C) *Picture identification charts (miniature toy test)*

1. Allen picture cards test,
2. Beale Collins picture charts test,
3. Domino cards test,

Table 2.1 *Milestones in the development of vision*

Age	Visual milestone	Visual acuity
Newborn	• Pupillary reaction to light • Blinking to light stimulus • Conjugate horizontal gaze developed	6/360–6/120 (by OKN)
1 week	• Vestibulo-ocular reflex	
2 weeks	• Small saccades develop • Follows horizontal moving objects	
1 month	• Fixation developing • Can watch mother's face for prolonged time	6/480–6/120 (by PL tests)
2 months	• Bifoveal fixation • Large saccades • Pursuits and convergence movements • Conjugate vertical gaze developed	6/120–6/60
3 months	• Watches movements of own hands and reaches out towards interesting objects • Prefers photographs to patterns	
4 months	• Foveal differentiation complete • Sensory fusion and accommodation begins to develops	6/120–6/30
5 months	• Blink response to visible threat (menace response) • Grasps and explores objects • Stereopsis begins to develop	6/90–6/24, 6/12–6/6 (by VER)
6 months	• Accommodation well developed • Fusional vergence well developed	6/90–6/24, 6/12–6/6 (by VER)
9 months	• Visual differentiation of objects • Picks up small objects	6/48–6/12, 6/6 (by VER)
18 months	• Visual acuity at adult levels on paediatric acuity card • Myelination of optic nerve completed	6/18–6/7.5
2–3 years	• Best visual acuity approaches near adult levels, but may not be 6/6 • Can play picture or letter recognition games • Can respond to some binocular vision tests • Contrast sensitivity well developed	6/12–6/6 (36 months)
5 years	• Stereopsis fully developed	6/6–6/5
8–10 years	• Critical period of monocular deprivation ends	6/6–6/5

4. Lighthouse test and
5. Miniature toy test of Sheridan.

(D) *Tests based on picture identification on behavioural pattern*

1. Cardiff acuity cards (CAC) test and
2. Bailey-Hall cereal test.

III. ***Resolution acuity tests***

1. Optokinetic nystagmus (OKN) test
2. Preferential looking test (PLT)
   - i. Two-alternative forced choice test,
   - ii. Operant variation looking test and
   - iii. Teller acuity cards (TAC) test.
3. Visually evoked response (VER)

Tests employed for visual acuity assessment at various age groups are summarized in Table 2.2.

MEASUREMENT OF VISUAL ACUITY IN INFANTS

ASSESSMENT OF VISUAL ACUITY FROM BIRTH UP TO 3 MONTHS

At birth, visual acuity is 1/60 which improves very fast to 2/60 at 1 month and 6/60 at 4 months. With 1/60 vision, the child is able to fix a face moving within 1 m. The fixation

Table 2.2 *Commonly used visual assessment tests at various age groups*

Age	Tests for assessment of vision	Type of visual acuity
Birth to 3 months	• Blink reflex • Pupillary light reflex • Vestibulo-ocular reflex test • Eye popping test	
	• OKN • VER	Resolution acuity
3–6 months	• Fixation and following of objects or small toys • CSM (central, steady, maintained) fixation • Response to occlusion	
	• OKN • VER	Resolution acuity
6–12 months	• Preferential looking tests (Teller acuity tests) • Catford drum test	Resolution acuity Detection acuity
1–3 years	• Cardiff acuity tests	Resolution + recognition acuity
	• Marble game test • STYCAR balls test • E game test • Boek candy test	Detection acuity
3–5 years	• Broken wheel test • Landolt's C test • Isolated hand figure test • Pictorial vision chart tests • Tumbling E test • HOTV test • Snellen's numbers • Snellen's letters	Recognition acuity
Above 5 years	• Snellen's numbers • Snellen's letter chart • LogMAR chart	Recognition acuity

reflex and following reflexes take about 6–8 weeks to develop before which an infant may fix for a few seconds and give up. There are a few bizarre movements that appear till the development of definite fixation reflex. Neonates have sporadic jerky movements made up of saccadic eye movements without smooth pursuit. So, visual acuity in a newborn and infant up to 3 months of age can be determined by the tests given below:

1. **Blink reflex test.** Blink reflex is present since birth (after 30 weeks of gestational age). It is occasionally present in decorticate infants as well. When bright light is shown, a normal infant should respond by blinking.
2. **Pupillary light reflex test.** Presence of pupillary light reflex indicates intact afferent visual neurologic pathways to the level of the brachium of the superior colliculus and efferent pathways to the iris sphincter. This reflex is present in premature babies over 29–31 weeks of gestational age. *This is the most reliable test to determine the presence of vision except in cortical blindness.* The test is best performed in a semidarkened room because the infant's pupils are smaller than that of a normal adult and constrict in the presence of bright light in the room. In the semidark room, the pupil comes to a state of semidilatation that reacts briskly. The light used should be small, well focused and bright. Visualization in very young children sometimes requires a magnifying glass, as their pupils are smaller than those of the older children (because of decreased sympathetic tone) and the light responses are of small amplitude.
3. **Vestibulo-ocular reflex (VOR) test.** The VOR is generally tested by turning the newborn's head on his/her long axis and observing for the doll's eyes response (the eyes deviate opposite to the direction of head rotation).
4. **Eye popping test.** Another behaviour that is unique to babies is *eye popping*. Sometimes, for a variety of reasons, very young infants do not show any distinguishable visual behaviour at all. In this case, the eye-popping reflex indicates at least the baby's ability to detect changes in the room illumination. When the room lights are suddenly dimmed, the baby's upper eyelids should pop open wide for a moment. The baby will often close its eyes when the lights are brought up back, but will again pop its eyes open when the lights are dimmed. This behaviour is documented as 'positive eye popping'.

5. OKN test. It is an objective method of visual assessment in infants and uncooperative children as well as adults. In this test, nystagmus is elicited by passing a succession of black and white stripes by means of OKN drum of the size 10 × 8 inches in diameter, which is rotated at 8–10 rpm through the patient's field of vision (Fig. 2.3). Eyes respond with a slow movement in the direction of drum lasting about 0.2 s and fast phase in the reverse direction of 0.1 s. The visual angle subtended by the smallest strip width that still elicits an eye movement (minimum separable) is a measure of visual acuity. The only cooperation required in this test is that the infant be awake and should hold both eyes open. It is reported that OKN acuity is at least 6/120 in the newborns and improves fairly rapidly during the first few months of life, reaching to a level of 6/60 at 2 months, 6/30 at 6 months and 6/6 by 20–30 months. OKN is asymmetric in newborns and becomes symmetric by 4–6 months of age.

6. VER. It refers to electroencephalographic (EEG) recording made from the occipital lobe in response to visual stimuli. VER is the only clinically objective technique available to assess the functional state of the visual system beyond the retinal ganglion cells. It is quite useful in assessing visual function in infants. It reflects acuity from the central retina and thus forms a good macular function test.

Flash VER is usually preformed in very young children or those incapable of fixing on a target. It just tells about the integrity of the macular and visual pathway.

Pattern reversal VER is recorded using some patterned stimulus, as in the checkerboard (Fig. 2.4). In it, the pattern of stimulus is changed (e.g. black squares go white and white squares become black), but the overall illumination remains the same. The pattern reversal VER depends on form sense and thus gives a rough estimate of the visual acuity. VER studies have shown visual acuity in infants to be 6/120 at the age of 1 month, which reaches to 6/60 at 2 months and 6/6–6/12 at the age of 6 months to 1 year.

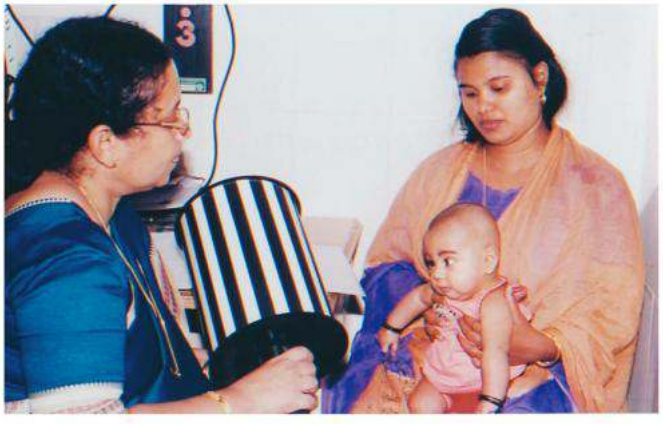


Fig. 2.3 *Optokinetic nystagmus test for visual acuity. (Courtesy: Dr Elizabeth Joseph.)*

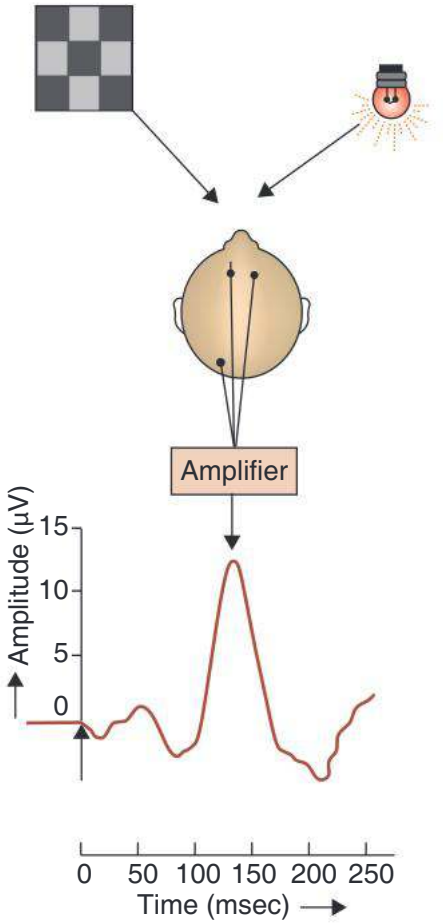


Fig. 2.4 *Technique of recording visually evoked response (VER) and record of normal VER pattern.*

Drawbacks of VER include:

- Expensive,
- Time consuming,
- Limited availability,
- Not standardized and
- Little clinical relevance.

Note: *The discrepancy between estimated visual acuity values with OKN, PLT and VER at 6 months of age must be kept in mind while performing these tests (*Table 2.3*).*

ASSESSMENT OF VISUAL ACUITY FROM 3 TO 6 MONTHS

Since the fixation to moving objects develops by 3–4 months of age, the visual acuity in this age group can be assessed, in addition to the above-mentioned tests, the help of following tests based on fixation behaviour of the infant.

1. **Fixation behaviour test.** Ability of the child to fix and follow the face of the examiner, toys or interesting object. The test is done first with both eyes open followed by monocular testing by occluding the other eye by hand. If the child habitually fixates with one eye, it indicates poor vision in the non-fixating eye and hence he or she will violently resist occlusion of the better eye.
2. **Central, steady, maintained (CSM) method.** CSM method is a useful test in this age group. It implies:
   - *Central.* The infant is asked to fixate on penlight and then the examiner looks at the corneal light reflex from a fixation light, which is falling at the centre of the pupil. The reflex is considered central if it falls in the same location in both the eyes in monocular condition.
   - *Steady.* This is tested with a small target (thumb-sized toy) which is coupled with light held in front of the child and moved slowly. Nystagmus or oscillation results in unsteady fixation.
   - *Maintained.* It is the ability to keep the eye fixed when either eye is covered.

Results of this test can be interpreted as follows:

- CSM: 6/9 to 6/6,
- Central steady not maintained (CSNM): 6/36 to 6/60 and
- Unsteady central fixation: <6/60.

3. **Brückner's red reflex test.** Brückner's reflex is helpful in children uncooperative to the cover test when an assessment is being carried out for small angle strabismus. In this test, fixation and binocular comparison of the red reflex is done. The examiner should stay far enough to illuminate both pupils by the same direct ophthalmoscope beam. The examination should be carried out in dim illumination and the child's attention to be fixed at a distance. Assess the red reflex both before and after dilatation to see how much of the pupillary space is obscured. An overall whitening of the red reflex across the entire pupil of one eye indicates strabismus or anisometropic amblyopia. While the absence of a Brückner's reflex is not a good indication of alignment, the presence of a Brückner's reflex is considered a positive result and is a good indication of strabismus, even of small amounts.
4. **Menace reflex test.** Menace reflex, i.e. reflex closure of the eyes on the approach of an object is usually present after the age of 5 months, if vision is normal.
5. **Cover test.** By 3–6 months, infants have adequate refixation reflex to permit cover test. This test is needed if there is a concern about strabismus. In patients with normal vision,

Table 2.3 *Estimated visual acuity at different ages*

Age (months)	Optokinetic nystagmus	Preferential looking test	Visually evoked response
1	6/120	6/120	6/120
2	6/60	6/60	6/60
6	6/30	6/30	6/6–6/12
Age (months) at which 6/6 is achieved	20–30	24–36	6–12

both eyes look at an object at the same time. Therefore, if one eye is occluded, the opposite eye should not move. In patients with strabismus, one eye is deviated. If the straight eye is covered, the other eye will make a movement to line up the visual target. If a patient is exotropic, the eye will make an inward movement. If an eye is esotropic, it will make an outward movement.

ASSESSMENT OF VISUAL ACUITY FROM 6 TO 12 MONTHS

In addition to the above-mentioned tests, the tests described below are more useful in the 6–12 months age group.

1. PLT. This test is based on the observation that when presented with two adjacent stimulus fields, one of which is striped and the other is homogeneous, the infant will tend to look at the striped pattern for a greater portion of the time. Test procedures have been developed in which an examiner is hidden behind a screen on which one projects a homogeneous surface on one side and black and white stripes on the other side. These two stimuli are alternated randomly. The observer is able to look at the eyes of the infant through a hole in the screen but is unaware of which target, stripes or homogeneous field is presented on which side of the screen.

TAC test. This is the most commonly used PLT in clinical practice. TAC is recommended to test visual acuity in infants from 1 month to 1 year of age. This test is the modification of PLT. This is simple to perform and very reliable and efficient test. The testing distance varies with the age of the child, like the test being performed at 36 cm in infants and toddlers, at 54 cm in children up to 3 years and at 84 cm in adults. Estimates of visual acuity, using the TAC grating targets, show a rapid increase in acuity during the first 6 months of life from 1 cycle per degree at 1 month of age to five cycles per degree by 6 months of age, then a gradual increase to 40 cycles per degree. Adults-like levels are reached at 5 years of age. The results are obtained in *cycles* which can be converted to *Snellen's equivalent*. There are 17 cards, on one-half of each card is a set of vertical black and white bars of varying size which form the pattern stimulus and on the other half, a uniform grey background which is the blank target (Fig. 2.5). In the centre of each card, there is a small hole through which the examiner observes the infant's fixation. In this by varying the spatial frequency of the bars shown, the finest bar which can no longer be resolved by the infant is used to determine the vision as the infant no longer shows the preference for patterned stimulus. This test can be used effectively on neurologically impaired children.

Visual acuity determined with this method has been reported to range from approximately 6/240 in the newborns to 6/60 at 3 months and 6/6 at 36 months of age. It must be well understood that grating acuity testing cannot automatically be equated with acuity testing based on recognition task, such as naming pictures or Snellen's letters. In normal children, grating acuity is better than recognition acuity. Further, it has been suggested that different neural processing mechanisms in the brain are involved with spatial discrimination and recognition tasks. Hence, it is not advisable to equate grating acuity with recognition acuity (Snellen's).

Limitations. TAC tests are relatively expensive and less cost-effective. Therefore, 'budget' versions of PLT acuity testing have emerged in the form of spatial frequency paddles.

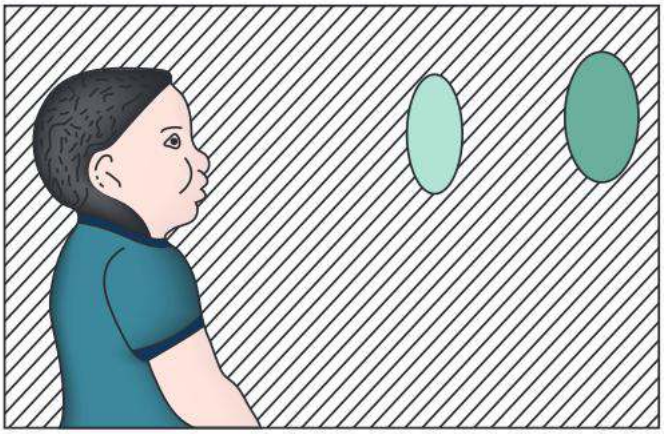


Fig. 2.5 *Teller acuity cards test (a type of PLT).*

Fig. 2.6 *Catford drum for visual acuity.*

2. Catford drum test. It is a *detection acuity test* useful in infants and children less than 2 years of age. In this test, the child is made to observe an oscillating drum with black dots of varying sizes ranging from 0.5 to 15 mm in diameter representing vision between 6/6 and 2/60 (Fig. 2.6). Rotation of disc at a distance of 60 cm evokes pendular movements. The smallest dot that evokes pendular eye movements (not an OKN) denotes the level of visual acuity. This test is unreliable, since it overestimates the vision.

ASSESSMENT OF VISUAL ACUITY FROM 1 TO 3 YEARS

Above 1 year of age, of visual acuity, the child is able to visually differentiate the small objects and is able to reach out for toys. So, in addition to the above-mentioned tests, the following detection acuity tests are more useful in this age group.

1. *CAC test.* CAC test or vanishing optotype test (Fig. 2.7) is used to measure visual acuity in this age group. The principle is that as long as the child can see the optotype (line drawings of pictures of fish, car, etc.), the child will show a preference for the picture as compared with the plain grey background. The black and white lines forming the pictures become finer with each set of three cards, until the picture cannot be seen (vanishing optotype) and the preference for fixation to the picture is lost. The pictures are presented on cards with the optotype appearing either on the top or the bottom of the card. The rest of the card is a homogenous grey that matches with the mean luminance of the picture. A total of 11 sets of cards are available, with acuity values ranging from 20/400 to 20/20, which have been calibrated for two presentation distances – 0.5 and 1 m. The patient is presented with one set of cards at a particular acuity equivalence, one card at a time. By observing the child's eye movements and fixations, the examiner must decide if the optotype is on the top or bottom of the card.

Fig. 2.7 *Cardiff acuity cards test.*

The acuity is determined by the narrowest white band for which the target is visible to the child and correct response is obtained at least 75% of the time when the particular finest line drawing is shown to the child.

Advantages include:

- It is an excellent way to determine minimum separable acuity in a child 1–3 years of age, unless the child can respond to recognition acuity chart.
- The fixations of the child to the pictures on the Cardiff cards are relatively easy to assess.
- CAC is a child friendly test.

Limitations include:

- May miss some cases of visually significant refractive errors.

- TAC is more dependable test to assess amblyogenic conditions despite the use of gratings.

2. ***Marble game test.*** In children of 6–12 months of age, reaching or placing games can be used to estimate visual function. One such game is the 'marble game'. In it, the child is asked to place marbles in the holes of a card or in a box. This test is not intended to measure visual acuity of each eye, but rather to compare the functioning of the child's eye when one or the other is closed. The vision of an eye is then noted as being 'useful' or 'less useful'.

3. ***Sheridan's ball test.*** Mary Sheridan (1960) used a series of styrofoam balls of progressively smaller sizes. One records the smallest ball that the infant can fixate and follow at a distance of 10 ft. Rolling the ball on a white or grey background and asking the child to pick it up, and noting the smallest size to which the child gives a good response is a rough way of estimating visual acuity.

4. ***Worth's ivory ball test.*** Ivory balls ranging in size from 0.5 to 2.5 inches in diameter are rolled on the floor in front of the child who is asked to retrieve each ball. Acuity is estimated on the basis of smallest size of the ball for the test distance.

5. ***Dot visual acuity test.*** Child is shown an illuminated box with black dots of different sizes printed on it. The smallest dot identified denotes the visual acuity of the child.

6. ***Coin test.*** In this test, the child is asked to identify the two faces of coins of different sizes held at different distances.

7. ***Miniature toy test.*** In this test, the child is shown a miniature toy from a distance of 10 ft and is asked to name or pick the pair from the assortment.

MEASUREMENT OF VISUAL ACUITY IN PRESCHOOL CHILDREN (3–5 YEARS)

At this age, the child is able to verbalize and recognize well, so in addition to the above-mentioned test, the following tests (based mainly on recognition acuity) are more useful for visual assessment.

1. ***Landolt's C test.*** This test attempts to test minimum separable acuity in young children who can understand the concept of break in the circle. Landolt's Cs are presented with the opening of the optotype at 3, 6, 9 or 12 o' clock. The child has to tell where the opening is. The separation at the break in the C represents 1 min of arc and the entire C subtends 5 min of arc at the eye for 20/20. (For further details, see page 54.)

2. ***Broken wheel test.*** This test is another subjective assessment of visual acuity in toddlers and preschoolers who are not able to perform matching tasks. A pair of cars in progressively smaller sizes, one of which has a wheel cut across, like Landolt's C (broken wheel), is shown to the child and the child is asked to identify the one with the broken wheel (Fig. 2.8).

The car represents on seven pairs of cards designed to use at 10 ft, providing Snellen's equivalents from 20/20 to 20/100 (shown in Fig. 2.8) presented in a forced choice paradigm without the need for verbal responses. The visual acuity tester holds up one pair of cards at a time and asks the child to point towards the car with the broken wheels. The child should correctly score four out of four responses and then the next smaller set of cards is used until the child can no longer consistently identify the car with broken wheels.

Advantages include:

- The child has to simply locate the broken wheel and need not to identify the direction of the opening.
- The broken wheel and Snellen's tests are highly correlated and that acuities measured with this test is equivalent to Snellen's chart with a certainty of 94% if using four-of-four criterion.

3. ***Illiterate E-cut-out test***. This test is useful in children between 2½ and 3 years of age. The child is given a cut-out of an E and asked to match this E with isolated Es of varying sizes. The first trial is not always successful. The mother may be instructed to teach E-game at

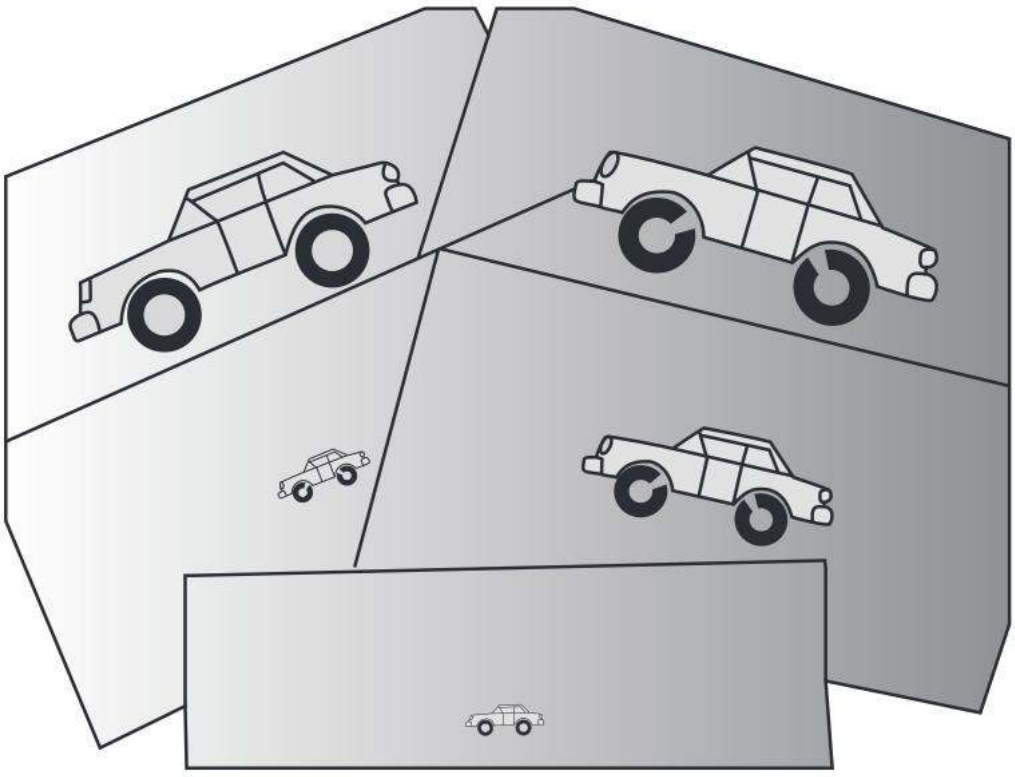


Fig. 2.8 *Broken wheel test.*

home. When the child starts understanding the orientation of E, a visual acuity chart consisting of Es oriented in various directions may be used.

4. ***Tumbling E-pad test.*** It consists of different sizes of E in one of the four positions (right, left, upward and downward) on a dice (Fig. 2.9). Basically, it is similar to E-cut-out test.

5. ***Isolated hand-figure test***. Sjögren has replaced the E with the isolated figure of a hand, and in some children, it works better than Es.

6. ***Sheridan–Gardiner HOTV test*** is another test similar to E-cut-out test (Fig. 2.10). This is an initiative test, used to test vision in the age group of 2–5 years. The child is handed a card with HOTV and is asked to match the letters on the chart. Snellen's equivalent of 6/6 to 6/60 can be estimated using this method.

7. ***Pictorial vision charts***. When the child is able to verbalize, visual acuity chart showing pictures, rather than symbols, may be used.

Fig. 2.9 *Tumbling E-pad test. Printed with large 20/200 E on one side and a series of five 20/20 tumbling Es on the other – calibrated to a 20-ft distance.*

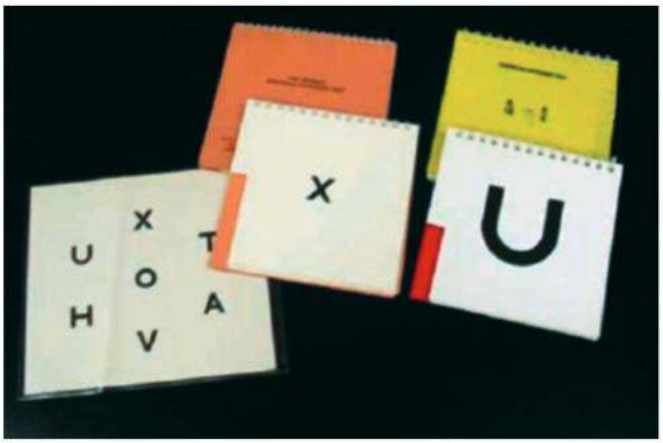


Fig. 2.10 *Sheridan–Gardiner single-letter optotypes.*

Fig. 2.12 *Kay picture test.*

Fig. 2.11 *Allen preschool test.*

Fig. 2.13 *Lea symbols test.*

Many such charts have been devised, and one should be chosen that presents pictures of objects with which the child is likely to be familiar. Pictorial vision charts include Kay picture test, Allen cards test, Lea symbols test and BUST (BUST is an acronym for the Swedish words for 'visual acuity and picture perception test').

- *Allen cards test* (Fig. 2.11). In this test, seven optotypes are presented to the child for recognition at a test distance of 15 ft (20/40) at 3 years of age and 20 ft (20/30) at 4 years of age.
- *Kay pictures* (Fig. 2.12) is another picture optotype developed to assess visual acuity in young children at distance as well as at near. The figures are child friendly with matching cards for children who cannot speak. The individual elements subtend a visual angle of 1 min of arc and the total figure subtends 10 min of arc at the eye. The available test booklets are for 6 and 3 m distance. The 3-m booklet is used for younger children who will not be attentive at 6 m. Near point cards are also available to assess near visual acuity.
- *Lea symbols test* (Fig. 2.13) was developed by Dr Lea Hyvärinen, a Finnish paediatric ophthalmologist, who developed a vast array of testing devices that have been standardized using four pictures – circle, square, house and apple. Lea numbers were developed in 1993 and calibrated in 1994. These optotypes can be presented as single characters, as a wall chart at a distance of 10–20 ft. They can be presented on a video display terminal screen or in the form of a flipbook. With the Landolt's C type being the reference optotype since 1988, earlier to which Snellen's E chart was the reference optotype, the size of the 1.0 (20/20, 6/6) optotypes was reduced from 7.5 to 6.84 min of arc.

  Lea symbols now have two important basic features of good optotypes that they blur equally and are calibrated against the

Landolt's C. This is a good way of testing individuals who do not use the Western alphabet. Hence, it eliminates the problem with language barriers.

- *BUST is* another picture test designed to test visual acuity of children with vision impairment and developmental handicaps. The range of visual acuity for distance acuity measurement values goes from 0.02 to 1.6 (20/1000 to 20/10).

8. *Boek candy bead test.* The child is asked to match beads at 40 cm. Snellen's visual acuity equivalent of 20/200 is estimated by this method.

9. *Light home picture cards.* A chart containing an apple, a house and an umbrella (Fig. 2.14), arranged in Snellen's equivalents of 20/200–20/10, is used and the child is asked to identify the pictures along the lines. The test is carried out at 10 ft.

MEASUREMENT OF VISUAL ACUITY IN SCHOOL CHILDREN (ABOVE 5 YEARS) AND ADULTS

- *Snellen's visual acuity charts* are most commonly employed in this age group. In illiterates, E charts and Landolt's C charts are used as alternative to Snellen's test types.
- *LogMAR charts* enable a more accurate estimate of acuity as compared to other charts. Because of high accuracy, these are the most commonly used charts in research settings/clinical trials.

1. SNELLEN'S TEST TYPES

The distant central visual acuity is usually tested by Snellen's test types. The fact that two distant points can be visible as separate only when they subtend an angle of 1 min at the nodal point of the eye forms the basis of Snellen's test types. It consists of a series of black capital letters on a white board, arranged in lines, each progressively diminishing in size. The lines comprising the letters have such a breadth that they will subtend an angle of 1 min at the nodal point. Each letter of the chart is so designed that it fits in a square, the sides of which are five times the breadth of the constituent lines. Thus, at the given distance, each letter subtends an angle of 5 min at the nodal point of the eye (Fig. 2.15). The letter of the top line of Snellen's chart (Fig. 2.16) should be read clearly at a distance of 60 m. Similarly, the letters in the

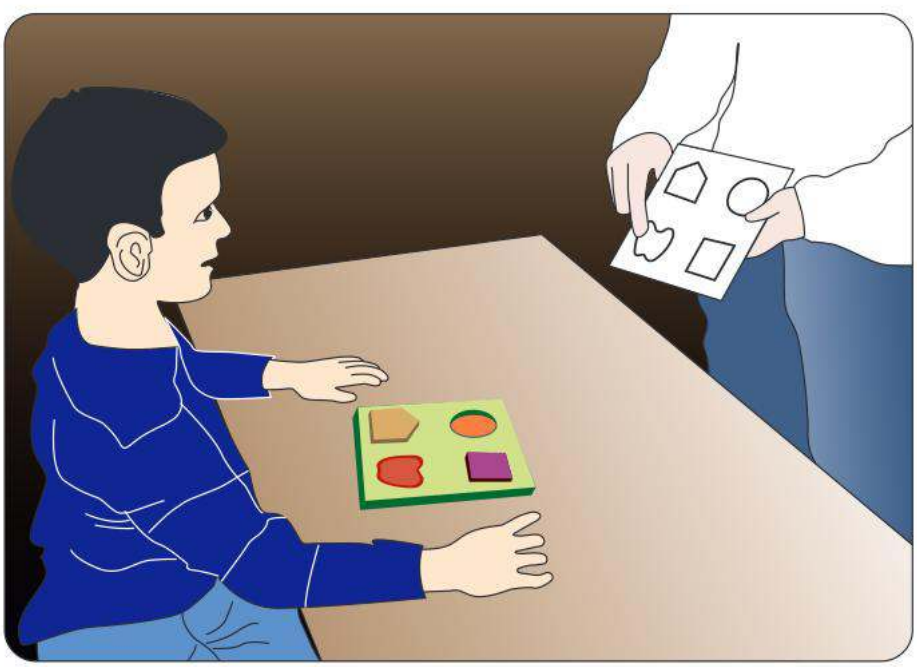


Fig. 2.14 *Light home picture cards.*

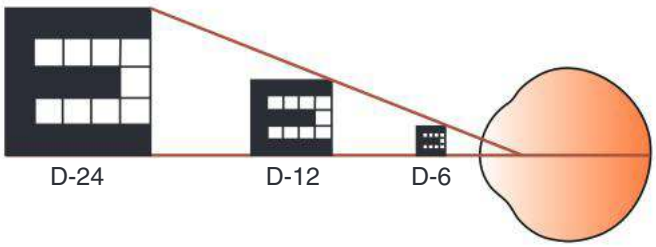


Fig. 2.15 *Principle of Snellen's test types.*

Fig. 2.16 *Snellen's test types.*

subsequent lines should be read from distances of 36, 24, 18, 12, 9, 6, 5 and 4 m.

Landolt's Test Types

It is similar to Snellen's test types except that in it instead of the letter the broken circles are used. Each broken ring subtends an angle of 5 min at the nodal point and is constructed similar to letter of Snellen's test types (Fig. 2.17).

With Snellen's letters, the end point consists of letter recognition; with Landolt's rings, it consists of the detection of the orientation of the break in the circle. Each method has advantages and disadvantages. Letter targets represent a practical visual test. However, the ability to recognize the target is influenced by literacy and past experience, even if the targets are somewhat blurred. Landolt's rings were designed to eliminate these factors and present a more objective test. However, since the gap can be placed in only four positions (up, down, left and right), guessing becomes an important factor. Also, letter tests remain much less confusing for the patient and the examiner, since the identification of letters is both immediate and unequivocal.

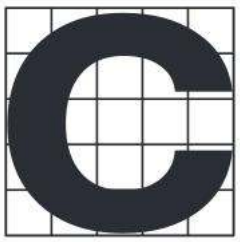


Fig. 2.17 *Construction of Landolt's visual acuity target.*

Procedure of Testing

For testing distant visual acuity, the patient is seated at a distance of 6 m from the Snellen's chart, so that the rays of light are practically parallel and the patient exerts minimal accommodation. The chart should be properly illuminated (not less than 20 foot-candle). The patient is asked to read the chart with each eye separately and the visual acuity is recorded as a fraction, the numerator being the distance of the patient from the letters and the denominator being the smallest letters accurately read.

When the patient is able to read up to 6-m line, the visual acuity is recorded as 6/6, which is normal. Similarly, depending upon the smallest line that the patient can read from the distance of 6 m, his or her vision is recorded as 6/9, 6/12, 6/18, 6/24, 6/36 and 6/60. If one cannot see the top line from 6 m, he or she is asked to slowly walk towards the chart till one can read the top line. Depending upon the distance at which one can read the top line, the vision is recorded as 5/60, 4/60, 3/60, 2/60 and 1/60.

If the patient is unable to read the top line even from 1 m, he or she is asked to count fingers (CF) of the examiner. His or her vision is recorded as CF-3′, CF-2′, CF-1′ or CF close to face, depending upon the distance at which the patient is able to CF. When the patient fails to CF, the examiner moves his or her hand close to the patient's face. If one can appreciate the hand movements (HM), visual acuity is recorded as HM positive. When the patient cannot distinguish the HM, the examiner notes whether the patient can perceive light (PL) or not. If yes, vision is recorded as PL positive and if not, it is recorded as PL negative.

Table 2.4 *Comparison between Snellen's and LogMAR visual acuity chart*

Snellen's chart	LogMAR chart
Irregular progression of letter size	Uniform progression of letter size
Variable number of letters in each line	Same number of letters in each line
Variable legibility (difficulty) of test letters	All letters with similar legibility
Distance between each letter is not uniform	Distance between each letter is equal to the width of the letter
Used at a distance of 6 m	Used at a distance of 4 m

2. LogMAR VISUAL ACUITY CHARTS

LogMAR stands for **Log**arithm of the **M**inimum **A**ngle of **R**esolution. A LogMAR chart comprises rows of letters and has equal number of letters in each line (Fig. 2.18). It is used at a distance of 4 m. It is designed to enable a more accurate estimate of acuity as compared to other charts (e.g. the Snellen's chart); for this reason, it is recommended in research settings.

The comparison of Snellen's and LogMAR visual acuity charts is shown in Table 2.4.

An observer who can resolve details as small as 1 min of visual angle scores LogMAR 0, since the base-10 logarithm of 1 is 0; an observer who can resolve details as small as 2 min of visual angle (i.e. reduced acuity) scores LogMAR 0.3, since the base-10 logarithm of 2 is 0.3; and so on. **Types of LogMAR charts** include the original Bailey-Lovie chart, its reduced versions and the Early Treatment Diabetic Retinopathy Study (ETDRS) charts.

The original Bailey-Lovie LogMAR chart consists of rectangular letters.

ETDRS chart is the modification of the original Bailey-Lovie LogMAR chart, where letter sizes are made square rather than rectangle.

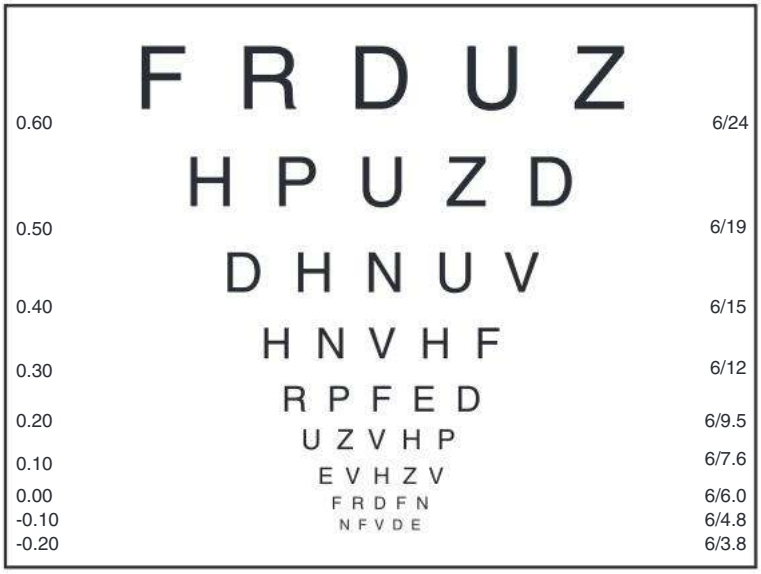


Fig. 2.18 *LogMAR visual acuity chart.*

Standardized ETDRS charts are available in three forms:

- *CSV-2000* is a fully computerized testing system that displays the ETDRS test charts on a computer monitor. The computer display light level is standardized through a patented technology called 'AcQviz'.
- *CSV-1000* offers a backlit ETDRS test and incorporates highly advanced miniature fluorescent light source technology that is standardized through automated calibration circuitry.
- *ESV-3000* is a large-format backlit ETDRS test device that incorporates advanced LED light source technology, also standardized through automated calibration circuitry.

Reduced LogMAR (RLM) chart was developed by Rosser and Laidlaw on the same principle as the ETDRS LogMAR chart with a reduction in the number of letters per line.

Compact reduced LogMAR (cRLM) chart was developed by Laidlaw *et al.*, which is closed spaced than the reduced LogMAR chart.

VISUAL ACUITY EQUIVALENTS IN DIFFERENT NOTATIONS

Table 2.5 indicates different ways for specifying visual acuity levels, viz. MAR, Snellen's acuity, efficiency rating, Snellen's fraction (i.e. the reciprocal of the MAR) and the logarithm of Snellen's fraction.

MEASUREMENT OF VISUAL ACUITY FOR NEAR

Near vision is tested by asking the patient to read a near-vision chart which consists of a series of different sizes of 'printer types' arranged in decreasing order and marked accordingly.

NEAR-VISION CHARTS

Commonly used near-vision charts are as follows.

1. ***Jaeger's chart.*** Jaeger, in 1867, devised the near-vision chart that consisted of the ordinary printers' fonts of varying sizes used at that time. Printers' fonts have changed considerably

Table 2.5 *Visual acuity equivalents in different notations*

MAR or minimum angle of resolution (min of arc)	Snellen's visual acuity		Snell–Sterling's visual efficiency (%)	Loss of central vision (%)	Snellen's fraction acuity relative	LogMAR acuity relative to 20/20
	ft	m				
0.5	20/10	6/3	109	0	2.0	0.3
0.75	20/15	6/4.5	104	0	1.33	0.1
1.00	20/20	6/6	100	0	1.0	0
1.25	20/25	6/7.5	96	4	0.8	–0.1
1.5	20/30	6/9	91	9	0.67	–0.18
2.0	20/40	6/12	84	16	0.5	–0.3
2.5	20/50	6/15	76	24	0.4	–0.4
3.0	20/60	6/18	70	30	0.33	–0.5
4.0	20/80	6/24	58	40	0.25	–0.6
5.0	20/100	6/30	49	50	0.2	–0.7
6.0	20/120	6/36	41	60	0.17	–0.78
7.5	20/150	6/45	31	70	0.133	–0.88
10.0	20/200	6/60	20	80	0.10	–1.0
20.0	20/400	6/120	3	90	0.05	–1.3

since then; however, it is now a general custom to use various sizes of modern fonts that approximate Jaeger's original choice. In this chart, prints are marked from 1 to 7 and accordingly patient's acuity is labelled as J1–J7, depending upon the print one can read.

2. ***Roman test types.*** The Jaeger's charts made from the modern fonts deviate considerably from the original standard, but they are probably sufficiently accurate for all practical purposes. However, to overcome this theoretical problem, the Faculty of Ophthalmologists of Great Britain in 1952 devised another near-vision chart. It consists of 'Times Roman' type fonts with standard spacing (Fig. 2.19). According to this chart, the near vision is recorded as N5, N6, N8, N10, N12, N18, N36 and N48.

3. ***Snellen's near-vision test types.*** Snellen introduced the so-called 'Snellen's equivalent for near vision' on the same principles as his distant types. The graded thickness of the letters of different lines is about 1/17th of the distant-vision chart letters. In this event, the letters equivalent to 6/6 line subtend an angle of 5 min at an average reading distance (35 cm/14 inches).

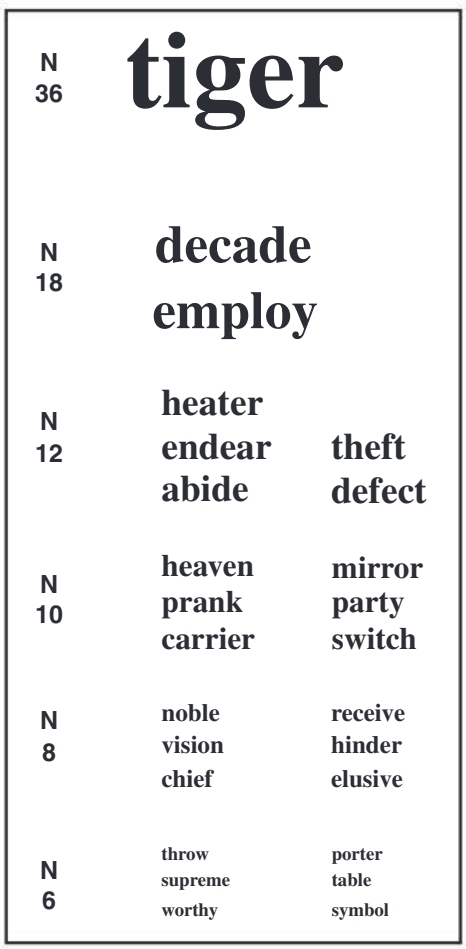


Fig. 2.19 *Near-vision chart.*

The unusual configuration of letters of this chart, however, cannot be constructed from the available printers' fonts. It can only be reproduced by a photographic reduction of the standard Snellen's distant-vision test types to approximately 1/17th of their normal size. Further, such a test has never become popular. The graded sizes of pleasing types of passages from literature, the reading of which helps in the interpretation, are habitually employed.

4. ***Lea near-vision cards.*** This test assesses a child's functional vision at near distances. It can also be used to familiarize child with testing procedure before introducing a distance test. It consists of cards measuring 8″ × 10″ (20.3 cm × 25.4 cm) which contain proportionally spaced (LogMAR) lines on one side and more tightly spaced symbols on the opposite side. Line sizes range from 20/400 to 20/10 (6/120 to 6/3) equivalent, 0.05 to 2.00. Response key is printed on test card. Testing distance is about 16 inches/40 cm.

Procedure of Testing

For testing the near vision, the patient is seated in a chair and asked to read the near-vision chart kept at a distance of 25–35 cm, with a good illumination thrown over his or her left shoulder. Each eye should be tested separately. The near vision is recorded as the smallest type that can be read comfortably by the patient. A note of the approximate distance at which the near-vision chart is held should also be made. Thus, near vision (NV) is recorded as follows:

NV = J_1 at 30 cm (in Jaeger's notation) and
NV = N_5 at 30 cm (in Faculty's notation).

Near-Vision Equivalents in Different Notations

These are shown in Table 2.6.

Table 2.6 *Equivalent visual acuity notations for near*

Visual angle (min)	Snellen's equivalent	American Medical Association notation	Decimal notation	Jaeger notation	Faculty's Roman test types notation	Metre notation (m)	Central visual efficiency for near (%)	Vision loss (%)
5.00	20/20	14/14	1.00	J1	N5	0.37	100	0
6.25	20/25	14/17	0.80	J1	N6	0.43	100	0
7.50	20/30	14/21	0.66	J2	N8	0.50	95	5
10.00	20/40	14/28	0.50	J4	N10	0.75	90	10
12.50	20/50	14/35	0.40	J6	N12	0.87	50	50
15.00	20/60	14/42	0.33	J8	N14	1.00	40	60
20.00	20/80	14/56	0.25	J10	N18	1.50	20	80
25.00	20/100	14/70	0.20	J1	N24	1.75	15	85
50.00	20/200	14/140	0.10	J17	N36	3.50	2	98

CONTRAST SENSITIVITY

INTRODUCTION

Contrast sensitivity is the ability to perceive slight changes in luminance between regions that are not separated by definite borders and is just as important as the ability to perceive sharp outlines of relatively small objects. It is only the latter ability that is tested by means of the Snellen's test types. In many diseases, loss of contrast sensitivity is more important and disturbing for the patient than is the loss of visual acuity. Further, contrast sensitivity may be impaired even in the presence of normal visual acuity.

TYPES OF CONTRAST SENSITIVITY

1. Spatial Contrast Sensitivity

Spatial contrast sensitivity refers to the detection of striped patterns at various levels of contrast and spatial frequencies. In its measurement, patient is presented with sine wave gratings of parallel light and dark bands (Arden gratings) and is asked to tell the minimum contrast at which the bars can be seen at each frequency. The width of the bars is defined as spatial frequency which expresses the number of pairs of dark and light bars subtending an angle of 1 degree at the eye. A high spatial frequency implies narrow bars, whereas a low spatial frequency indicates wide bars.

2. Temporal Contrast Sensitivity

Here, the contrast sensitivity function is generated for time-related (temporal) processing in the visual system by presenting a uniform target field modulated sinusoidal in time, rather than as a function of spatial position.

Both temporal and spatial contrast sensitivity testing yield significantly more complete and systematic data on the status of visual performance than the conventional tests.

MEASUREMENT OF CONTRAST SENSITIVITY

When a subject is presented with the grating frequencies and contrast below which resolution is impossible, it indicates the threshold level; and the reciprocal of this contrast threshold gives the contrast sensitivity.

Contrast sensitivity is measured as $(L_{max} - L_{min})/(L_{max} + L_{min})$, where L is the luminance recorded by photocells scanning across the gratings.

VARIABLES IN THE MEASUREMENT

There are three variables in the measurement of contrast sensitivity:

1. *Average amount of light reflected* depends on illumination of paper and darkness of ink.
2. *Degree of blackness* in relation to the white background, i.e. contrast.

3. *Distance between the grating periods* or cycles per degree of visual angle.

METHODS OF MEASUREMENT

Various methods have been developed to measure contrast sensitivity. Bodis-Wollner, introducing contrast sensitivity measurement in clinical practice, suggested the name *visuogram*, analogue to an *audiogram*, to describe a patient's 'contrast sensitivity curve'. The deficits were expressed in terms of decibels, and three types of deficits were described:

1. *High-frequency type* characterized by increasing loss at high frequencies.
2. *A level-loss type* characterized by a similar loss for all spatial frequencies.
3. *A selective-loss type* characterized by deficits of spatial frequencies in a narrow band.

In general, the methods recommended to measure contrast sensitivity include simple plates, cathode ray tube display on a screen, letter acuity charts, laser interferometer (LI) that produces grating on the retina, visual field testing using low contrast rings on stimuli, pattern discrimination test, prototype for forced choice printed test, visually evoked cortical potentials to checkerboard pattern reversal dependent contrast threshold measurement, two-alternative forced choice test and many more.

Some of the simple, inexpensive but reliable methods of measuring contrast sensitivity are described in brief in the following text.

1. Arden Gratings

Arden, in 1978, introduced a booklet containing seven plates: one *screening plate* (No. 1) and six *diagnostic plates* (No. 2–7). The contrast changes from top to bottom and covers a range of approximately 1.76 log units. The plates are studied at 57 cm, with spatial frequency increasing from 0.2 to 6.4 cycles/degree, each being double the frequency of the previous one. A score of 1–20 is assigned to each plate, depending upon the amount of plate uncovered. Sum of six plates with an upper limit of 82 was established for normal subjects together with an interocular difference of less than 12.

2. Cambridge Low-Contrast Gratings

Cambridge low-contrast gratings consist of a *set of 10 plates* containing gratings in a spiral bound booklet. To perform the test, the booklet is hung on a wall at a distance of 6 m. The pages are presented in pairs, one above the other. One page in each pair contains gratings and the other is blank (Fig. 2.20), but the pages have the

Fig. 2.20 *Cambridge low-contrast gratings.*

same mean reflectance. The subject is simply required to choose which page, top or bottom, contains the gratings. The pages are shown in the order of descending contrast and are stopped when the first error is made. Four descending series are shown separately to each eye. When no error is made at plate 10, then a score of 11 is given. Depending upon the total score of the patient from four series, the contrast sensitivity is noted from the conversion table (Fig. 2.21).

3. Pelli–Robson Contrast Sensitivity Chart

This chart consists of letters that subtend an angle of 3 degrees at a distance of 1 m. The chart is printed on both the sides. The two sides have different letter sequence but are otherwise identical. The letters on chart are organized as triplets, there being two triplets in each line (Fig. 2.22A and B). The contrast decreases from one triplet to the next. The log contrast sensitivity varies from 0.00 to 2.25.

To perform the test, the chart is hung on the wall, so that its centre is approximately at the level of the subject's eye. The chart is illuminated as uniformly as possible, so that the luminance of the white areas is between the acceptable range of 60 and 120 cd/m, which corresponds to a photographic exposure between 1/15 and 1/30 s at f/5.6 with an ASA of 100. The luminance is determined with the help of a light meter.

While recording, the subject sits directly in front of the chart at a distance of 1 m (with the best distance correction) (Fig. 2.23). The subject is made to name or outline each letter on the chart, starting from the upper left corner and reading horizontally across the line. Subject is made to guess, even when he or she believes that the letters are invisible. The test is concluded when the subject guesses two of the three letters of the triplet incorrectly. The subject's sensitivity is indicated by the finest triplet for which two of the three letters are named correctly.

4. The Vistech Chart

This chart consists of sine wave gratings and is used at a distance of 3 m from the subject. In

CAMBRIDGE LOW CONTRAST GRATINGS
SCORE SHEET

Patient's Name ..... Date of Birth .....
Record Number..... Date of testing .....

Examined by .....

Summary of procedure

1. Test each eye separately.
2. Show demonstration pages and instruct patient to choose which page ("top" or "bottom") contains the stripes.
3. Show subsequent pairs of pages in numerical order.
4. Encourage patient to respond, guessing if necessary.
5. Stop when the first error occurs (or at No. 10).
6. Note number on which error occurred in the table below; enter 11 if no errors.
7. Go back four plates from where you stopped (or to demonstration).
8. Repeat steps 3–7 until four series have been completed.
9. Add the four scores together and enter total in table below.
10. Convert total score to contrast sensitivity using conversion table.
11. Repeat steps 3–10 for the other eye, beginning the first series with stimulus No. 1.

Left eye	Right eye
Error on :	Error on :
Series 1	Series 1
Series 2	Series 2
Series 3	Series 3
Series 4	Series 4
Total	Total

Contrast Sensitivity

Conversion table

Total score	Contrast sensitivity
4	10
5	13
6	16
7	20
8	24
9	28
10	33
11	37
12	43
13	49
14	55
15	62
16	70
17	78
18	88
19	99
20	110
21	120
22	130
23	140
24	150
25	170
26	180
27	190
28	210
29	230
30	250
31	270
32	290
33	310
34	340
35	370
36	400
37	440
38	480
39	520
40	560

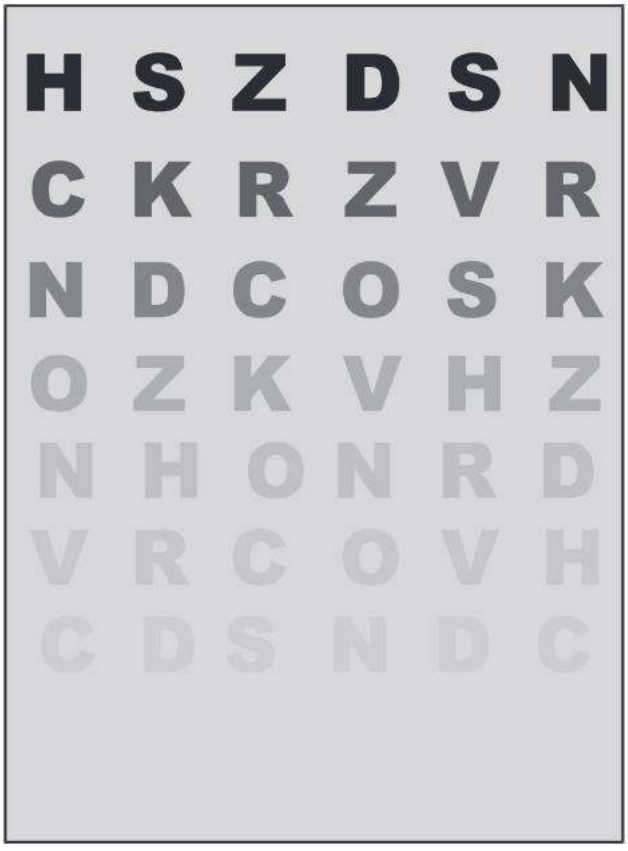
Percentile limits of normal performance on the published version of the Cambridge Low Contrast Gratings

Age range	90th percentile	95th percentile	97.5th percentile
10–19	24	22	20
20–29	29	27	28
30–39	29	28	27
40–49	28	25	24
50–59	21	18	18
60–80	24	23	22

Total scores lower than those tabulated may be considered abnormal, i.e. poorer than those expected from 90, 95 and 97.5% of the normal population.

Fig. 2.21 *Cambridge low-contrast gratings score sheet and conversion table.*

A



B

0.00	H	S	Z	D	S	N	0.15
0.30	C	K	R	Z	V	R	0.45
0.60	N	D	C	O	S	K	0.75
0.90	O	Z	K	V	H	Z	1.05
1.20	N	H	O	N	R	D	1.35
1.50	V	R	C	O	V	H	1.65
1.80	C	D	S	N	D	C	1.95
2.10	K	V	Z	O	H	R	2.25

Fig. 2.22 *Pelli–Robson contrast sensitivity chart: A, photograph; B, log contrast sensitivity score of each triplet.*

this test, contrast is assessed at several spatial frequencies (distance of the separation of the grating bars) and the subject has to identify the orientation of the grating, i.e. whether vertical or 15 degrees clockwise, or anticlockwise.

5. Vector Vision Chart

Vector vision CSV 1000 (USA) chart test frequency of 3, 6, 12 and 18 cpd.

6. Fact CS Chart

The fact CS chart tests for 1.5, 3, 6, 12 and 18 cpd.

FACTORS AFFECTING CONTRAST SENSITIVITY AND DIAGNOSTIC APPLICATIONS

FACTORS AFFECTING CONTRAST SENSITIVITY

1. ***Refractive errors.*** Visibility of low spatial frequencies is not limited by the refractive property of the eye; the refractive errors affect only the higher frequencies.
2. ***Age.*** There occurs a definite decrease in contrast sensitivity with increasing age. It has been reported that from the age of 20 years, contrast sensitivity scores for normal population decline with age by about 10% for each decade of life. The average decline over the lifespan is similar to the range of sensitivity within the normal population at any given age.
3. ***Lenticular changes.*** Early lens changes can reduce contrast sensitivity essentially for low spatial frequencies. This decrease in contrast sensitivity is not related to the visual acuity.
4. ***Ocular and systemic diseases.*** Contrast sensitivity is also found to be affected by various ophthalmic as well as systemic diseases. It is decreased in cases with retinal, optic nerve and visual pathway diseases, glaucoma, ocular hypertension, retrobulbar neuritis, multiple sclerosis, amblyopia, diabetes mellitus, pituitary adenoma, etc.

DIAGNOSTIC APPLICATIONS

The contrast sensitivity function, in recent years, has become popular as a possible diagnostic indicator of visual function. Deviations from normal standards have been reported in a number of conditions; some of which are listed above. It has been reported that contrast sensitivity (modulation transfer functions) may provide a fairly complete statement of the relations among spatial frequency or the fineness of visual details, the contrast required for resolution of detail and the luminance of the stimulus.

Fig. 2.23 *Measurement of contrast sensitivity with Pelli–Robson chart.*

TESTS FOR POTENTIAL VISION

Tests for potential vision have been developed in an effort to determine whether the individuals with obvious impaired vision have a potential to see well after the cataract surgery (i.e. whether the significant cause of their visual impairment is cataract or any other associated retinal pathology). Various subjective and objective tests are available for this purpose. Interferometry and PAM tests are currently the most popular ones and have been reported to be the most useful and accurate instruments in predicting postoperative visual acuity.

INTERFEROMETRY

Interferometry refers to the technique of estimation of visual acuity through mild-to-moderate ocular media opacification, e.g. cataract and corneal opacity by projecting a resolution target directly on the macula. The device used to perform this test is termed the interferometer.

PRINCIPLE

Interferometry utilizes the principle of light interference. The idea of projecting a resolution target directly on the macula after bypassing the opacities of the ocular media occurred to Dr Daniel Green and his colleagues at the University of Michigan. They reported that a proper resolution target could be a set of interference fringes of light and dark bands (Fig. 2.24). These patterns can be produced on the retina by the interaction of waves from two coherent light beams (each <0.1 mm in diameter). Since these are not images in the usual sense, they are

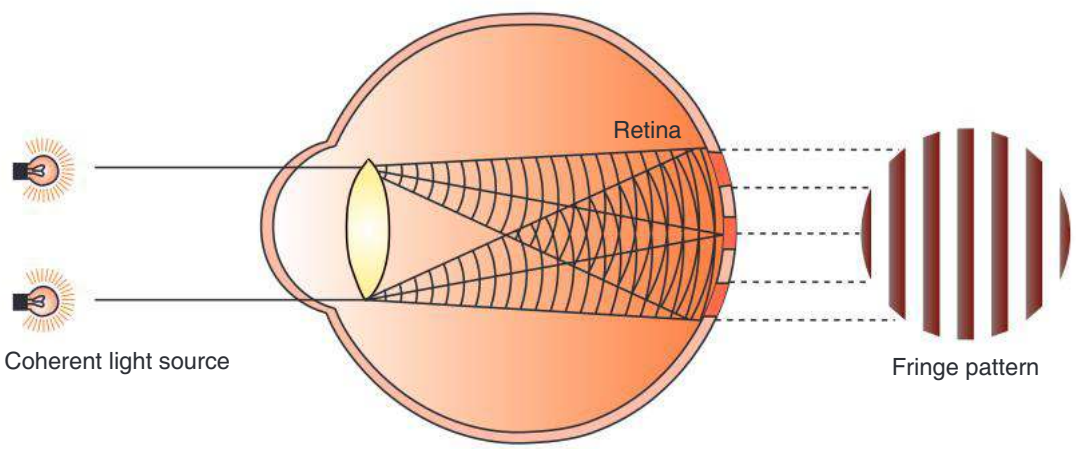


Fig. 2.24 *Fringe pattern on retina behind the cataract or media opacity.*

not affected by ordinary optical defects, defects of focus and imperfections in the refracting system of the eye. Whether an observer sees these fringes, depends only on the ability of the retina to conduct signals from the photoreceptors into the nervous system. Therefore, by using the interference fringes, it is possible to separate the retinal and neurological factors from the opacities of ocular media, thereby limiting visual resolution.

TYPES OF INTERFEROMETERS

Two types of clinical interferometers are available:

1. *LIs.* These exploit the coherent nature of laser light (Fig. 2.25). The two point-light sources come from a safe, low-power He–Ne laser (helium–neon gas laser; λ = 632.8 nm). Laser light, being coherent and of one pure colour, can come to a very fine point focus and produce vivid interference patterns. The light of the He–Ne laser being red is also scattered less than other visible wavelengths and thus penetrates the opaque media more clearly.

2. *White-light interferometers.* These interferometers use polychromatic white-light incandescent bulb as a source of light. These interferometers work similar to LIs except that the contrast of the gratings may be reduced by chromatic aberrations.

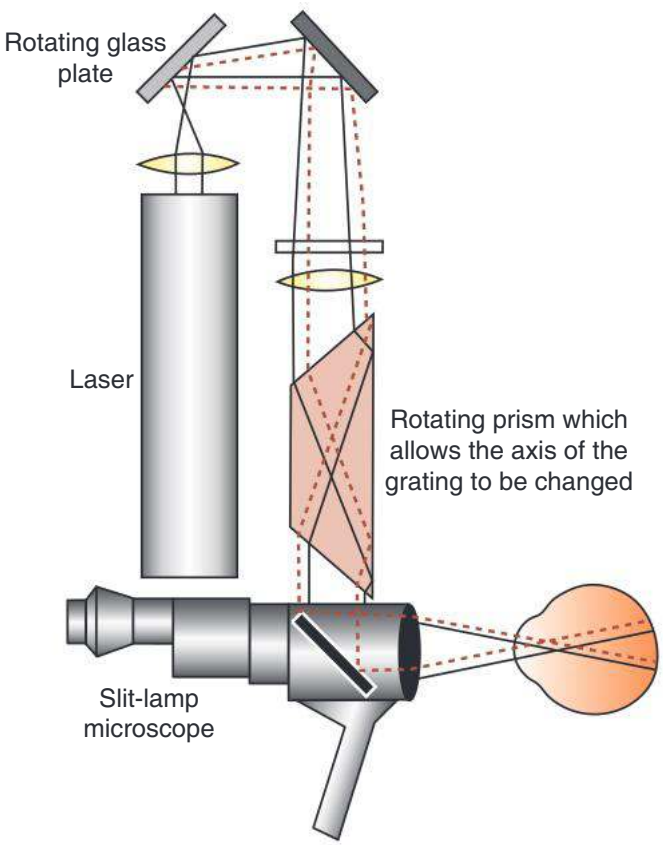


Fig. 2.25 *Laser interferometer attached with slit lamp.*

OPTICS

The working optics of both types of interferometers is similar. The optics of interferometer producing interference fringes uses low-frequency patterns by having two periodic waves go in-phase and out-of-phase with one another. The *maxima* refers to the points on the retina at which both beams are 'in-phase' and are seen as bright white bars. The *minima* refers to the points at which the beams are 'out-of-phase' and are seen as black bars (Fig. 2.26). The spacing of a fringe pattern (fringe pitch) is a function of the separation of the two pinpoint beam areas (grating angle). Increasing the separation produces a finer fringe pattern, which requires greater macular resolution.

The space between the fringes is repeatedly adjusted by the examiner till the patient can no longer detect their orientation. The last repeatedly perceived grating value recorded in a decimal-system reading is converted to Snellen's potential acuity. Thirty-three maxima per

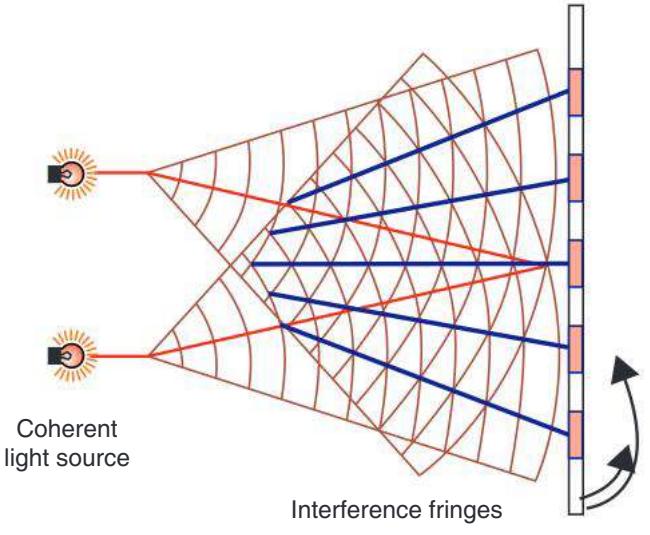


Fig. 2.26 *Interaction of wavefronts from two coherent light sources, producing interference images.*

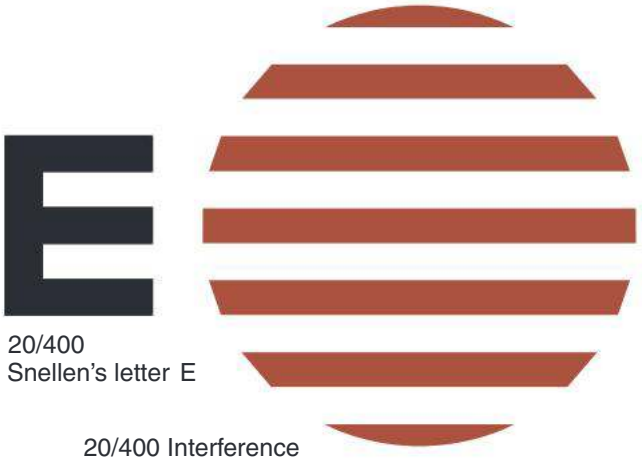


Fig. 2.27 *Correlation between Snellen's acuity and interference acuity.*

degree of visual angle corresponds to Snellen's equivalent of 6/6 (Fig. 2.27).

Production of fringe patterns depends on the amplitude of the electromagnetic wave and not on the intensity of light. Hence, as little as 20% transmission of each beam is needed for a reading. The field size of the interference fringe ranges from 1.5 to 8 degrees. The procedure is independent of refractive errors.

TECHNIQUE OF INTERFEROMETRY

1. ***Explanation to the patient.*** Before starting measuring the visual acuity by interferometry, the possible fringe pattern responses should be demonstrated to the patient from a display card (Fig. 2.28). The patient should be explained that partial patterns (scotomas) may be seen and that the patient should look only for band pattern direction, ignoring the scotomas. No prolonged 'light' testing, e.g. ophthalmoscopy should be performed just prior to the test.

2. ***Instrument and patient adjustment.*** The interferometer is mounted on the slit lamp. The patient, with his or her pupils fully dilated, is made to sit in front of the slit lamp, with the chin resting on the chin rest and forehead apposed to the forehead rest. The room is darkened and slit lamp is switched on. Alternatively, a hand-held interferometer may be used, with the patient seated on a chair with the eyes aligned with the instrument.

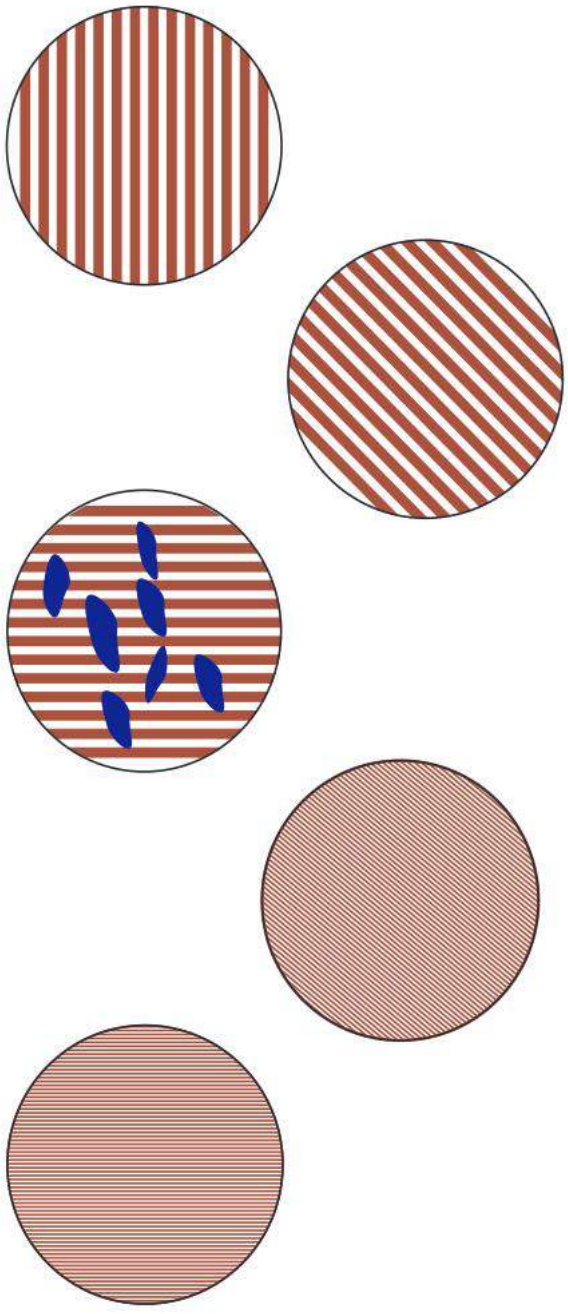


Fig. 2.28 *Possible responses on display card, demonstrated to the patient.*

3. ***Measuring visual acuity.*** Using the retroillumination technique, the region of the highest transparency in the patient's crystalline lens is identified and the instrument's beam is directed there. When the patient acknowledges visualization of pattern lines, one of the knobs is adjusted to allow an entrance pupil of 1.5 mm. Testing is started and the fringe pitch is increased in steps of 0.1 by adjusting another

knob. The patient is asked to indicate the direction of fringes (vertical, horizontal or oblique). The orientation can be changed by the examiner using the third knob. The end point is usually indicated by slower patient response. Four consecutive correct responses are needed for final potential acuity reading. With very low media transparency, it is helpful to increase the voltage from initial 5–7.5 V. The patient's end point fringe pitch decimal reading is read off from one of the knobs and converted to Snellen's equivalent, using the conversion table supplied.

INTERPRETATION OF RESULTS

1. ***A normal patient without any opacities in the media*** sees a circular field filled with a system of parallel alternating dark and light stripes. As the patient breathes, the spots move and thus the pattern moves, and the disordered pattern may replace the ordered ones.
2. ***Patients with opacities in the ocular media*** frequently first report seeing only a disordered, moving array of 'shooting stars', 'jumble' or 'moving worms'. This disorder is the effect of the opacity on the interference fringes. The spatial structure of this disordered array can give clues as to which sites are least opaque. In the relatively clear areas, the size of the 'stars' or 'worms' increases. A perfectly clear area is an area in which the 'star' increases in size to cover the whole field. Consequently, the patient is instructed to ignore the distorted and moving patterns and to concentrate his or her attention on the regular stripes within the bright area in the field.

If the patient sees the stripes, he or she is asked to identify the orientation of the stripes. The acuity is taken to be of the finest stripe pattern that the patient can perceive. On occasions, the patient reports seeing stripes but is unable to identify their orientation correctly. With more patience and longer tutoring, these patients might learn to see the pattern.

3. ***Patients with very dense opacities in media*** see no pattern, whatsoever, since their opacities are too dense to be penetrated, even by the laser acuity technique.

VALIDATING THE TEST

1. ***The predictive value*** of the interference visual acuity test can be assessed by comparing the patient's postoperative acuity with preoperative acuity measured by the interference fringe. There is a good correlation between predicted and achieved visual acuity for patients who learn to see the fringes. The results seem to be random for those patients who fail to see the fringes. Consequently, inability to see the fringe pattern, especially in severely opacified eyes, does not necessarily indicate lack of potential for good vision. However, the ability to see fine interference fringes should be considered a favourable sign. For patients who would be operated on only if indications of existing potential visual acuity can be obtained, testing with LIs is invaluable. It succeeds in evaluating macular function in many instances in which the usual methods of testing visual potential can provide only crude estimates of retinal function.
2. ***False-positive test*** may be achieved in the following situations:
   - *Tilted retinal receptors* generally result in poor Snellen's acuity (Stiles–Crawford phenomenon). However, if these receptors are viable, they can result in a normal reading interferometry test producing false-positive results.
   - *Healthy photoreceptors* in patients with cystoid macular oedema can also show false-positive result.
   - *Viable parafoveal tissue stimulation* is also believed to produce false-positive result in patients with cystoid macular oedema, geographic atrophy of macula, macular hole and macular cystoid.
3. ***False-negative results*** may be obtained in the following conditions:
   - Poor pupillary dilation,
   - Very dense cataract and
   - Dense vitreous haemorrhage.

POTENTIAL ACUITY METER TEST

INSTRUMENT DESIGN AND OPTICS

The PAM was introduced by Guyton and Minkowski in 1980. It is a small device that

Fig. 2.29 *Potential acuity meter.*

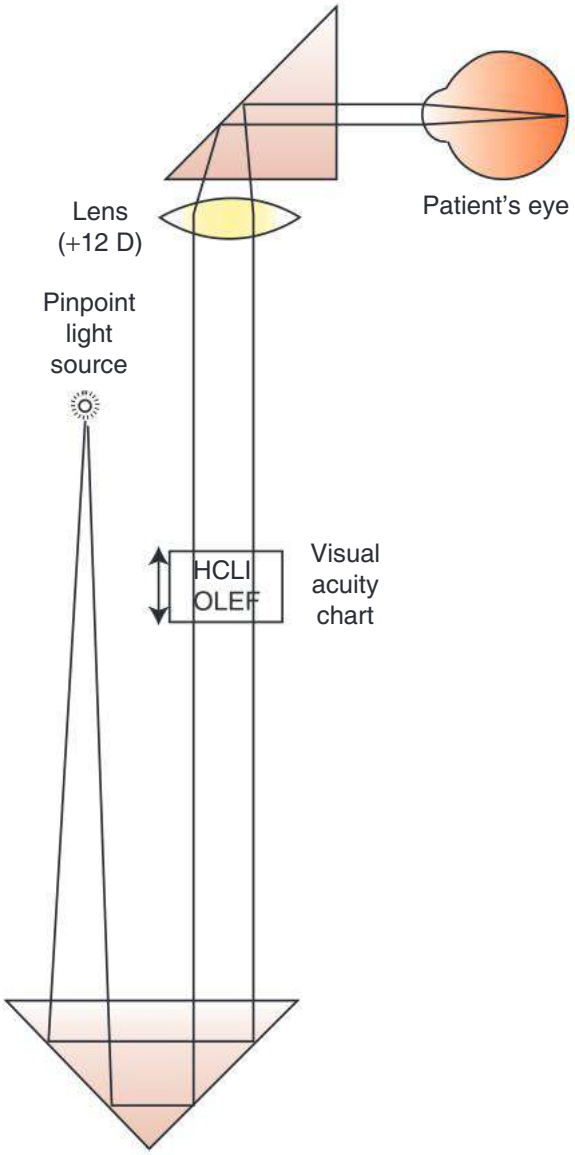


Fig. 2.30 *Optical diagram of potential acuity meter (PAM).*

mounts on a slit lamp (Fig. 2.29) and projects an image of a Snellen's visual acuity chart, using a 0.15 mm diameter aperture, through clear areas in the lens (windows of cataract) on to the retina. The optical diagram of the PAM is shown in Fig. 2.30. As the beam diverges in the eye, the image of the Snellen's chart is carried to the retina (Fig. 2.31). A knob on the PAM permits rapid focusing of the letter chart, using a slide scale ranging from +13 to –10 D. Black optotypes on a white background create a range of Snellen's acuities from 20/20 to 20/400.

TECHNIQUE

The test is best performed with the pupil dilated. The patient should also wear his or her best spectacle correction, or trial lenses duplicating the refractive error should be placed in the instrument. The beam of light is now directed through the clearer areas of the cataract, and the patient is asked to read the chart. Disturbing entoptic imagery is seen, and the letters on the chart appear and disappear as the patient's eye moves and while he or she talks. However, slowly after adjustment, the patient should be able to read a small line, if the macula is normal.

VALIDATING THE TEST

1. The PAM has been found to be a very promising instrument. On reviewing the literature and various studies conducted on PAM, it has been found that the PAM correctly predicts the postoperative visual acuity in patients with moderate cataracts (20/200 vision or better) to within three lines on Snellen's chart in 100% of cases and to within two Snellen's lines in 91% of cases.

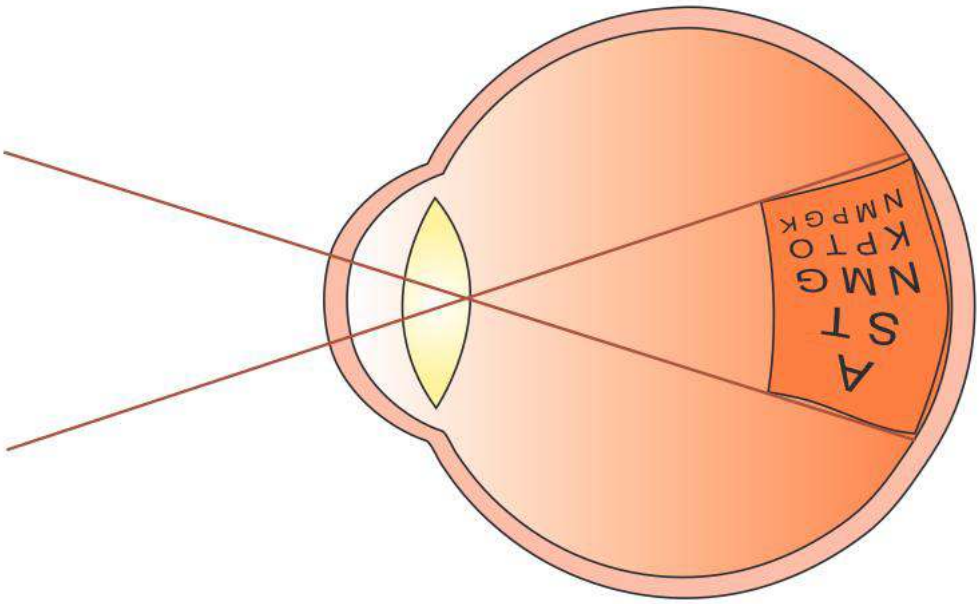


Fig. 2.31 *Snellen's chart projected on to the retina in PAM test.*

2. The PAM may also erroneously predict improved or worse vision in eyes with cystoid macular oedema, serous detachment of the sensory epithelium of the macula, recent postoperative reattached retina, geographic atrophy of the retinal pigment epithelium of the macula, macular hole or cyst, dense opacities (e.g. dense cataract) or glaucoma. However, unlike laser interferometry (LI), amblyopia does not appear to interfere with the ability of the PAM to make accurate predictions.

3. At times, it may also be difficult to find a clear window through which to project the fine beam of light with a dense posterior subcapsular cataract or diffuse cortical changes; therefore, often where we need the information most, we are least able to estimate retinal acuity.

COMPARATIVE STATUS OF LI AND PAM

The LI and the PAM both rely on the patient's subjective responses. The PAM has the advantage of using the Snellen's chart, which is familiar to the patients. The interpretation of sine wave patterns required by interferometers may be an unfamiliar task for most patients. In general, in unselected cataract patients, both the interferometers and the PAM give accurate predictions (within two Snellen's lines) of postoperative vision in 75%–90% of cases.

FACTORS AFFECTING ACCURACY OF PAM AND LI

There are several factors that may affect the accuracy of the PAM and LI tests, and these should be considered when interpreting predicted vision, especially in preoperative counselling of patients.

- Severity of the cataract is the most important factor affecting accuracy of LI and PAM. If the Lens Opacities Classification System II (LOCS II) is used to describe the type and severity of cataracts, it is found that the PAM and LI tests are more accurate in predicting visual outcome for eyes with moderate cataracts than for eyes with severe cataracts.
- *Type of cataract* likewise affects the accuracy of these instruments. The PAM and LI tend to underestimate visual outcome more in eyes with posterior subcapsular cataracts. This may be due to increased density and centrality of the opacities, unlike nuclear cataracts which are more diffuse and cortical cataracts which are usually in the periphery and hence may be bypassed more easily by these instruments.

- *Preoperative visual acuity of 20/200 or worse* also affects the accuracy of the PAM and LI. Both of these are less effective in predicting postoperative visual acuity at these levels of vision. For eyes with other ocular diseases, the LI tends to overestimate the probable visual outcome more than the PAM, especially in patients with poor retinal function as in macular degeneration, retinal degeneration and retinitis pigmentosa. This may lead to much disappointment postoperatively, especially for the patient.

CONCLUSIONS

- *In moderate cataracts*, both LI and PAM are useful.
- *In severe cataracts*, the PAM underestimates the potential vision more than the LI.
- *For eyes with retinal disorders*, the LI test overestimates the potential vision more than the PAM test, and the results need to be interpreted with caution.
- *In patients with posterior subcapsular cataracts,* both instruments tend to underestimate potential vision.
- *The LI and PAM test results* are not always in agreement, but both instruments, when used together, supplement each other.

3 Errors of Refraction and Binocular Optical Defects

Chapter Outline

EMMETROPIA AND AMETROPIA

EMMETROPIA

Emmetropia (optically normal eye) can be defined as a state of refraction wherein the parallel rays of light coming from infinity are focused at the sensitive layer of retina with the accommodation being at rest (Fig. 3.1). Thus, an emmetropic eye will have a clear image of a distant object without any internal adjustment of its optics. While axial length of most emmetropic eyes is approximately 24 mm, a larger eye can be emmetropic if its optical components are weaker and a smaller eye can be emmetropic if its optical components are stronger.

Normal age variation in the refractive status of eye is as follows:

- *At birth,* the eyeball is relatively short, having +2 to +3 D hypermetropia, which is gradually reduced.
- *By the age of 5–7 years,* the eye is emmetropic and remains so till the age of about 50. However, emmetropia is just a theoretical ideal. Practically, occurrence of small amount of astigmatism is not uncommon.

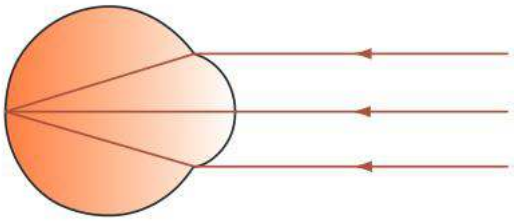


Fig. 3.1 *Refraction in an emmetropic eye.*

- *After 50 years of age*, there is a tendency to develop hypermetropia again, which gradually increases until at the extreme of life, and by 80 years, the eye has the same +2 to +3 D with which it started. This senile hypermetropia is due to changes in the crystalline lens. It is mainly of index type. Curvature changes in the lens may also play some role. Some amount of latent hypermetropia may become manifest due to decreased ciliary function with age. Some individuals, however, develop index myopia due to nuclear sclerosis with age. In these patients, near vision improves and so may not any more need glasses for near vision. This phenomenon is referred to as *'second sight'*.

AMETROPIA

Ametropia (a condition of refractive error) is defined as a state of refraction wherein the parallel rays of light coming from infinity (with accommodation at rest) are focused either in front or behind the sensitive layer of retina, in one or both the meridia. *Ametropia* includes the following:

- Myopia,
- Hypermetropia and
- Astigmatism.

Note: The related conditions, aphakia and pseudophakia, are also discussed here.

Components of Ametropia

The overall refractive state of the eye is determined by four components:

- Corneal power (ranges from 40 to 45 D, mean 43 D),
- Anterior chamber depth (mean 3.4 mm),
- Crystalline lens power (ranges from 15 to 20 D in its non-accommodative state) and
- Axial length (mean 24 mm).

Emmetropization, during the development of the eyeball, is the result of cooperation of these components. It seems possible that the process of emmetropization is coordinated by the retina–brain complex, which might tune each component to ensure a sharp image. Experimental studies suggest that emmetropization is largely programmed on a genetic basis.

Prevalence of Ametropia

Though it is not possible to exactly comment on the prevalence of ametropia, the *Stenström's study from Uppsala, Sweden*, may be considered reflective of the general population. Prevalence of ametropia according to this study is as follows:

- Low myopia (≤2 D): 29%,
- Moderate myopia (2–6 D): 7%,
- High myopia (>6 D): 2.5%,
- Emmetropia and hypermetropia up to 2 D (0–2 D): 61% and
- High hypermetropia: 0.5%.

HYPERMETROPIA AND RELATED CONDITIONS

HYPERMETROPIA

The term hypermetropia, first suggested by Kastner in 1755, is derived from the words *hyper* (meaning in excess), *met* (meaning measure) and *opia* (meaning of the eye). Optically, the term hypermetropia (hyperopia) or long-sightedness refers to the refractive state of the eye wherein parallel rays of light coming from infinity are focused behind the retina with accommodation being at rest (Fig. 3.2). Thus, the posterior focal point is behind the retina, which, therefore, receives a blurred image.

AETIOLOGICAL TYPES

Aetiologically, depending upon the mechanism of production, hypermetropia may be axial, curvatural, index, positional and due to absence of lens.

1. ***Axial hypermetropia*** is by far the commonest form. In this condition, the total refractive power

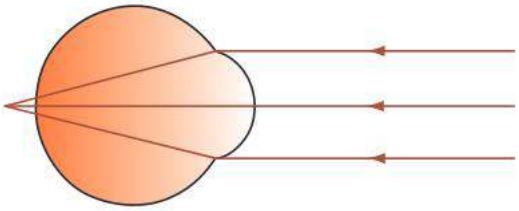


Fig. 3.2 *Refraction in a hypermetropic eye.*

of the eye is normal, but there is an axial shortening of eyeball. About 1 mm shortening of the anteroposterior diameter of the eye results in 3 D of hypermetropia. Axial hypermetropia is usually developmental and may be physiological or non-physiological.

Non-physiological hypermetropia occurs in microphthalmos and nanophthalmos due to markedly short axial length (usually less than 20 mm).

2. ***Curvatural hypermetropia*** is the condition in which the curvature of cornea, lens or both is flatter than the normal, resulting in a decrease in the refractive power of eye. About 1 mm increase in radius of curvature results in 6 D of hypermetropia. It may be developmental and rarely acquired.

3. ***Index hypermetropia*** occurs due to change in refractive index of the lens in old age. It may also occur in diabetics under treatment.

4. ***Positional hypermetropia*** results from posteriorly placed crystalline lens (congenitally or following trauma).

5. ***Absence of crystalline lens*** either congenital or acquired (following surgical removal or posterior dislocation) leads to aphakia – a condition of high hypermetropia.

6. ***Consecutive hypermetropia*** may result following:

- *Overcorrected myopia* after refractive surgery (laser-assisted in situ keratomileusis [LASIK], implantable contact lenses [ICL]) and
- *Underpowered intraocular lens* (IOL) in cataract surgery and refractive lens exchange (RLE).

CLINICAL TYPES

There are four clinical types of hypermetropia:

- Congenital hypermetropia
- Simple hypermetropia
- Pathological hypermetropia
- Secondary hypermetropia.

1. Congenital hypermetropia is not a common condition.

- *Age of onset*: Congenital hypermetropia is present since birth.
- *Anisometropia* is almost always present as the condition is unilateral due to abnormally small one eye.
- *Magnitude of refractive error* is high and often remain constant, i.e. not a progressive condition.

2. Simple hypermetropia is the commonest form. It results from normal biological variations in the development of the eyeball. *Simple hypermetropia* may be hereditary. Inheritance is usually dominant, which may be irregular. It includes the following:

- *Axial hypermetropia* due to congenital/developmental short eyeball and
- *Curvatural hypermetropia* due to congenital/developmental flatter cornea.

3. Pathological hypermetropia results due to atypical/abnormal development of the eyeball, which is outside the normal biological variations of the development.

Pathological hypermetropia is seen in following conditions:

- Microphthalmos,
- Microcornea,
- Congenital posterior subluxation of the lens and
- Congenital aphakia.

4. Secondary hypermetropia The term secondary hypermetropia may be used for all types of acquired hypermetropia caused by other eye disorders or factors which are not the known risk factors for simple or physiological hypermetropia.

Following conditions can be included in secondary hypermetropia:

i. ***Senile hypermetropia***, or frequently designated as *acquired hypermetropia*, occurs in old age due to two causes:

- *Curvatural hypermetropia* due to decreased curvature of the outer lens fibres developing later in life.
- *Index hypermetropia* due to acquired cortical sclerosis. In youth, the index of refraction of

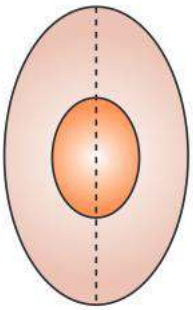


Fig. 3.3 *Structure of the crystalline lens depicting a central lens surrounded by two menisci.*

the cortex is considerably less than that of nucleus, and this inequality results in the formation of combination of a central lens surrounded by two converging menisci (Fig. 3.3). This results in an increase in the refracting power of the lens as a whole. In old age, refractive index of the cortex increases. As a result, the lens becomes more homogeneous and acts as a single lens. Consequently, the converging power of the lens as a whole decreases, resulting in index hypermetropia.

ii. ***Positional hypermetropia*** may occur due to acquired (traumatic or spontaneous) posterior subluxation of the lens.

iii. ***Aphakia*** due to acquired absence of lens (traumatic or surgical).

iv. ***Consecutive hypermetropia*** due to surgically overcorrected myopia or pseudophakia with undercorrection.

v. ***Acquired axial hypermetropia.*** Retrobulbar orbital tumours may sometime manifest as hypermetropia by anteriorly pushing the posterior wall of the eyeball (axial hypermetropia).

vi. ***Acquired curvatural hypermetropia*** may occur due to post-traumatic or post-inflammatory corneal flattening.

vii. ***Functional hypermetropia*** results from paralysis of accommodation as seen in patients with third nerve paralysis and internal ophthalmoplegia.

NOMENCLATURE OF COMPONENTS OF HYPERMETROPIA DEPENDING UPON THE EFFECT OF ACCOMMODATION

Accommodation in hyperopia is of greater importance than the structural factors leading to it because accommodation is a key dynamic factor in correcting at least part of the refractive error. Nomenclature for various components of the hypermetropia is as follows.

Total hypermetropia is the total amount of refractive error, which is estimated after complete cycloplegia with atropine. It consists of latent and manifest hypermetropia.

1. ***Latent hypermetropia*** implies the amount of hypermetropia (about 1 D) which is normally corrected by the inherent tone of ciliary muscle. The degree of latent hypermetropia is high in children and gradually decreases with age. The latent hypermetropia is disclosed when refraction is carried after abolishing the tone with atropine.
2. ***Manifest hypermetropia*** is the remaining portion of total hypermetropia, which is not corrected by the ciliary tone. It consists of two components, *facultative* and *absolute* hypermetropia.
   i. *Facultative hypermetropia* constitutes that part which can be corrected by the patient's accommodative effort.
   ii. *Absolute hypermetropia* is the residual part of manifest hypermetropia, which cannot be corrected by the patient's accommodative efforts.

Thus, ***total hypermetropia*** = latent + manifest (facultative + absolute).

Note. With increasing age due to decreasing accommodation, the facultative hypermetropia goes on decreasing and the absolute hypermetropia goes increasing.

CLINICAL PICTURE

Symptoms

In patients with hypermetropia, the symptoms vary depending upon the age of the patient and the degree of refractive error. These can be grouped as follows:

1. ***Asymptomatic.*** A small amount of refractive error ***(<1 D)*** in young patients is usually corrected by mild accommodative effort, without producing any symptom.
2. ***Asthenopic symptoms.*** At times the hypermetropia ***(1–2 D)*** is fully corrected (thus vision is normal), but due to sustained accommodative

efforts the patient develops asthenopic symptoms. These include:

- Tiredness of eyes,
- Frontal or frontotemporal headache,
- Watering and
- Mild photophobia.

These asthenopic symptoms worsen as the day progresses and are aggravated by prolonged use of near vision.

3. ***Defective vision with asthenopic symptoms.*** When the amount of hypermetropia ***(2–4 D)*** is such that it is not fully corrected by the voluntary accommodative efforts, then the patient complains of defective vision more for near than distance associated with asthenopic symptoms due to sustained accommodative efforts.

4. ***Defective vision only.*** When the amount of hypermetropia is more ***(>4 D)***, the patients usually do not accommodate (especially adults) and there occurs marked defective vision for near and distance.

5. ***The effect of ageing on vision.*** There occurs a progressive loss of accommodative power with ageing, thus moving the eye from latent and facultative hypermetropia to greater degrees of absolute hyperopia. There occurs progressive defective vision. To start with, near visual acuity blurs at a younger age than in the emmetrope, e.g. in the late 30s. This is aggravated when the patient is tired, printing is indistinct or lighting conditions are suboptimal.

6. ***Intermittent sudden blurring of vision*** may occur due to spasm of accommodation inducing pseudomyopia. Such a condition is detected by cycloplegic refraction, which reveals the underlying hyperopia.

7. ***Crossed-eye sensation.*** Some patients may feel that their eyes are crossing without any diplopia. It also occurs due to excessive accommodation.

Signs

1. *Visual acuity* varies with the degree of hypermetropia and power of accommodation. In patients with low degree of refractive error, visual acuity may be normal.

On the basis of the degree of absolute hypermetropia, a rough estimate of visual acuity is depicted in Table 3.1.

Table 3.1 *Estimate of visual acuity in absolute hypermetropia*

Absolute hypermetropia (D)	Snellen's visual acuity
10.5	6/9
10.75	6/12
11.0	6/12–6/18
11.5	6/24
12.0	6/24 (Partial)
12.5	6/36–6/60
13.5	4/60
14.5	3/60

2. *Size of the eyeball* may be normal or may appear small as a whole.

3. *Cornea* may be slightly smaller than the normal. There can be cornea plana.

4. *Anterior chamber* is comparatively shallow and the angle is narrow.

5. *Fundus examination may reveal following:*

- *Optic disc* which may look small and more reddish in colour with ill-defined margins and even *simulate papillitis* (though there is no swelling of the disc, and so it is called *pseudopapillitis*).
- *Macula*. Foveal reflects may be situated at greater distance from the disc margin. It may cause large positive angle kappa (producing apparent divergent squint).
- *General background.* The retina as a whole may shine due to greater brilliance of light reflections (*shot silk appearance*).
- *Retinal vessel* reflexes may be accentuated. The vessels may show undue tortuosity or abnormal branching.

6. *A-scan ultrasonography* (biometry) may reveal a short anteroposterior length of the eyeball.

Grading of Hypermetropia

American Optometric Association (AOA) has defined three grades of hypermetropia:

- Low hypermetropia, ≤+2 D
- Moderate hypermetropia, +2 to +5 D
- High hypermetropia, ≥+5 D.

COMPLICATIONS

If hypermetropia is not corrected for a long time, the following complications may occur:

1. ***Recurrent styes, blepharitis or chalazia*** may occur, probably due to infection introduced by repeated rubbing of the eyes, which is often done to get relief from fatigue and tiredness.
2. ***Accommodative convergent squint*** may develop in children (usually by the age of 2–3 years) due to excessive use of accommodation.
3. ***Amblyopia*** may develop in some cases. It may be:
   - Anisometropic amblyopia (in unilateral hypermetropia),
   - Strabismic amblyopia (in children developing accommodative squint) or
   - Ametropic amblyopia (seen in children with uncorrected bilateral high hypermetropia).
4. ***Predisposition to develop primary angle closure glaucoma.*** The eye in hypermetropes is small with a comparatively shallow anterior chamber. Due to regular increase in the size of the lens with increasing age, these eyes become prone to develop primary angle closure disease. This point should be kept in mind while instilling mydriatics in elderly hypermetropes.

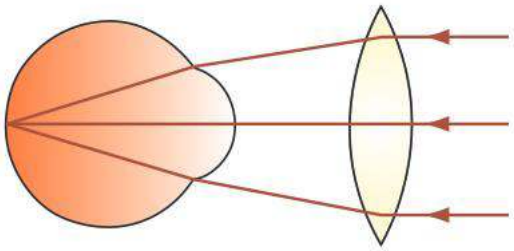


Fig. 3.4 *Refraction in a hypermetropic eye corrected with convex lens.*

TREATMENT

A. Optical Treatment

Basic principle of treatment is to prescribe convex (plus) lenses, so that the light rays are brought to focus on the retina (Fig. 3.4).

Guidelines for refractive correction in infants and young children, as described in Preferred Practice Pattern: Paediatric Eye Evaluation, AAO, 2012, are summarized in Table 3.2.

Fundamental rules for prescribing glasses in hypermetropia include the following:

I. *General rules* are as follows:
   - *Total amount of hypermetropia* should always be discovered by performing refraction under complete cycloplegia.

Table 3.2 *Guidelines for refractive correction in infants and young children*

Type of refractive error	Magnitude of refractive errors (dioptres)		
	Age <1 year	Age 1–2 years	Age 2–3 years
Isoametropia (similar refractive error in both eyes)			
Myopia	–5.00 or more	–4.00 or more	–3.00 or more
Hyperopia (no manifest deviation)	+6.00 or more	+5.00 or more	+4.50 or more
Hyperopia with esotropia	+2.50 or more	+2.00 or more	+1.50 or more
Astigmatism	3.00 or more	2.50 or more	2.00 or more
Anisometropia (without strabismus)[a]			
Myopia	–4.00 or more	–3.00 or more	–3.00 or more
Hyperopia	+2.50 or more	+2.00 or more	+1.50 or more
Astigmatism	2.50 or more	2.00 or more	2.00 or more

Notes: These values were generated by consensus and are based solely on professional experience and clinical impressions because there are no scientifically rigorous published data for guidance. The exact values are unknown and may differ among age groups; they are presented as general guidelines that should be tailored to the individual child. Specific guidelines for older children are not provided because refractive correction is determined by the severity of the refractive error, visual acuity and visual symptoms.

[a]Threshold for correction of anisometropia should be lower if the child has strabismus. The values represent the minimum difference in magnitude of refractive error between eyes that would prompt refractive correction.

- *Total manifest refractive error* when small, e.g. 1 D or less, correction is given only if the patient is symptomatic.
- *Spherical correction given* should be comfortably acceptable to the patient. However, the astigmatism should be fully corrected.

II. ***For children,*** follow the guidelines described in Table 3.2 and the rules given below:

- *Children younger than 4 years* who require hypermetropic correction can usually accept the full cycloplegic measurement. Once a child reaches school age, consider reducing the plus for the refractive prescription by about one-third, but the child is not required to accommodate more than 2.5 D continually for the distance.
- *The older children* may not accept full cycloplegic refraction because of blur at distance. So, always first undercorrect and prescribe the glasses that the child accepts comfortably. Gradually increase the spherical correction at 6-month interval till the patient accepts manifest hypermetropia.
- *If there is associated exophoria,* the hyperopia should be undercorrected by 1–2 D.
- *In the presence of accommodative convergent squint,* full correction should be given at the first sitting.
- *If there is associated amblyopia,* full correction with occlusion therapy should be started.
- *It is important to remember that hypermetropia may diminish with the growth of the child.* So, refraction should be carried out every 6 months, and if necessary, the correction should be reduced.

III. ***For adults,*** give the manifest correction. Correct for infinity rather than for 6-m distance in the examination room.

Modes of Prescription of Convex Lenses

1. ***Spectacles*** are most comfortable, safe and easy method of correcting hypermetropia.

2. ***Contact lenses*** are indicated in unilateral hypermetropia (anisometropia). For cosmetic reasons, contact lenses should be prescribed once the prescription has stabilized; otherwise, they may have to be changed many a time.

Advantages of contact lenses over spectacles include:

- Cosmetically better,
- Increased field of vision,
- Less magnification and
- Elimination of aberrations and prismatic effect.

B. Surgical Treatment

Surgical treatments for hypermetropia include:

- Conductive keratoplasty (CK), also known as corneal refractive therapy (CRT),
- Laser thermal keratoplasty (LTK),
- Hyperopic LASIK or PRK or their other variants,
- Phakic IOLs (ICL) and
- RLE.

For details, see page 437.

C. Visual Hygiene

- While reading or doing intensive near work, take a break about every 30 min.
- When reading, maintain proper distance; i.e. the book should be at least as far from your eyes as your elbow when you make a fist and hold it against your nose.
- Sufficient illumination.
- Place a limit spent watching television and watching video games.
- Sit 5–6 ft away from the television.

APHAKIA AND PSEUDOPHAKIA

APHAKIA

Aphakia literally means absence of crystalline lens from the eye. However, from the optical point of view, it may be considered a condition in which the lens is absent from the pupillary area and does not take part in refraction. Aphakia produces a high degree of hypermetropia.

Causes

1. *Congenital* absence of lens. May occur in a very rare condition.

2. *Surgical aphakia* occurring after removal of lens is the commonest presentation.

3. *Aphakia due to absorption of lens matter* is noticed rarely after trauma in children.

4. *Traumatic extrusion* of lens from the eye also constitutes a rare cause of aphakia.
5. *Posterior dislocation* of lens in vitreous (traumatic or spontaneous) produces optical aphakia.

Optics of Aphakia

Von Helmholtz first worked on the optics of aphakia. Then Benito Daza De Valdés suggested that aphakia could be corrected by spectacles.

Optics of aphakia can be discussed under following heads:

- Changes in cardinal data of the eye,
- Image formation in the aphakic eye,
- Visual acuity in aphakia,
- Accommodation in aphakia and
- Binocular vision and aphakia.

Changes in Cardinal Data of the Eye

Following optical changes occur after removal of crystalline lens (Fig. 3.5):

- *Total power of the eye* is reduced to about +44 D from +60 D. So, the eye becomes highly hypermetropic.

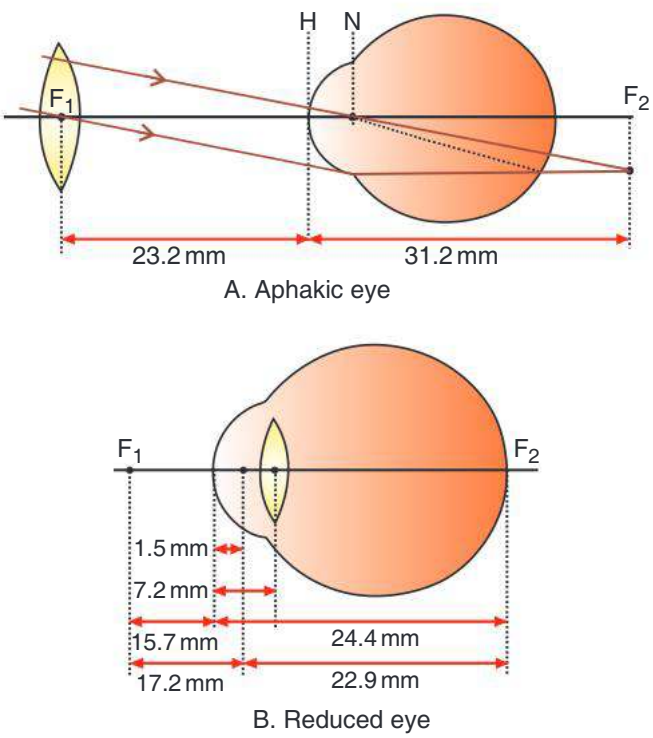


Fig. 3.5 *Cardinal data of an aphakic eye (A) vis-à-vis a normal reduced eye (B).*

- *Anterior focal point* becomes 23.2 mm in front of the cornea.
- *Posterior focal point* is about 31 mm behind the cornea, i.e. about 7 mm behind the eyeball. (The anteroposterior length of the eyeball is about 24 mm.)
- *Two principal points* are almost at the anterior surface of cornea.
- *Nodal points* are very near to each other and are located about 7.75 mm behind the anterior surface of cornea.

Image Formation in Aphakia

Figure 3.6 shows comprehensively the size of image formed in emmetropia, uncorrected aphakia, spectacle-corrected aphakia, contact lens-corrected aphakia and IOL-corrected aphakia. Figure 3.7 (a graph taken from Bennet's figure) indicates that with aphakic spectacles, depending upon keratometry and axial length, the image size can vary from 20% to as much as 50%, but by an average of 30%. The shaded area in the figure represents the range. With contact lens correction, this range is from 5% to 45%, directly related to the preoperative degree of myopia (Fig. 3.7).

Average image magnification reported by different methods of aphakia correction (in a preoperative emmetropic eye) is about:

- Spectacle : 33%,
- Contact lens : 10%,
- Anterior chamber IOL : 2%–5% and
- Posterior chamber IOL : 0%.

Visual Acuity in Aphakia

The Snellen's visual acuity in spectacle-corrected aphakia is falsified due to a large image size. The vision recorded is theoretically better than the actual visual acuity in terms of visual angles. The visual acuity of 6/9 in a spectacle-corrected aphakic eye should be considered equivalent to 6/12 of an emmetropic eye.

Accommodation in Aphakia

There occurs a total loss of accommodation due to absence of lens. Therefore, either bifocal or two separate pairs of glasses – one for distant

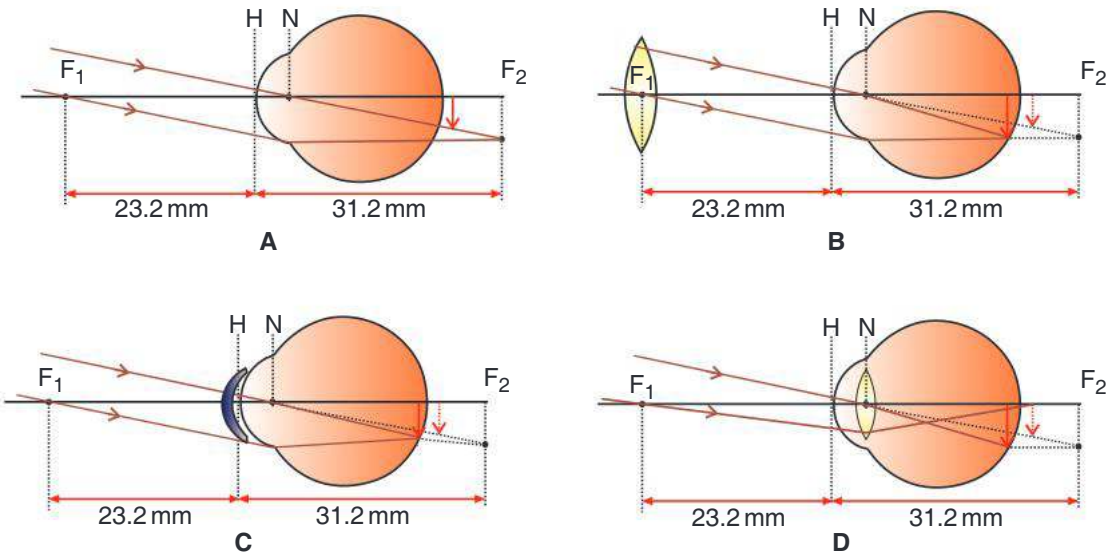


Fig. 3.6 *Image formation and image magnification in aphakia: A, uncorrected aphakia; B, spectacle-corrected aphakia; C, contact lens-corrected aphakia; D, aphakia corrected by a posterior chamber IOL.*

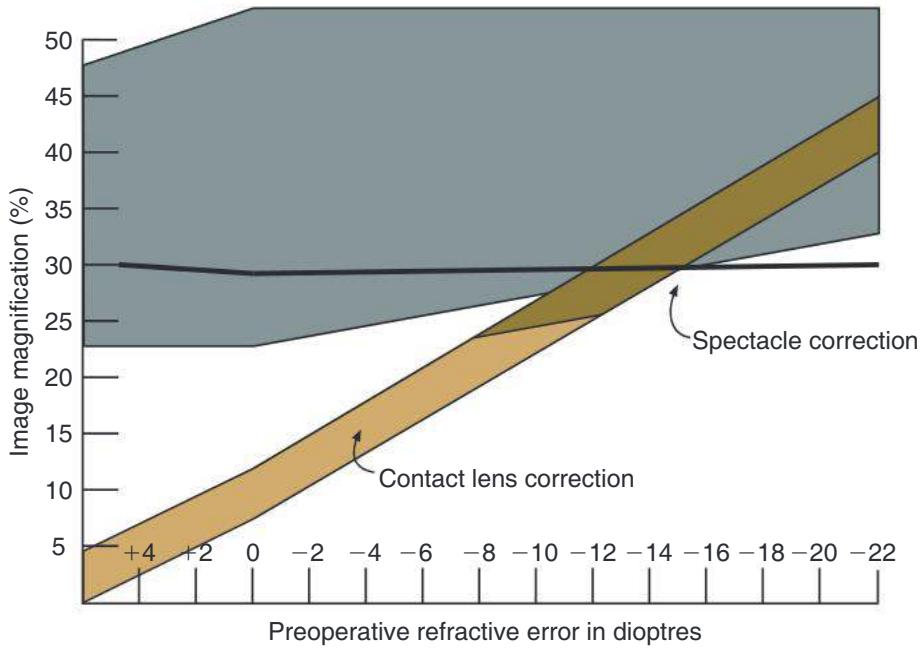


Fig. 3.7 *Relationship of image magnification in aphakia with preoperative dioptric power of the eye.*

vision and another for near vision – are required. With such glasses, patients do feel handicapped for intermediate distances, but they learn to adjust. Progressive or varifocal glasses, perhaps, provide better alternative.

Binocular Vision and Aphakia

The presence of aniseikonia is detrimental to the development of normal binocular functions. It has been reported that aniseikonia less than 5% is compatible with binocular vision. In monocular aphakic children, the major hindrance to development of binocular vision is aniseikonia of 30% due to anisometropia. Such children usually develop suppression amblyopia. The neglected patients of this type develop deviation of the operated eye.

When spectacles are given for correction of aphakia in adult patients who have normal or useful vision in the other eye, binocular single

vision is difficult or impossible. Such patients usually develop annoying diplopia. Thus, to attain binocularity in unilateral aphakia is a big problem. Even in bilateral aphakia, binocularity is not always present. Worth's four-dot test many a time reveals suppression or diplopia in such cases. It is not advisable that a long period should lapse between the operations of the two eyes in bilateral cataracts. During this period, as the eyes are dissociated, convergence becomes poor and stereopsis and even fusion may not be attained, if the interval is prolonged. Fortunately, use of IOLs has largely solved the problems associated with uniocular aphakia. The IOLs are claimed to offer no barrier to fusion since the image size of the pseudophakic eye is almost the same as that of the phakic emmetropic eye. Even in pseudophakic patients, binocularity is not attained in 100% of cases. In a study in unilateral pseudophakic (other eye emmetropic), all the three grades of binocular single vision were present in 90% of cases. Six per cent of patients had no binocular single vision, 2% of patients had only grade I of simultaneous perception and the other 2% had grades I and III of binocular vision (no fusion was present). According to Burian, lower degrees of stereopsis may be present in the absence of sensory fusion.

Clinical Features

Symptoms. The only symptom in aphakia is marked defective vision for near and far.

Signs of aphakia include the following:

1. *Limbal scar* may be seen in surgical aphakia.
2. *Anterior chamber* is deeper than normal.
3. *Iridodonesis*, i.e. *tremulousness* of iris can be demonstrated.
4. *Pupil* is jet black in colour.
5. *Purkinje's image test* shows only two images (normally four images are seen).
6. *Absence of lens* from patellar fossa is best elucidated on slit-lamp examination.
7. *Fundus examination* shows hypermetropic small disc.
8. *Retinoscopy* reveals high hypermetropia.

Treatment

Optical principle is to correct the error by convex lenses of appropriate power, so that the image is formed on the retina (Fig. 3.4).

Modalities for correcting aphakia include:

- Spectacles,
- Contact lens,
- IOL and
- Refractive corneal surgery.

1. Spectacles

Spectacle prescription had been the most commonly employed method of correcting aphakia in the past. However, presently, use of aphakic spectacles has been markedly decreased. Roughly, about +10 D with cylindrical lenses for surgically induced astigmatism are required to correct aphakia in previously emmetropic patients. However, exact power of glasses will differ in individual cases and should be estimated by refraction. An addition of +3 to +4 D is required for near vision to compensate for loss of accommodation.

Advantages of spectacles. It is a cheap, easy and safe method of correcting aphakia.

Disadvantages of spectacles are marked and include the following:

i. ***Image magnification.*** The image size is magnified by 30% on an average (Figs 3.6 and 3.7). It has been stated that if the correcting lenses are worn at the anterior principal point, the size of the retinal image is uninfluenced by the correcting lens. This statement does not hold true for aphakia. The size of the image varies in comparison with that of an emmetropic eye by an amount depending on the difference between their anterior focal distances. On calculation, this ratio works out to be 1.36:1.00.

Since the image is magnified by 30%, so spectacles are not useful in unilateral aphakia (produce diplopia). For this reason, the aphakic is required to make a considerable adaptation to the visual environment because the larger image of a familiar object is interpreted as indicating that the object is much closer than it really

is. In fact, initially the patient is visually uncoordinated; e.g. he or she pours water on to the table instead of into a glass until eventually, usually after some months of trial and error, he or she learns a new coordination of the eye and hand.

ii. ***Spherical aberrations*** due to thick aphakic lenses also pose a problem, producing *pincushion* distortion (Fig. 3.8). The patient finds himself or herself in a parabolic world; i.e. the straight lines become curves and the linear world becomes one consisting of parabolics, which continuously change their shapes when patient moves the eyes. When the objects are viewed through the periphery, they look enlarged, nearer and elongated in radial direction. The moving objects appear to be moving faster.

iii. ***Prismatic aberration*** produces *roving ring scotoma*, usually described as *Jack-in-the-box* phenomenon (Fig. 3.9). A ring scotoma of about 15 degrees, extending from 50–65 degrees from central fixation is produced by the prismatic effect at the periphery of the correcting lens when it is placed a short distance in front of the eye and the eye is in primary position. This scotoma moves against the movement of the eye (Fig. 3.9). As the eye moves to a peripheral lens position, the scotoma moves to a more central one, opposite to the direction of the movement of the eye. Thus, when the patient sees an object and turns the eye towards it, the scotoma may move a sufficient distance inwards to occlude the object. On shifting the eye from the object, the scotoma again shifts and the object becomes visible again as to pop in and out of view (Jack-in-the-box phenomenon).

iv. ***Restricted field of vision.*** The monocular as well as binocular field of vision is markedly restricted. It is about 50 degrees all around.

v. ***Coloured vision.*** The patient may complain of coloured hue in the vision. It occurs due to the absence of natural filter of a crystalline lens and due to the chromatic aberration.

vi. ***Cosmetic blemish.*** Thick glasses are cosmetically embarrassing, as the eyes also appear larger behind the glasses. This effect is more felt by young aphakics.

vii. ***Cumbersome to use.*** The glasses are very thick and heavy and so are cumbersome to use.

viii. ***Problem of near vision.*** Thick bifocal glasses are especially difficult to adjust with.

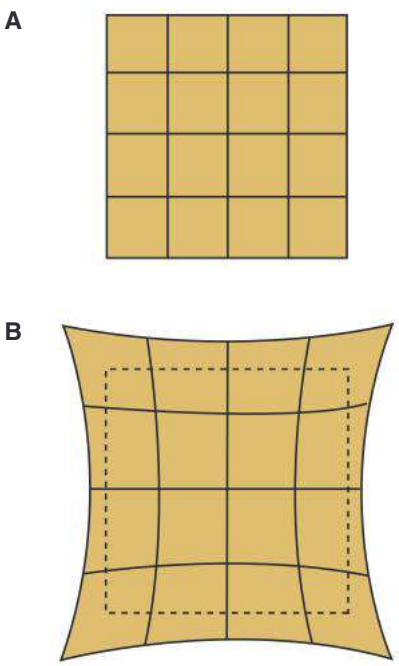


Fig. 3.8 *Pincushion phenomenon: A, an object viewed through a plane glass; B, the same object viewed through a convex lens (pincushion effect). The dotted lines in B indicate normal size.*

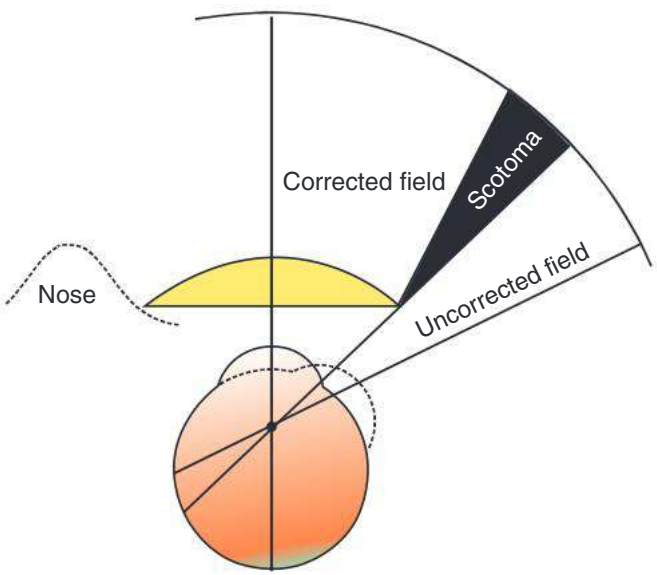


Fig. 3.9 *Roving ring scotoma in spectacle-corrected aphakia. Depending on the position of the eye, the objects tend to appear and disappear.*

Patients may have to keep separate pair of glasses for near and distance vision.

2. Contact Lenses

Advantages of contact lenses over spectacles include:

i. Less magnification of image,
ii. Elimination of aberrations and prismatic effect of thick glasses,
iii. Wider and better field of vision,
iv. Cosmetically more acceptable and
v. Better suited for uniocular aphakia.

Disadvantages of contact lenses:

i. More cost,
ii. Cumbersome to wear, especially in old age and in childhood and
iii. Corneal complications may be associated.

3. Intraocular Lens Implantation

IOL implantation is the ***best available method of correcting aphakia***. Therefore, it is the commonest modality being employed nowadays. For details, see pseudophakia.

4. Refractive Corneal Surgery

Refractive corneal surgery is under trial for the correction of aphakia. It includes the following:

i. ***Keratophakia.*** In this procedure, a lenticule prepared from the donor cornea is placed between the lamellae of the patient's cornea (Fig. 3.10).
ii. ***Epikeratophakia.*** In this procedure, a lenticule prepared from the donor cornea is stitched over the surface of the patient's cornea after removing the epithelium (Fig. 3.11).
iii. ***Hyperopic LASIK*** (see page 438).

■ PSEUDOPHAKIA

The condition of aphakia when corrected with implantation of an IOL is referred to as pseudophakia, or more precisely artiphakia.

Calculation of IOL Power

Power of an IOL to be implanted is calculated by taking into consideration the keratometric reading and axial length of the eyeball. For details, see page 344.

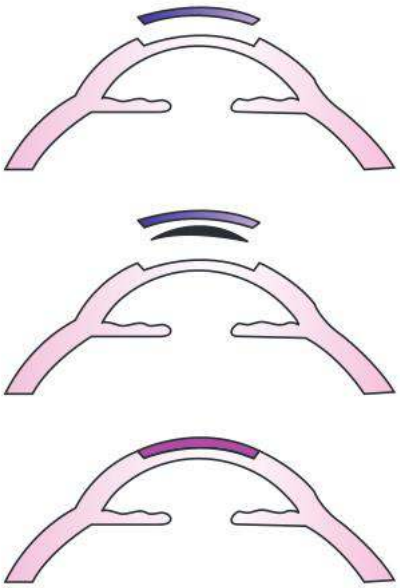


Fig. 3.10 *Keratophakia.*

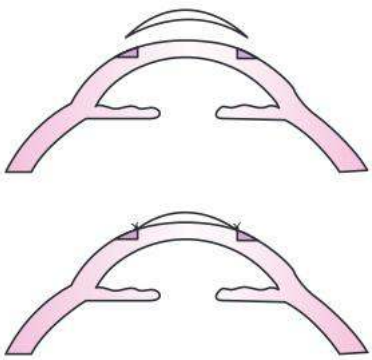


Fig. 3.11 *Epikeratophakia.*

Refractive Status of a Pseudophakic Eye

It depends upon the power of the IOL implanted as follows:

1. ***Emmetropia*** is produced when the power of the IOL implanted is exact. It is the most ideal situation. Such patients need plus glasses for near vision.
2. ***Consecutive myopia*** occurs if the IOL implanted overcorrects the refraction of eye. Such patients require glasses to correct the myopia for distance vision and may or may not need glasses for near vision depending upon the degree of myopia.
3. ***Consecutive hypermetropia*** develops when the underpower IOL is implanted. Such patients require plus glasses for distance vision and additional +2 to +3 D for near vision.

Note. Varying degree of surgery-induced astigmatism (SIA) is also present in pseudophakia.

Signs of Pseudophakia (With Posterior Chamber IOL)

1. *Surgical limbal/corneal scar* may be seen.
2. *Anterior chamber* is slightly deeper than normal.
3. *Mild iridodonesis* (tremulousness) of iris may be demonstrated.
4. *Purkinje image test* shows four images.
5. *Pupil* is blackish in colour, but when light is thrown in pupillary area, shining reflexes are observed.
6. Presence of IOL is confirmed when examined under magnification after dilating the pupil.
7. *Visual status and refraction* will vary, depending upon the power of IOL implanted as described above.

Management

An uncomplicated pseudophakic patient may need management in the form of:

1. *Spectacles for near vision* only are often required following monofocal IOL implantation and
2. *Bifocal/progressive add glasses* may be required for correcting associated consecutive refractive error along with near vision deficiency due to loss of accommodation.

Note. Nowadays, many patients and surgeons are opting for EDOF, trifocal and multifocal IOLs and such patients may have near normal uncorrected visual acuity for near as well as distance.

MYOPIA

Myopia or short-sightedness is a type of refractive error in which parallel rays of light coming from infinity are focused in front of the retina when accommodation is at rest (Fig. 3.12A). Myopia is a Greek wording meaning 'close the eye'.

OPTICS OF MYOPIA

- *Optical system* of a myopic eye is too powerful for its axial length.

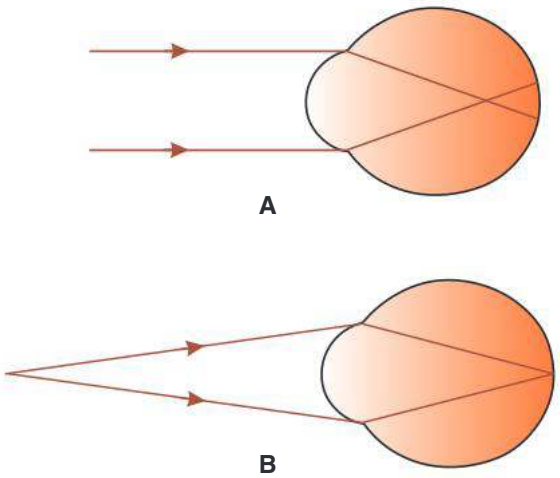


Fig. 3.12 *Optics of myopia: A, parallel rays are focused in front of retina; B, divergent rays from an object situated at the far point of the eye are focused at the retina.*

- *Image of distant object* on the retina is made up of the circles of diffusion formed by the divergent beam, since the parallel rays of light coming from infinity are focused in front of the retina (Fig. 3.12A).
- *Far point* of the myopic eye is a *finite* point in front of the eye. Therefore, a near object situated at the far point is focused without an effort of accommodation (Fig. 3.12B).
- *Nodal point* in a myopic eye is further away from the retina. Therefore, the image formed will be appreciably larger than it would be in the emmetropic eye (Fig. 3.13A) and in spectacle corrected eye (Fig. 3.13B). To some extent, this compensates for the poor visual acuity.
- *Angle alpha* of the myopic eye may be negative, resulting in an apparent convergent squint.
- *Accommodation* in uncorrected myopes is not developed normally, since they need not accommodate to see the near objects clearly. For this reason, they may suffer from convergence insufficiency, exophoria and early presbyopia, as they grow older.

AETIOLOGICAL TYPES

Aetiologically, myopia may be of the following types:

1. *Axial myopia* results from increase in anteroposterior length of the eyeball. It is the commonest form.

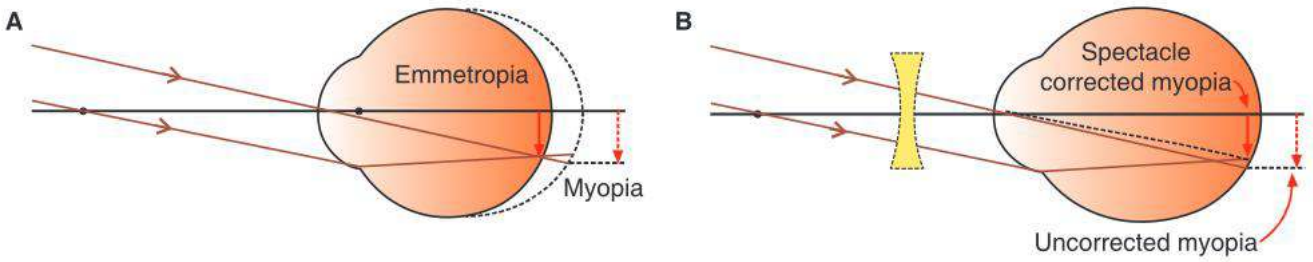


Fig. 3.13 *Image formed in an uncorrected myopia is larger than that formed by an emmetropic eye (A) and spectacle-corrected myopia (B).*

2. *Curvatural myopia* occurs due to increased curvature of the cornea, lens or both.
3. *Positional myopia* is produced by anterior placement of crystalline lens in the eye.
4. *Index myopia* results from increase in the refractive index of crystalline lens associated with nuclear sclerosis.
5. *Myopia due to excessive accommodation* occurs in patients with spasm of accommodation.

CLINICAL TYPES OF MYOPIA

- Congenital myopia
- Simple or developmental myopia
- Pathological or degenerative myopia
- Secondary myopia.

Depending upon the age of onset, following terms are in vogue:

- *Congenital myopia* present since birth.
- *Youth-onset myopia* usually occurs under the age of 20 years (simple myopia).
- *Early adult-onset myopia* develops between 20 and 40 years of age (acquired index myopia due to early nuclear sclerosis).
- *Late adult-onset myopia* occurs at more than 40 years of age (acquired index myopia due to age-related nuclear sclerosis).

I. CONGENITAL MYOPIA

Aetiology

Congenital myopia is usually associated with an increase in axial length and overall globe size. It is seen more frequently in children who were born prematurely or with various birth defects, such as Marfan syndrome and homocystinuria.

Clinical Features

- *Present since birth*. Congenital myopia is usually diagnosed by the age of 2–3 years.
- *High degree of error*. Usually the error is of about 8–10 D, which mostly remains constant.
- *Anisometropia*. Most of the time, the error is unilateral and manifests as *anisometropia*. Rarely, it may be bilateral.

Associations. Congenital myopia may be associated with congenital convergent squint and other congenital anomalies such as cataract, microphthalmos, aniridia, megalocornea and congenital separation of retina.

Diagnosis

- Unilateral congenital myopia is frequently discovered either by routine screening examination or after a strabismus develops because of the associated amblyopia.
- If the myopia is bilateral, the child will generally display some noticeable difficulty in seeing distant objects and will tend to hold things very close for viewing.

Treatment

Early diagnosis and correction of congenital myopia is desirable to help the child to develop normal distant vision and perception of the world.

The full cycloplegic refractive error including any astigmatic correction should be prescribed. Even then it may not always be possible for these children to achieve 6/6 visual acuity in either eye.

Prognosis

The prognosis for good vision and normal binocularity is poor in unilateral cases, if the anisometropia and myopia are severe.

II. SIMPLE MYOPIA

Simple or developmental myopia, also known as physiological, is the commonest variety. It is considered as a physiological error not associated with any disease of the eye. Usually, the onset occurs at school going age, i.e. between 8 and 12 years of age, so it is also called school myopia. About 29% of general population have low myopia (≤2 D) and about 7% have moderate myopia (2–6 D).

Aetiology

Simple myopia results from normal biological variation in the development of eye, which may or may not be genetically determined. Some factors associated with simple myopia are as follows:

- *Axial type of simple myopia* may signify just a physiological variation in the length of the eyeball, or it may be associated with precocious neurological growth during childhood.
- *Curvatural type* of simple myopia is considered to be due to underdevelopment of the eyeball.
- *Role of genetics.* Genetics plays some role in the biological variation of the development of eye, as prevalence of myopia is more in children with both parents myopic (20%) than the children with one parent myopic (10%) and children with no parent myopic (5%). Inheritance is considered to be autosomal dominant. However, there are a number of reports which claim that recessive mode of inheritance is more common.
- *Role of diet* in early childhood has also been reported, without any conclusive results.
- *Theory of excessive near work* in childhood is gaining importance. It is being believed that myopia is aggravated by close work, watching television, smart phones, computer and other VDUs and by not using glasses.

Clinical Picture

Clinical course. Simple myopia is rarely present at birth. Most of such patients are rather born hypermetropic, but during development, the normal mark is overshooted and the child becomes myopic. Simple myopia usually begins between 7 and 10 years of age and may increase during the years of growth until stabilizing around the mid-teens usually at about –5 D or less and it never exceeds –8 D. There is no effective method for halting the progress of this so-called *school myopia* once it has started.

Symptoms

1. ***Poor vision for distance*** (short-sightedness) is the main symptom of myopia. The visual acuity beyond the punctum remotum is severely affected. A rough measure of visual acuity vis-à-vis degree of myopia is shown in Table 3.3.
2. ***Half shutting of the eyes*** may by complained by the parents of the child. The child does so to achieve greater clarity of stenopaeic vision.
3. ***Asthenopic symptoms*** may occur in patients with small degree of myopia. Symptom of eye strain develops due to dissociation between convergence and accommodation. Any of the two situations may arise:
   - i. Since myopes need not accommodate for near vision, so they may develop convergence weakness and exophoria and suppression in one eye.
   - ii. Alternately, while focusing at near objects, the patients converge and so there may occur associated excessive accommodation, thus inducing ciliary spasm and artificially increasing the amount of myopia.

   In practice, the first situation is of more common occurrence than the latter.

Table 3.3 *A rough measure of visual acuity vis-à-vis degree of myopia*

Degree of myopia	Visual acuity
–0.5	6/9–6/12
–1.0	6/18
–1.5	6/24
–2.0	6/36
–3.0	6/60
–4.0	4/60
–5.0	3/60
–6.0	2/60

4. ***Change in psychological outlook*** of the uncorrected myopic children is very common. These children take the poor far vision for granted and concentrate their energy into indoor activities. They usually become introvert, studious and develop little interest in outdoor activities.

Signs

1. *Predominant eyeballs.* The myopic eyes typically are large and somewhat prominent.
2. *Anterior chamber* is slightly deeper than normal.
3. *Pupils* are somewhat large and a bit sluggishly reacting.
4. *Fundus* is normal; rarely temporal myopic crescent may be seen.
5. *Magnitude of error*. In simple myopia, usually the error does not exceed 6–8 D.

Diagnosis is confirmed by performing retinoscopy (page 130).

III. PATHOLOGICAL MYOPIA

Pathological/degenerative/progressive myopia, as the name indicates, is a rapidly progressive error which starts in childhood at 5–10 years of age and results in high myopia (7–6 D) during early adult life which is usually associated with degenerative changes in the eye. Prevalence of pathological myopia in general population is about 2%–3%.

Aetiology

It is unequivocal that the pathological myopia results from a rapid axial growth of the eyeball, which is outside the normal biological variations of development. To explain this spurt in axial growth, various theories have been put forward. So far, no satisfactory hypothesis has emerged to explain the aetiology of pathological myopia. However, it is definitely linked with (1) heredity and (2) general growth process.

1. ***Role of heredity.*** It is now confirmed that genetic factors play a major role in the aetiology, as the progressive myopia is:
   - i. Familial,
   - ii. More common in certain races like Chinese, Japanese, Arabs and Jews and
   - iii. Uncommon among Negroes, *Nubians* and Sudanese.

At present, high myopia (>6 D) is considered to be a sex-linked, recessive inherited disorder. It is presumed (not confirmed) that *heredity-linked growth of retina is the determinant* in the development of myopia. The sclera because of its distensibility follows the retinal growth, but the choroid undergoes degeneration due to stretching, which in turn causes degeneration of retina. Agarwal and Khosla have advanced the theory of multiple gene defect inheritance as the cause of variable picture in pathological myopia. According to them, the increased axial length, degenerative changes in retina and choroid, vitreous changes and pathological complications are determined by different genes. They further suggested that the related genetic influence of one factor on the other could not be denied.

2. ***Role of general growth process***, though minor, cannot be denied in the progress of myopia. Lengthening of the posterior segment of the globe commences only during the period of active growth and probably ends with the termination of the active growth. Therefore, the factors (such as nutritional deficiency, debilitating diseases, endocrinal disturbances and indifferent general health) which affect the general growth process may also have some influence on the progress of myopia.

The aetiological hypothesis for pathological myopia is summarized in Figure 3.14.

Clinical Picture

Symptoms

1. ***Defective vision***. There is considerable failure in visual function as the error is usually high. Further, an uncorrectable loss of vision may occur due to progressive degenerative changes.
2. ***Muscae volitantes*** and floating black opacities in front of the eyes are also complained by many patients. These occur due to degenerated liquefied vitreous.
3. ***Night blindness*** may be complained by very high myopes having marked chorioretinal degenerative changes.

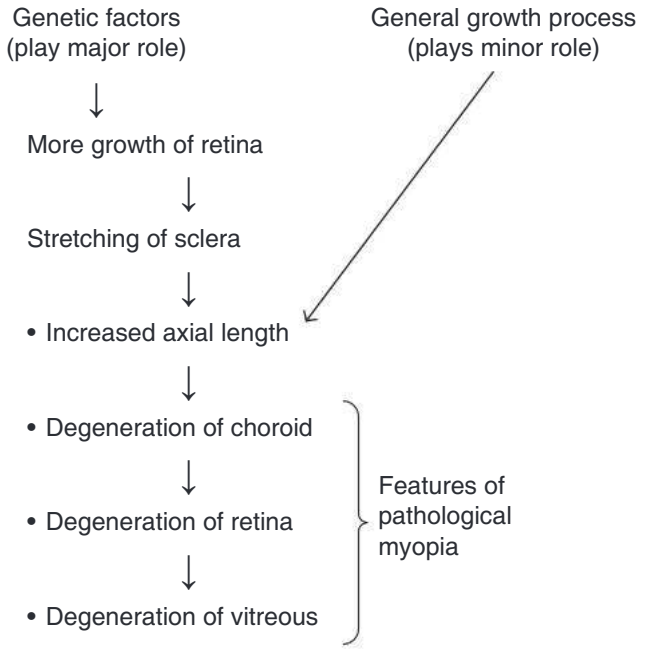


Fig. 3.14 *Flowchart summarizing aetiology of pathological myopia.*

Signs

1. ***Prominent eyeballs.*** The eyes are often *prominent*, appearing elongated and even simulating an exophthalmos, especially in unilateral cases. The elongation of the eyeball mainly affects the posterior pole and surrounding area; the part of the eye anterior to the equator may be normal (Fig. 3.15).
2. ***Cornea*** is large.
3. ***Anterior chamber*** is deep.
4. ***Pupils*** are slightly large and react sluggishly to light.
5. ***Magnitude of refractive error*** increases by as much as 4 D yearly and usually stabilizes at about the age of 20, but occasionally may progress until mid-30s and frequently results in myopia of 10–20 D, which may even progress to 30–40 D.
6. ***Fundus examination*** reveals following characteristic signs:
   - i. *Optic disc* appears large and pale and at its temporal edge, a characteristic myopic crescent is present (Fig. 3.16). Sometimes, peripapillary crescent encircling the disc may be present, where the choroid and retina are distracted away from the disc margin. A supertraction crescent (where the retina is pulled over the disc margin) may be present on the nasal side.
   - ii. *Degenerative changes in retina and choroid* are common in progressive myopia (Fig. 3.17).

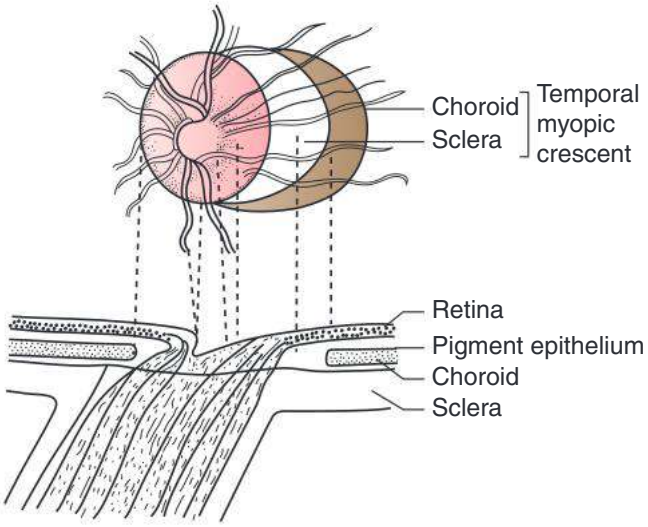


Fig. 3.16 *Myopic crescent.*

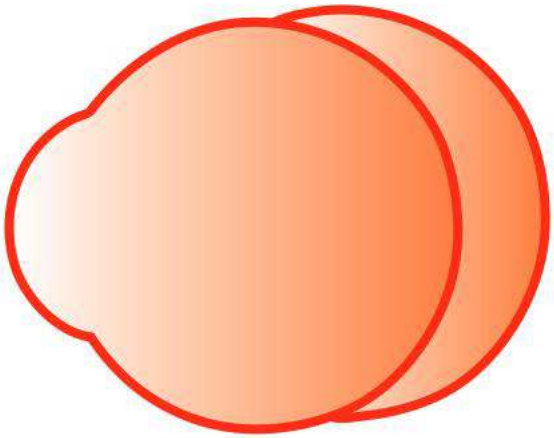


Fig. 3.15 *Elongation of the eyeball posterior to equator in pathological myopia.*

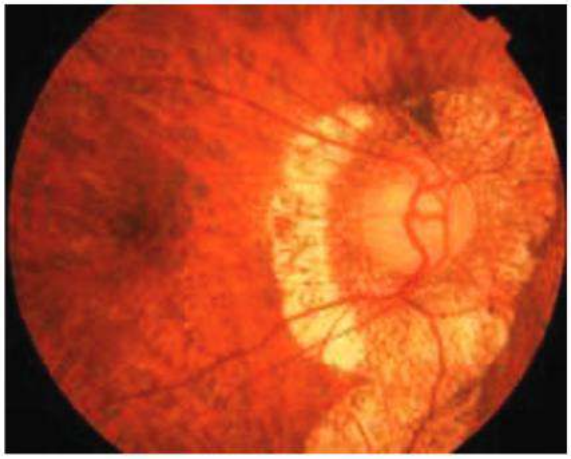


Fig. 3.17 *Fundus changes in pathological myopia.*

Initially, there occurs a *tigroid* appearance of the fundus because of visible prominent large choroidal vessels following atrophy of retinal pigment epithelium and *choriocapillaris*. In later stages, there occurs total disappearance of choroidal tissue, which is characterized by white atrophic patches due to visible sclera with a little heaping up of pigment around them. These changes are more marked at the posterior pole.

- *Förster–Fuchs' spot* (dark red circular patch due to subretinal neovascularization and choroidal haemorrhage) may be present at the macula.
- *Cystoid degeneration* may be seen at the periphery.
- Total chorioretinal atrophy, particularly in the central area, may occur in an advanced case.
- *Lattice degeneration* and/or *snail track lesion* may be associated.
- Retinal *tears*, haemorrhage and even retinal detachment may be seen as complications of myopic chorioretinal degeneration.

iii. ***Posterior staphyloma*** due to ectasia of sclera at posterior pole may be apparent as an excavation, with the vessels bending backward over its margins.

iv. ***Degenerative changes in vitreous*** include liquefaction, vitreous opacities and posterior vitreous detachment, appearing as Weiss' reflex. It is important that these degenerative changes in the fundus are not necessarily comparable with the degree of myopia, for they may be more marked when the myopia is slight and less marked when the error is very high.

7. ***Visual fields*** show contraction and in some cases, ring scotoma may be seen.
8. ***Electroretinography*** reveals subnormal electroretinogram due to chorioretinal atrophy.

Complications

1. *Retinal tears* and retinal detachment may occur.
2. *Complicated cataract*. It occurs probably due to an aberration of lenticular metabolism.
3. *Nuclear sclerosis* is the common occurrence in myopics. It may lead to aggravation of the myopia refraction.
4. *Vitreous haemorrhage*. It usually accompanies a retinal tear. A choroidal haemorrhage may also leak into the vitreous and fill it with blood.
5. *Choroidal haemorrhage and thrombosis* are quite common and may lead to severe visual loss when involving foveal region.
6. *Primary open angle glaucoma* is not a complication but a common association of myopia.

IV. SECONDARY MYOPIA

It occurs secondary to some other diseases of eye. Some of the causes of secondary myopia are as follows:

1. ***Index myopia*** is seen in following circumstances:
   - *Nuclear sclerosis.* In this condition, nucleus becomes more and more hyper-refringent pari passu, with which develops a progressive myopia.
   - *Incipient cataract* may also produce index myopia.
   - *Diabetic myopia* occurs due to a decrease in the refractive index of cortex.
2. ***Curvatural myopia*** may be corneal or lenticular.
   - *Corneal curvatural myopia* develops in pronounced cases of a true increase of corneal curvature in diseased conditions such as corneal ectasias and conical cornea (keratoconus).
   - *Lenticular curvatural myopia.* Rarely curvatural myopia may also develop due to increase of lenticular curvature in conditions such as lenticonus anterior and lenticonus posterior.
3. ***Positional myopia*** may occur in conditions producing anterior subluxation of the lens.
4. ***Consecutive myopia*** may occur under following circumstances:
   - *Surgical overcorrection* of hypermetropias and
   - *Pseudophakia* with overcorrecting IOL.
5. ***Pseudomyopia*** or the so-called *artificial myopia or accommodational myopia* may be

produced in conditions such as excessive accommodation and spasm of accommodation. Artificial myopia also develops after too full a hypermetropic correction in children.

6. *Space myopia.* This condition is experienced when the individual has no stimulation for distance fixation. The eyes tend to choose a near fixation plane which can be very variable. The degree of myopia due to this condition is never more than 0.75–1.5 D. It is particularly troublesome to aviators when flying in cloud or fog or at night.

7. *Night myopia or twilight myopia.* The shift from photopic to scotopic vision at twilight is associated with increased sensitivity to the shorter wavelengths of light. The emmetropic eye, if accommodated for the middle range of the visual spectrum, will be slightly myopic for the shorter wavelengths.

8. *Drug-induced myopia* may be seen with the following:

- *Cholinergic drugs* such as pilocarpine, echothiophate and di-isopropyl fluorophosphate.
- *Steroid-induced* myopia may occur because of water metabolism changes involving the crystalline lens.
- *Sulphonamides* may also produce myopia for the same reason or because of slight changes in the refractive indices of the media.

9. *Myopia of prematurity (MOP)* may occur without retinopathy of prematurity (ROP) (true MOP) or following treatment of ROP (myopia of ROP).

MYOPIA OF PREMATURITY

MOP is now a well-established entity, distinct from simple and pathological myopia.

Pathophysiologic features of MOP. MOP may occur without ROP (true MOP) or following treatment of ROP (myopia of ROP). It is characterized by the abnormal development of anterior segment in the form of:

- Increased corneal curvature,
- Thick crystalline lens,
- Shallow anterior chamber and
- Characteristically shorter axial length relative to their dioptric value.

Mechanism of anterior segment aberrations seen in MOP is not exactly known. Views put forward are as follows:

- *Mechanical restriction of ocular growth* may be the main mechanism as the degree of MOP is less in laser-treated eyes as compared with cryo-treated eyes; and in eyes treated with intravitreal anti-VEGF injections than in eyes treated with laser.
- *Other views* put forward include bone deficiency, retinal dysfunction and temperature interactions.

Types of MOP. Following types of MOP have been described:

- *True MOP*, i.e. myopia seen in premature infants without ROP.
- *Myopia of ROP* is the term used for myopia occurring as the result of treatment of ROP. As stated above, myopia of ROP is of higher degree in cryo-treated than laser-treated eyes, and still over in eyes treated with intravitreal anti-VEGF injections.
- *Myopia of spontaneously regressed ROP* may occur as anisometropia and myopic astigmatism.

TREATMENT OF MYOPIA

1. *Optical treatment* of myopia constitutes prescription of appropriate concave lenses, so that clear image is formed on the retina (Fig. 3.18).

i. *Basic rule of correcting myopia*. Conversely to hypermetropia, the minimum acceptance providing maximum vision should be prescribed in myopia.

ii. *Guidelines for correcting low degrees of myopia up to –6 D:*

- *In children up to 3 years of age*, guidelines for correcting myopia, as described in Preferred Practice Pattern: Paediatric Eye Evaluation, AAO, 2012, are summarized in Table 3.2.
- *In children above 3 years of age*, myopia should be fully corrected and instructed to use their glasses constantly, both to avoid developing the habit of squinting

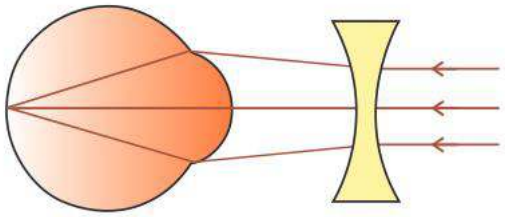


Fig. 3.18 *Refraction in a myopic eye corrected with concave lens.*

and to enhance developing a normal accommodation–convergence reflex. It must be impressed upon the patient that, in the matter of near work, the glasses are not meant to improve the vision but to make one read at proper distance and to keep one's eyes in proper relationship.

- *Never overcorrect myopia*. Young myopia patients will often prefer more minus power in the manifest refraction than they need for best acuity because the additional minus enhances the contrast of the dark test letters on the light chart background. During the subjective refraction, to help prevent overcorrection, ask the patient if the letters are actually clearer and if detail is more easily seen, or if the letters are just darker and smaller.
- *Adults*, younger than 30 years, usually accept their full myopic correction. However, those older than 30 years are not able to tolerate a full correction over 3 D if they have never worn glasses before, as their ciliary muscles are not accustomed to accommodate. So, such patients may be prescribed less than full correction with which the patient has comfortable near vision, with resulting undercorrected distance vision. The patients should be told that a full correction may be given in the future, if desired.

iii. *Guidelines for correcting high myopia.* Irrespective of the age of the patient, full correction can rarely be tolerated in case of high myopia (more than –10 D). An attempt should be made to undercorrect as little as is compatible with comfort for binocular near vision. Usually an undercorrection to the tune of 1–3 D or even more may be required, depending upon the age of the patient and degree of myopia. Undercorrection is always better to avoid the problem of near vision and that of minification of images.

Modes of prescribing concave lenses are spectacles and contact lenses. Their advantages and disadvantages over each other are the same as described for hypermetropia.

Contact lenses are particularly justified in cases of high myopia as they avoid peripheral distortion and minification produced by strong concave spectacle lens. Some authors report that perhaps hard contact lenses also slow down the progress of myopia. Less has been heard of this phenomenon recently, and it seems not to apply to soft lens wearers in any case. It is important that a myope wearing a full contact lens correction needs more accommodation for near work as compared with a spectacle wearer. So, they develop presbyopia comparatively earlier.

2. Surgical treatment of myopia has become very popular nowadays. For details, see page 395.

3. Preventive measures which may be useful include the following:

I. *Therapeutic interventions* reported to prevent progression of myopia are as follows:

- *Atropine,* even in low strength of 0.01% eye drops, instilled nightly are reported to slow down the progression of myopia by blocking the muscarinic receptors of sclera (ATOM 2 study) with minimum side effects. Mydriasis and cycloplegia, however, may be of some concern.
- *Pirenzepine* 2% gel, applied twice a day, is also reported to prevent the myopia progression. Unlike atropine, which is equipotent in binding to M3 (accommodation and mydriasis) and M1 muscarinic receptors, pirenzepine is relatively selective for the M1 muscarinic receptors and thus is less likely than atropine to produce mydriasis and cycloplegia.

II. General measures empirically believed to affect the progress of myopia (unproven

usefulness) include balanced diet rich in vitamins and proteins, and early management of associated debilitating disease.

iii. **Genetic counselling.** As the pathological myopia has a strong genetic basis, the hereditary transfer of disease may be decreased by advising against marriage between two individuals with progressive myopia. If they do marry, they should be warned not to produce children, otherwise any offspring will be liable to the same disability according to the laws of recessive Mendelian inheritance. There need not be any restraint on marriage and procreation among simple myopes.

4. **Visual hygiene** is very important to avoid asthenopic symptoms. Care needs to be taken for a proper posture and adequate illumination during close work. The clarity of the print should be good to avoid undue ocular fatigue.
5. **Low-vision aids** are indicated in patients of progressive myopia with advanced degenerative changes, where useful vision cannot be obtained with spectacles and contact lenses (see page 371).

Prognosis

1. *In simple myopia,* the prognosis is good. The error usually does not progress beyond 6–8 D and stabilizes by the age of 21 years.
2. *In pathological myopia,* visual prognosis is always guarded. In all cases, the possibility of progressive visual loss due to degenerative changes and danger of complication such as retinal detachment should be borne in mind. It is always wise to advise such young patients to choose a career that to some extent can be continued even if the vision falls seriously.

ASTIGMATISM

Astigmatism is a type of refractive error wherein the refraction varies in different meridia. Consequently, the rays of light entering the eye cannot converge to a point focus but form the focal lines. Broadly, there are two types of astigmatism: regular and irregular.

REGULAR ASTIGMATISM

The astigmatism is regular when the refractive power changes uniformly from one meridian to another (i.e. there are two principal meridia).

Aetiology

Some risk factors known to be associated with astigmatism include:

- Family history of the astigmatism,
- Preterm birth/low birth weight,
- Advancing age,
- Corneal scarring due to injury,
- Corneal thinning,
- Pre-existing refractive errors of the eye such as myopia or hypermetropia,
- Severe allergies resulting in constant rubbing of the eyes and
- Diabetes.

Aetiologically, astigmatism may be defined as follows:

1. ***Corneal astigmatism*** is the result of abnormalities of curvature of cornea. It constitutes the most common cause of astigmatism. Corneal astigmatism is usually congenital. Acquired corneal astigmatism is also not infrequent, but it is often irregular.
2. ***Lenticular astigmatism*** is comparatively rare. It may be of the following types:

   i. *Curvatural*. Small amount of curvatural astigmatism due to congenital abnormalities of curvature of lens is frequently seen. Marked lenticular astigmatism may be seen in lenticonus.

   ii. *Positional.* Small amount of astigmatism due to congenital tilting or oblique placement of the lens is not uncommon. Varying degree of positional astigmatism occurs in congenital or traumatic subluxation of the lens.

   iii. *Index astigmatism* may occur rarely due to variable refractive index of lens in different meridia in patients suffering from diabetes and those developing nuclear sclerosis and/or cataract.
3. ***Retinal astigmatism*** due to oblique placement of macula may also be seen occasionally.

Types of Regular Astigmatism

Depending upon the axis and the angle between the two principal meridia, regular astigmatism can be classified into the following types:

1. ***With-the-rule astigmatism.*** In this type, the two principal meridia are placed at right angles to one another, but the vertical meridian is more curved than the horizontal. Thus, correction of this astigmatism will require the concave cylinders at 180° ± 20° or convex cylindrical lens at 90° ± 20°. This is called 'with-the-rule' astigmatism because similar astigmatic condition exists normally (the vertical meridian is normally rendered 0.25 D more convex than the horizontal meridian by the pressure of eyelids).
2. ***Against-the-rule astigmatism*** refers to an astigmatic condition in which the horizontal meridian is more curved than the vertical meridian. Therefore, correction of this astigmatism will require the prescription of convex cylindrical lens at 180° ± 20° or concave cylindrical lens at 90° ± 20° axis.
3. ***Oblique astigmatism*** is a type of regular astigmatism where the two principal meridia are not the horizontal and vertical, though these are at right angles to one another (e.g. 45 degrees and 135 degrees). Oblique astigmatism is often found to be symmetrical (e.g. cylindrical lens required at 30 degrees in both eyes) or complementary (e.g. cylindrical lens required at 30 degrees in one eye and at 150 degrees in the other eye).
4. ***Bi-oblique astigmatism.*** In this type of regular astigmatism, the two principal meridia are not at right angle to each other, e.g. one may be at 30 degrees and the other at 100 degrees.

Optics of Regular Astigmatism

As already mentioned, in regular astigmatism, the parallel rays of light are not focused on a point but form two focal lines. The configuration of rays refracted through the astigmatic surface (toric surface) is called *Sturm's conoid* and the distance between the two focal lines is known as *focal interval of Sturm*. The length of this focal interval is a measure of the degree of astigmatism. The shape of bundle of rays at different levels (after refraction through astigmatic surface) is described on page 26.

Refractive Types of Regular Astigmatism

Depending upon the position of the two focal lines in relation to retina, the regular astigmatism is further classified into three types:

1. ***Simple astigmatism*** wherein the rays are focused on the retina in one meridian and either in front (simple myopic astigmatism – Fig. 3.19A) or behind (simple hypermetropic astigmatism – Fig. 3.19B) the retina in the other meridian.

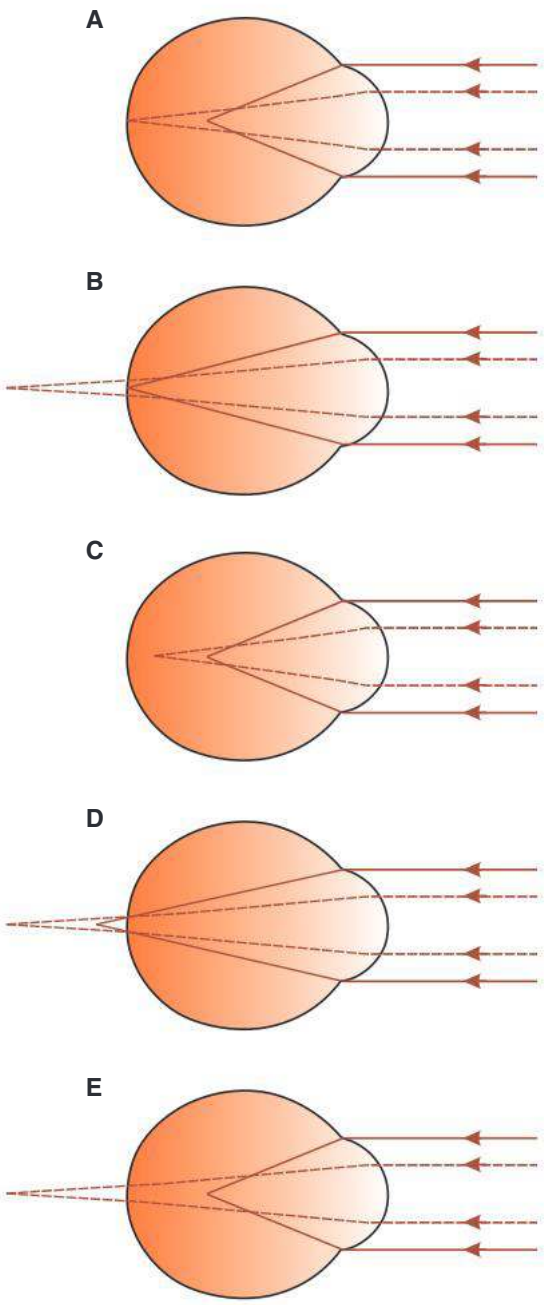


Fig. 3.19 *Refractive types of regular astigmatism: A, simple myopic; B, simple hypermetropic; C, compound myopic; D, compound hypermetropic; E, mixed.*

2. ***Compound astigmatism.*** In this type, the rays of light in both the meridia are focused either in front or behind the retina and the conditions are labelled as compound myopic or compound hypermetropic astigmatism, respectively (Fig. 3.19C and D).

3. ***Mixed astigmatism*** refers to a condition wherein the light rays in one meridian are focused in front and in other meridian behind the retina (Fig. 3.19E). Thus, in one meridian, the eye is myopic and in another, hypermetropic. Such patients have comparatively less symptoms as 'circle of least diffusion' is formed on the retina (see Fig. 1.37, page 26).

Symmetric astigmatism refers to the regular astigmatism in which the principal meridia in each eye have similar but opposite axes, e.g. 15 degrees in left eye and 165 degrees in right eye, which together add up to 180° ± 15°. Many patients with regular astigmatism have symmetric astigmatism.

Incidence

Infants. About 50% of full-term infants in their first year of life have astigmatism of over 1 D.

Adults. The incidence of astigmatism decreases as the child grows and by adulthood about 15% of the people have astigmatism >1 D and only 2% have astigmatism >3 D.

Rough estimate about the incidence of astigmatism is as follows:

- Almost all individuals have a minor degree of (physiological) astigmatism.
- About 60% cases of refractive errors have astigmatism, which needs to be corrected.
- Astigmatism occurs with equal frequency in males and females.
- The approximate distribution according to degree of astigmatism is as follows:

0.25–0.5 D	50%
0.75–1.0 D	25%
1.0–4.0 D	24%
>4.0 D	1%

- The most common type of astigmatism is compound myopic followed by compound hypermetropic, mixed, simple myopic and simple hypermetropic.
- One study reports distribution of astigmatism as follows:

With-the-rule	38%
Against-the-rule	30%
Oblique	32%

Clinical Features

Which of the following symptoms will be more marked will depend upon the degree and type of astigmatism?

1. ***Blurring of vision.*** In patients with low astigmatism (<1 D), there occurs *transient* blurring of vision when doing precision work at a fixed distance, which is relieved by closing or rubbing the eyes. The patient makes an effort to focus one meridian clearly and the meridian nearest to emmetrope is chosen. More often than not, the patient exhibits a preference for the vertical meridian. When the error is high, the blurring of vision is marked. Further, since a focal line is made the object of attention, the vision in an astigmatic patient in addition to being indistinct shows following peculiarities:

- Circles become elongated into ovals (Fig. 3.20A).
- A point of light appears tailed off.
- A line appears as a succession of strokes fused into a blurred image (Fig. 3.20B and C).

2. ***Asthenopic symptoms.*** These include tiredness of eyes, headaches varying from a mild frontal ache to violent explosions of pain and a whole gamut of reflex nervous disturbances such as dizziness, neurasthenia, irritability and

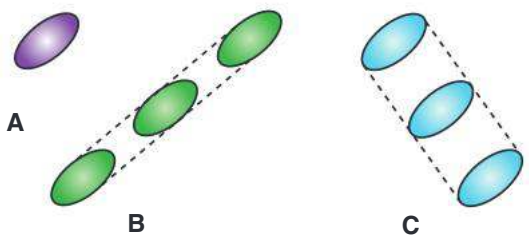


Fig. 3.20 *The retinal image in uncorrected astigmatism: A, the blur ellipse due to a small point; B, the blurred image of a line parallel to the major axis of the blur ellipse; C, the blurred image of a line perpendicular to the major axis of the blur ellipse.*

fatigue. Peculiarities about occurrence of asthenopic symptoms are as follows:

- Asthenopic symptoms occur more frequently in patients with astigmatism than in those with spherical ametropia.
- Symptoms are more marked in patients with low astigmatism, for here, the measure of success which the accommodative effort achieves stimulates it to greater endeavour.
- With-the-rule astigmatism produces more symptoms but clearer vision than the same amount of against-the-rule astigmatism.
- Symptoms are more severe in hypermetropic astigmatism, for here, the accommodation makes further efforts to overcome the hypermetropia.

3. ***Tilting of the head.*** Some patients with high oblique astigmatism may hold the head tilted to one side so as to reduce image distortion. Because of this habit, some children may even develop scoliosis.

4. ***Squinting,*** **i.e.** ***half-closure of the lids,*** is frequently seen in patients with high astigmatism (>1 D). This is done in order to make a stenopaeic slit, and so by cutting out the rays in one meridian, the object may appear more distinct.

5. ***Reading material may be held close to eyes*** by many patients with high astigmatism in a bid to achieve large but blurred retinal image (as in myopes).

6. ***Burning and itching*** sensation may be experienced by patients with low astigmatic error. Consequently, the patient may develop a habit of rubbing the eyes, resulting in falling of lashes, hyperaemia of lid margin and recurrent stye and chalazia.

Investigations

1. ***Retinoscopy*** and autorefractometry reveal different power in two different axes (see page 130).

2. ***Keratometry and computerized corneal topography*** reveal different corneal curvature in two different meridia in corneal astigmatism.

3. ***Astigmatic fan test.*** Fogging technique using astigmatic fan is a sensitive test for finding out the astigmatism (see page 161).

4. ***Jackson cross cylinder test*** is very useful in confirming the power and axis of cylindrical lenses (see page 160).

Treatment

I. ***Optical treatment*** of regular astigmatism comprises prescribing the appropriate cylindrical lens, discovered after accurate refraction. The cylindrical lenses may be prescribed in the form of spectacles.

Spherical hard contact lenses may correct up to 2–3 D of regular astigmatism. For higher degrees of astigmatism, toric contact lenses are needed.

Guidelines for optical treatment of astigmatism:

Guidelines described in Practice Preferred Pattern: Paediatric Eye Evaluation, AAO, 2012, are summarized in Table 3.2.

1. *Small astigmatism* (0.5 D or less) should be treated only if producing asthenopic symptoms or deterioration of vision. However, when low astigmatism is to be treated a meticulous refraction and utmost care is required in prescribing the cylindrical lenses.

2. *High astigmatism* always needs to be treated. As a rule, every attempt should be made to correct the cylindrical error fully. However, an adult patient may not accept full correction when prescribed for the first time. Under such circumstances, the error should be undercorrected until the patient is accustomed to the cylinder. Such patients should be checked at regular intervals and adjustment made till full correction is accepted.

3. *Change in the axis of astigmatic correction*, especially in adults used to their old axis, should be done very cautiously. Such changes are often poorly tolerated. In such a situation, the patient may be asked to wear the prescription in a trial frame and walk around for a few minutes.

4. *New astigmatic correction*, especially in adults, should be preferably avoided, as it may produce intolerable distraction for the patient even if measurable visual acuity is improved. If necessary, ascertain that the new astigmatic

correction produces significant improvement in both distance and mean acuity. Under such circumstances, always advise the patients that there may be a period of adjustment for the new correction.

5. *Bi-oblique astigmatism*, mixed astigmatism and high astigmatism are better treated by contact lenses than by spectacles.

6. *Spherical component* should be prescribed as per guidelines for treatment of myopia or hypermetropia, as the case may be.

II. *Surgical correction* of astigmatism is quite effective. For details, see page 433.

■ IRREGULAR ASTIGMATISM

It is characterized by an irregular change of refractive power in different meridia. There are multiple meridia which admit no geometrical analysis.

Aetiological Types

1. *Corneal irregular astigmatism* is found in patients with extensive corneal scars or keratoconus.

2. *Lenticular irregular astigmatism* is seen due to variable refractive index in different parts of the crystalline lens and may occur rarely during maturation of cataract.

3. *Retinal irregular astigmatism* is seen due to distortion of the macular area due to scarring or tumours of retina and the choroid pushing the macular area.

Clinical Features

Symptoms of irregular astigmatism include:

- Defective vision,
- Distortion of objects and
- Polyopia (seeing multiple images).

Signs depicted on investigations are as follows:

1. *Retinoscopy* reveals irregular pupillary reflex.

2. *Slit-lamp examination* may reveal corneal irregularity of *keratoconus*.

3. *Placido's disc test* reveals distorted circles.

4. *Photokeratoscopy and computerized corneal topography* give photographic record of irregular corneal curvature.

Treatment

1. *Optical treatment* of irregular astigmatism consists of prescribing contact lens, which replaces the anterior surface of the cornea for refraction.

2. *Phototherapeutic keratectomy (PTK)* performed with excimer laser may be helpful in patients with superficial corneal scar responsible for irregular astigmatism.

3. *Surgical treatment* is indicated in extensive corneal scarring (when vision does not improve with contact lenses) and consists of penetrating keratoplasty (PK).

BINOCULAR OPTICAL DEFECTS

■ ANISOMETROPIA

The optical state with equal refraction in the two eyes is termed *isometropia.* When the total refraction of the two eyes is unequal, the condition is called *anisometropia.* Small degree of anisometropia is of common occurrence and of not much concern. A difference of 1 D in two eyes causes a 2% difference in the size of the two retinal images. A difference up to 5% in retinal images of the two eyes is well tolerated. In other words, an anisometropia up to 2.5 D is well tolerated and that between 2.5 and 4 D can be tolerated depending upon the individual sensitivity. However, if it is more than 4 D, it is not tolerated and is a matter of concern.

Aetiology

1. *Congenital and developmental anisometropia* occurs due to differential growth of the two eyeballs.

2. *Acquired anisometropia* may occur under the following circumstances:

- Uniocular aphakia after removal of cataractous lens,
- Implantation of IOL of wrong power,
- Inadvertent surgical treatment of refractive error,
- Trauma to the eye,
- Keratoplasty in one eye and
- Asymmetric age changes.

Clinical Types

1. ***Simple anisometropia***. In this case, one eye is normal (emmetropic) and the other eye is either myopic (simple myopic anisometropia) or hypermetropic (simple hypermetropic anisometropia).
2. ***Compound anisometropia***. In this case, both eyes are either hypermetropic (compound hypermetropic anisometropia) or myopic (compound myopic anisometropia), but one eye is having higher refractive error than the other.
3. ***Mixed anisometropia***. In this case, one eye is myopic and the other is hypermetropic. This is also called *antimetropia.*
4. ***Simple astigmatic anisometropia***. When one eye is normal and the other has either simple myopic or hypermetropic astigmatism.
5. ***Compound astigmatic anisometropia***. When both eyes are astigmatic but of unequal degree.
6. ***Mixed astigmatic anisometropia***. In this case, one eye has hypermetropic astigmatism and the other has myopic astigmatism.

Status of Binocular Vision in Anisometropia

Three possibilities exist as follows:

1. *Binocular single vision* is present in small degree of anisometropia (<3 D).
2. *Uniocular vision.* When refractive error in one eye is of high degree (>2.5 D difference in the two eyes), this eye is suppressed and develops anisometropic amblyopia. Thus, the patient has only uniocular vision.
3. *Alternate vision* occurs when one eye is emmetropic or moderately hypermetropic and the other myopic. The emmetropic/hypermetropic eye is used for distant vision and myopic for near. Such patients are usually comfortable and seldom seek any optical aid.

Diagnosis

1. **Retinoscopic examination** in patients with defective vision is used to make diagnosis.
2. **Testing for state of binocular vision** may be done by either FRIEND test or Worth's four-dot test.

i. ***FRIEND test***. In this test, the letters F, I, N are written in green and R, E, D in red. It is incorporated in the Snellen's vision box. The patient is made to sit at a distance of 6 m after wearing diplopia goggles with red glass in front of right eye and green in front of the left eye and is asked to read these letters. Results are interpreted as follows:

- In the presence of *binocular single vision,* the patient will read FRIEND at once.
- In the presence of *uniocular vision,* the patient will persistently read either FIN or RED.
- In the presence of *alternate vision,* the patient will read FIN at one time and RED at other time.

ii. ***Worth's four-dot test.*** For this test, the patient wears goggles with red lens in front of the right eye and green lens in front of the left eye and views a box with four lights: one red, two green and one white (Fig. 3.21).

Interpretation is as follows:

- If the patient sees all the four lights in the absence of manifest squint, he or she has normal binocular single vision (Fig. 3.21A).
- In abnormal retinal correspondence, the patient sees four lights even in the presence of a manifest squint (Fig. 3.21B).
- When the patient sees only two red lights, it indicates left suppression (Fig. 3.21C).

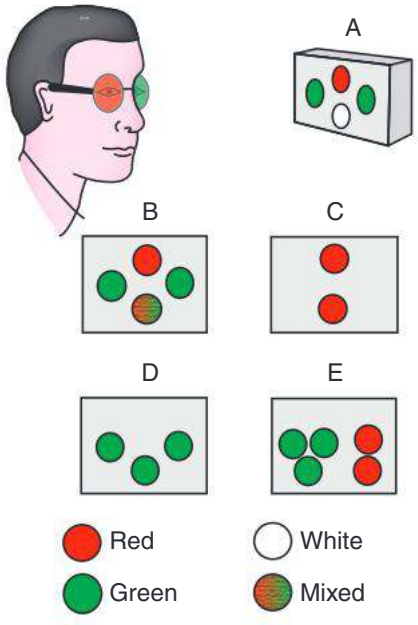


Fig. 3.21 *Worth's four-dot test.*

- If the patient sees only three green lights, he or she has right suppression (Fig. 3.21D).
- When he or she sees three green lights and two red lights, alternately, it indicates the presence of alternating suppression.
- If the patient sees five lights (two red and three green), he or she has diplopia (Fig. 3.21E).

Treatment

1. ***Glasses.*** The corrective spectacles can be tolerated comfortably up to 2.5 D, and rarely to a maximum difference of 4 D. After that, there occurs diplopia. Therefore, in children (younger than 12 years) where best visual correction is required in both the eyes, one must think of alternative modes of prescription, such as contact lenses. However, in adults, compromise may be made by prescribing the best correction that will not result in ocular discomfort. Usually, the more ametropic (poorer) eye is undercorrected. Thus, a patient who ought to have but does not tolerate +3 and +7 D sphere may be happy with a +3 and +5 D. Failing this, both eyes can be given a prescription of less ametropic eye (i.e. +3 and +3 D). Further, in adults with alternating vision – one eye being hypermetropic and used for distance, and the other myopic and used for near work – or with monocular vision – one eye being used exclusively for all functions – the condition usually is best left alone.

2. ***Contact lenses*** are advised for higher degrees of anisometropia. Contact lenses may be very useful in young children with high anisometropia, who might otherwise become amblyopic on the side of the more ametropic eye.

3. ***Anisometropic spectacles*** (Fig. 3.22) are an alternative modality for treatment of anisometropia. In these spectacles, the margin of the stronger lens is made weaker, thus minimizing the annoyance caused by peripheral prismatic effect of conventional lenses. They have, however, to a large extent been ousted by contact lenses and other modalities of treatment described below.

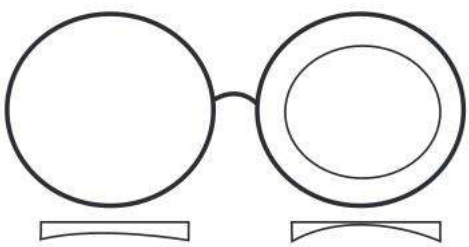


Fig. 3.22 *Anisometropic spectacles.*

4. ***Refractive surgeries for anisometropia*** are presently the most preferred ones. These include the following:

i. *IOL implantation* for uniocular aphakia.

ii. *Refractive corneal surgery* (LASIK, PRK, SMILE) for unilateral myopia, astigmatism and hypermetropia.

iii. *Phakic refractive lenses* (PRLs) are good option for refractive error of 4–10 D.

iv. *Refractive lens exchange (RLE)* is a better option for high refractive error of >10 D.

Note:

- *In children*, efforts should be made to fully correct the anisometropia to prevent anisometropic amblyopia.
- *In adults* with amblyopia, under correction of more ametropic eye may be required to avoid ocular discomfort.

ANISEIKONIA

Aniseikonia is an anomaly of binocular vision in which the ocular images are unequal in size or shape or both up to 5% aniseikonia can be well tolerated. It should be borne in mind that aniseikonia is the cause of curable ocular discomfort, suffered by a relatively small but not insignificant number of people. It is highly regrettable that little attention is paid to this anomaly of binocular space perception, which can be corrected or alleviated by altering the relative dimensions of the right and left retinal images.

Aetiology

1. *Optical aniseikonia* may occur due to inherent or acquired anisometropia of high degree.

2. *Retinal aniseikonia* may develop due to:

- Displacement of retinal elements towards the nodal point in one eye and
- Stretching or oedema of the retina.

3. *Cortical aniseikonia* implies a symmetrical simultaneous perception in spite of equal size of images formed on the two retinae.

Clinical Types

Clinically, aniseikonia may be of different types (Fig. 3.23):

1. **Symmetrical aniseikonia**
   - **i.** *Spherical.* In it, image may be magnified or minified equally in both meridia (Fig. 3.23A).
   - **ii.** *Cylindrical*. In it, image is magnified or minified symmetrically in one meridian (Fig. 3.23B).
2. **Asymmetrical aniseikonia**
   - **i.** *Prismatic.* In it, image difference increases progressively in one direction (Fig. 3.23C).
   - **ii.** *Pincushion*. In it, image distortion increases progressively in both directions, as seen with high plus correction in aphakia (Fig. 3.23D).
   - **iii.** *Barrel distortion*. In it, image distortion decreases progressively in both directions, as seen with high minus correction (Fig. 3.23E).
   - **iv.** *Oblique distortion*. In it, the size of image is same, but there occurs an oblique distortion of shape (Fig. 3.23F).

Clinical Features

Tolerance for aniseikonia varies from patient to patient; some patients apparently are able to tolerate rather large amounts and others have severe symptoms with much smaller levels. It is when the difference in image size or meridional distortions approaches the patient's tolerance that the symptoms of aniseikonia become manifest and troublesome. Thus, *clinical aniseikonia* may be defined as the amount of aniseikonia that is necessary to correct to eliminate the patient's symptoms. It usually occurs when the difference in image size between the two eyes approaches 0.75%. Meridional distortions are more poorly tolerated, especially when they are oblique. The oblique meridional aniseikonia causes a rotatory

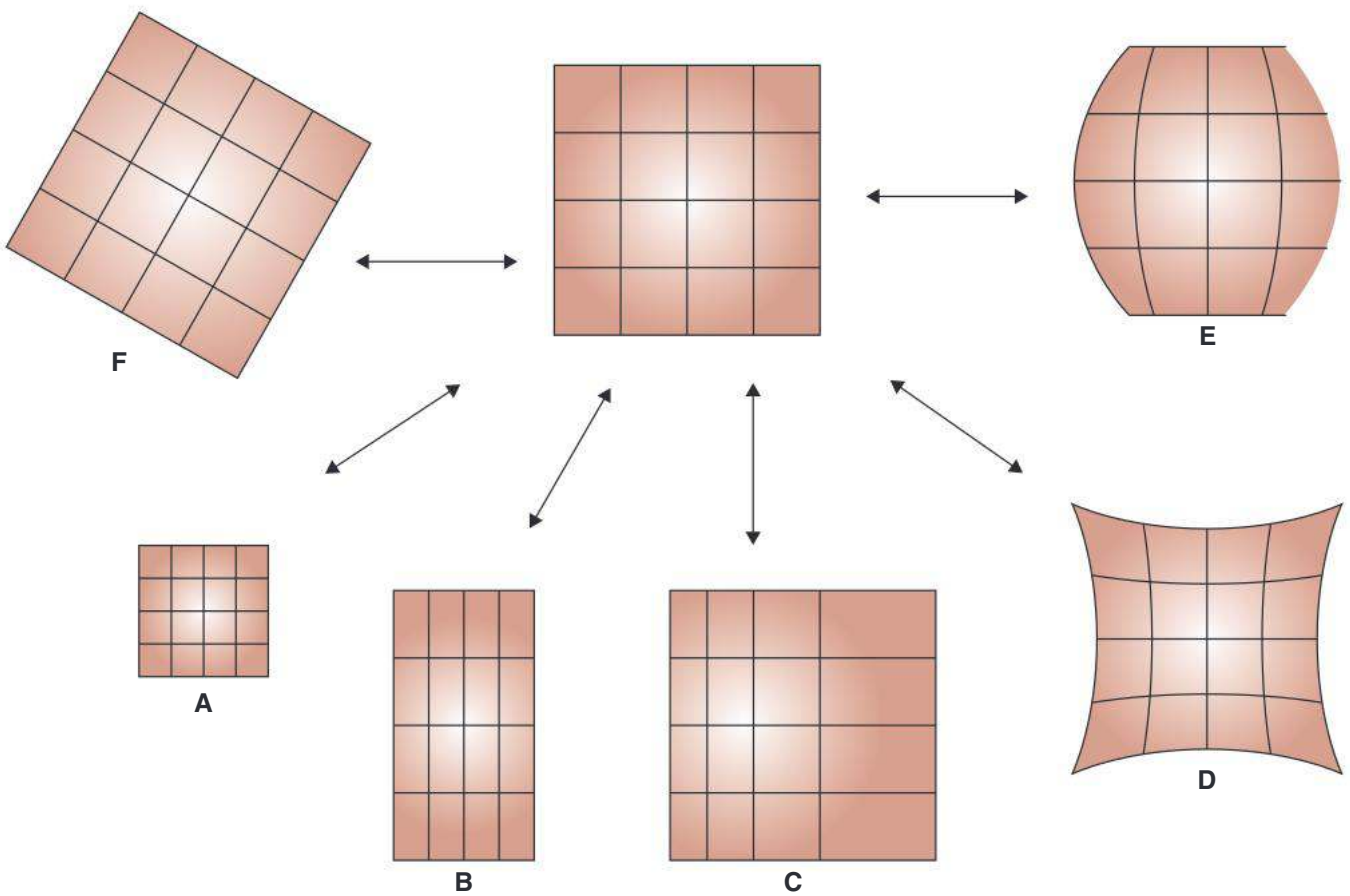


Fig. 3.23 *Types of aniseikonia: A, spherical; B, cylindrical; C, prismatic; D, pincushion; E, barrel distortion; F, oblique distortion.*

deviation between the fused images of vertical lines in the two eyes; this is termed *declination.* Declination becomes clinically troublesome when it approaches 0.3 degrees.

Symptoms of aniseikonia can be grouped as follows:

1. ***Asthenopic symptoms.*** These usually occur when the differences in size of the images of two eyes are between 0.75% and 5%. The severity of symptoms is not necessarily related to the degree of aniseikonia.

   Asthenopic symptoms include local eye discomfort (tiring), headache, difficult reading, photophobia, difficulty of fixation, vertigo, nausea, motility difficulty, nervousness and physical fatigue.

2. ***Disturbances of binocular vision*** in the form of confusion and diplopia occur only if the difference between the images of the two eyes exceeds 5%. Ordinarily escape from disturbances of binocular vision is attained by suppression of one eye at an early stage in life, and comfort is attained in uniocularity. However, when sudden aniseikonia is introduced in visually mature patient (e.g. unilateral aphakia in adults with well-established binocular vision), intractable diplopia results.

3. ***Spatial disorientations or disturbances in depth perception*** occur due to disturbances of the normal incongruity of the visual images caused by aniseikonia. This is particularly true when the horizontal meridian is involved, since horizontal disparities are the basis for the stereoscopic perception of depth. In practice, the stereoscopic visual functions adapt psychologically to considerable incongruity, especially in a condition which has been present since childhood. However, when the patient is fatigued or is transferred to surroundings in which there is minimum of uniocular perspective clues, such as in aviation or sometimes in motoring, distortions in space may become evident, with resulting errors in the judgement of distances. In general, disturbances of spatial orientation may occur in the following ways:

- Objects in the right half of the field appear larger and farther away than objects of the same size and at the same distance in the left field.
- A flat surface, such as a table, slants down on the right and up on the left.
- While walking, the ground appears tilted and the patient may feel as if he or she is walking on a hill.
- Squares appear as rectangles, circles as ellipses and tabletops as trapezoids.

Measurement of Degree of Aniseikonia

1. ***Space eikonometer method.*** The degree of aniseikonia can be exactly measured with the help of an instrument called space eikonometer. This instrument is expensive, cumbersome to use and of little therapeutic value. Therefore, in practice, it is not used and so not discussed here.

2. ***Rough estimate*** of degree of aniseikonia can be made by the 'rule of thumb' given to the practitioner by the Dartmouth studies, which is as follows: 'If the difference in image size associated with anisometropia is primarily of refractive origin, the aniseikonia produced will be about 1.5% per dioptre of anisometropia, but since the anisometropia may be partly axial, an estimate of 1% per dioptre is more useful clinically'.

Treatment

1. ***Optical aniseikonia*** can be corrected as given below:
   - *Unilateral aphakia* is best corrected by IOL implantation.
   - *Contact lenses* are a better choice than spectacles for correcting anisometropic aniseikonia.
   - *Refractive corneal surgery* is probably the best choice at present for treating aniseikonia.
   - *Aniseikonic spectacles* are difficult to make and expensive. These have been reported to be very effective in relieving the symptoms. However, nowadays they are sparingly used.

2. ***Retinal aniseikonia*** is corrected by treating the causative disease.

3. ***Cortical aniseikonia*** is very difficult to treat.

4 Asthenopia, Digital Eye Strain, Anomalies of Accommodation and Convergence

Chapter Outline

ASTHENOPIA AND DIGITAL EYE STRAIN

ASTHENOPIA

Asthenopia is one of the very frequently made diagnoses and is often considered a waste-basket term encompassing slight ocular discomfort to every imaginable type of headache. Asthenopia is a term used to describe a number of symptoms like general eye strain, easy fatigability after reading, heaviness of lids and sleepiness after reading.

■ CAUSES OF ASTHENOPIA

Asthenopia may result from the following:

1. Uncorrected refractive errors,
2. Defects of ocular motility and
3. Accommodation and convergence insufficiency.

1. Asthenopia in Uncorrected Refractive Errors

Small to moderate refractive errors cause most of the symptoms, as in large refractive errors, the patient cannot compensate and resorts to monocularity or learns to tolerate the resultant reduced visual acuity. On the other hand, in

small to moderate refractive errors, the defect is compensated by the patient with increased muscular effort which then results in muscular fatigue and thus asthenopic symptoms.

i. ***Myopia.*** In an uncompensated myopic patient, blurring occurs while reading, if a book is held at a reading distance that is farther than his or her far point. The patient must hold the reading material closer to secure clarity. But the greater proximity of target requires more convergence. Therefore, asthenopia results because the patient must rely on increased positive fusional convergence for single vision to the near point to replace the absent reflex positive accommodative convergence. The uncorrected myope frequently develops an accommodative response that is less than equivalent of the near stimulus, i.e. low positive relative accommodation and a lower than usual amplitude for the age of the patient. Such patients may have asthenopic symptoms after correction.

ii. ***Hypermetropia.*** In a hypermetropic patient, the eye at rest receives only blurred images on the retina and in order to get clear images, one has to increase the refractive power by continuous activity of the ciliary muscle – the nearer the object, the more powerful must be the effort.

iii. ***Astigmatism.*** Uncorrected astigmatism, particularly small astigmatic errors are important cause of symptoms of eye strain. The symptoms are more severe in cases of hypermetropic astigmatism, in which accommodation makes further efforts to overcome hypermetropia.

iv. ***Anisometropia.*** The patient with anisometropia has an unequal blur. The attempts to clear it result in imbalance in accommodative demand. Such differential accommodation may be a cause of asthenopia in sensitive persons with anisometropia of 0.5 D or less.

2. Asthenopia in Accommodation/ Convergence Insufficiency

i. ***Presbyopic, i.e. physiological accommodation insufficiency.*** In presbyopes, presbyopia attempts are made to stimulate accommodation when it is becoming physiologically impossible and results in asthenopic symptoms.

ii. ***Non-physiological accommodation insufficiency,*** i.e. inability to accommodate without the help of convergence. Such patients typically complain of headache, eye strain and intermittent blurring after 20–40 min of reading. Usually, the patient has good vision with insignificant refractive error.

The typical patient is able to read Jaeger 2 print easily, but may be noticed to squint or frown when reading. The diagnosis is made by placing +1.0 or +1.25 D sph. in front of each eye; an immediate positive response is elicited by the patient. The patient is seen to relax the facial muscles. If the patient reports better vision, the test is negative.

iii. ***Convergence insufficiency.*** An absolute insufficiency is said to exist (in the absence of presbyopia), when the near point is greater than 11 cm from baseline (9.5 cm from the apex of cornea) or when there is difficulty in attaining 30 degrees of convergence. It occurs typically in uncorrected myopes and is seen in hypermetropes and presbyopes when their refraction is corrected for the first time or in those suffering from accommodative insufficiency. General disease or debility due to illness, toxic conditions or metabolic or endocrine disorders may also be the cause of insufficiency. The diagnosis is based on the presence of orthophoria for distance, periodic increase of relative divergence as the near point is reached, the remoteness of near point (beyond 9.5 cm), the low prism convergence (below 15 D) and normal prism divergence.

3. Asthenopia in Defects of Ocular Motility

Development of asthenopia in heterophoria depends on the state of sensory motor system and the general well-being of the patient. In patients of heterophoria, the discrepancy between the deviation and the amplitudes of motor fusion results in asthenopia. If the amplitudes are inadequate to cope comfortably with the deviation, asthenopic symptoms may arise.

Vertical deviations are especially likely to cause symptoms, since the vertical fusion amplitudes are limited. Even if the amplitudes are

adequate, patients sometimes develop asthenopic symptoms or even diplopia following a debilitating disease.

1. *Photogenous asthenopia* occurs due to excessive or improper illumination.
2. *Nervous asthenopia* occurs due to functional or organic nervous disease commonly seen in anxiety.
3. *Asthenopia due to overuse of digital screen*. It is also known as 'digital eye strain (DES)' or computer vision syndrome (CVS); and is described as a separate entity.

CLINICAL FEATURES

Asthenopia principally occurs secondary to increased muscular work and muscular fatigue. Symptoms of asthenopia are very variable and are related to use of eyes.

1. ***Nonvisual ocular symptoms*** are described as tired, aching or bleary eyes. The patient usually complains of tiredness of the eye after near work. A temporary relief is obtained by resting or rubbing them. The continuation of work, however, can result in feeling of actual pain, which on occasions can be acute and severe. The nature of pain is often described as dull aching, boring superficial, deep-seated or migrainous.

Objectively, the eyes frequently have a typical appearance. The continued state of irritability and congestion brings about an unhealthy condition of lids and conjunctiva with a characteristic look: watery, suffered and bleary. This is especially notable in children, in whom an intractable blepharitis or conjunctivitis should always suggest an examination of the refraction.

2. ***Headache*** is one of the common symptoms of asthenopia, which occurs in multitude of varieties. It may be localized around the region of eyes; it may be frontal, temporal, vertical or occipital, or the pain may extend down the neck or even into the arms. It may remain limited to any part, being associated frequently with a tender area in the vertex or the temple, but as a general rule, when thus limited, it occurs as a 'browache' over the immediate neighbourhood of the eyes.

It varies widely in nature. Sometimes it is superficial and resembles a cutaneous hyperaesthesia. Sometimes it is deep-seated and boring, or full and throbbing; it may be dull and heavy ache, difficult to describe or localize accurately or it may be neuralgic in nature: sharp, shooting and lancinating. The *occurrence* of headache may be permanent or periodic, or it may come on at quite irregular intervals.

Mechanism of headache is not fully understood, but presumably it rests upon same basis as other referred pain of visceral origin. So, ciliary pain caused by increased muscular efforts in asthenopia is referred to the areas associated with the cervical segments which connect with the superior cervical ganglion, the somatic outflow from which is represented by the bulbospinal root of the trigeminal and the upper cervical nerves. The ophthalmic division of the fifth nerve is represented most caudally, so that ciliary pain is primarily frontal and occipital in distribution.

3. ***Visual symptoms*** are intermittent in nature. In cases of small refractive errors, the defect may be compensated more or less completely by the patient, and vision remains good. Visual symptoms arise in periods of unusual strain or during temporary deterioration of general health and vitality, when fatigue comes on and visual acuity falls. This is especially seen in those who use the eyes much for reading or for study of small objects over long periods of time, while fine sewing, the cinema, motor driving, in the distraction of confusing traffic or any relaxation or employment which calls for a high degree of visual acuity combined with attention or anxiety. Here the ciliary muscle gives up any attempt to focus and the image becomes indistinct, or the ocular muscles slip back into their conditions of rest and diplopia results.
4. ***Other general symptoms of eye strain*** are of more uncertain status. Digestive upsets such as dyspepsia, nausea, vague nervous disorders such as dizziness, insomnia and depression, and many other symptoms have all

in the past been variously attributed to eye strain. Although these attributions can be considered exaggerated, but eye strain does probably have effect on general health and mental well-being of the patient.

MANAGEMENT OF ASTHENOPIA

Management of asthenopia includes management of cause of asthenopia. Refraction, checking near point of accommodation (NPA) and convergence and orthoptic workup are essential in each patient of asthenopia. General health status of the patient should also be considered.

1. ***Refractive correction.*** Refraction is mandatory for all patients of asthenopia caused by refractive error. Refractive correction will reduce the demand for muscular effort and thus relieve the symptoms.

For patients of accommodative insufficiency, reading glasses of +1.0 to +1.25 D sph. are very beneficial. The patient should be given simple half-eye reading glasses. The patient should be instructed that the benefit of the glasses will be apparent only after approximately 20 min or so of reading.

2. ***Orthoptic treatment.*** Orthoptic exercises play an important role in management of asthenopia. Orthoptic treatment in the form of adduction exercises best results in convergence insufficiency as the fusion amplitude is large and voluntary efforts can be enlisted to aid its facilitation.
3. ***Prismotherapy.*** Base-in (BI) prisms are prescribed in few cases of convergence insufficiency only if orthoptic exercises fail.
4. *Correction of strabismus,* if required should be done.
5. *Artificial tears* with lid hygiene and warm compresses give soothing effect.
6. *Ocular hygiene*, i.e. use of proper illumination, proper posture, proper font size, taking breaks in between doing constant near work.
7. ***General management.*** Management of general disease or debility due to illness and improving general well-being of patient is equally important for successful management of asthenopia. Pain relievers can be prescribed for severe pain/headache as and when required.

DIGITAL EYE STRAIN

Digital eye strain (DES) is characterized by a range of eye and vision-related symptoms and has been recognized an ocular health problem for the last 20 years. Its incidence has increased markedly during and after COVID-19 pandemic. The terms visual fatigue (VF) and DES are also used for the condition, reflecting the variety of digital devices linked to the potential problems.

Pathophysiology

Visual work with a digital screen is associated with frequent saccadic eye movements (ocular motility), accommodation (continuous focusing) and vergence (alignment demands); all of which involve continuous relaxation and contraction of the eye muscles. Frequent focusing and refocusing of the eye by the ciliary body creates fatigue and even lag of accommodation, which leads to ocular symptoms related to CVS.

Risk Factors

Risk factors contributing to DES include the following:

- *Patient factors:* Uncorrected refractive error, presbyopia, pre-existing phorias, convergence insufficiency, accommodation insufficiency and muscle imbalance.
- *Computer system related factors:* Poor resolution of screen, imbalanced lighting of computer screen and surrounding.
- *Computer use and environmental related factors:* Improper illumination, poor seating posture and improper viewing distance.

Clinical Features

Symptoms of DES are categorized into four main groups:

- *Asthenopic symptoms*: Eye strain, eye fatigue, pain around the eyes, frontal headache.

- *Ocular surface-related symptoms*: Dry eyes, watery eyes, itching and burning sensation.
- *Visual symptoms*: Blurred vision, difficulty in focussing, double vision.
- *Extraocular symptoms*: Neck pain, back pain, shoulder pain.

Clinical Workup

The history-taking component is most essential and must include number and type of devices being used and amount of time used per device. After taking a history, a thorough ocular examination should include refraction, binocular vision assessment and tear film evaluation, but not limited to these. Evaluating blink rate is also considered as an important tool for diagnosis as well as treatment purpose.

Prevention and Treatment

- *Modification of the working environment* is also one of the important and easy methods to minimize the risk.
- *Correction of refractive error* is the most important means of treating DES.
- *Reducing screen luminance* is one of the methods to increase the blinking rate and proper room lightening during computer use. The mean distance of viewing a computer is suggested to be in the range of 60–80 cm.
- *Using 20-20-20 rule* is a simple method to prevent DES, which means after every 20 min of computer usage, look at distance of 20 ft for 20 s and try to blink 20 times.
- *Lubricating eye drops*, to prevent and treat dry eyes has been shown to reduce symptoms such as tiredness, dryness and difficulty in focusing during sustained computer use.
- *Supplement of Vitamin D_3 and Omega 3 fatty acid* improves tear stability as well as decreases symptoms of DES.
- *Eye muscle exercise* prevents ocular fatigue and pain.
- *Use of computer glasses* with antiglare and UV coating also have preventive role.
- *Proper posture, neck and back muscle exercises* are recommended to prevent/treat the associated neck and back pain.

ACCOMMODATION

PHYSIOLOGICAL ASPECTS

DEFINITION OF ACCOMMODATION AND RELATED TERMS

Accommodation

As we know that in an emmetropic eye, parallel rays of light coming from infinity are brought to focus on the retina, with accommodation at rest. Our eyes have been provided with a unique mechanism by which we can even focus the diverging rays coming from a near object on the retina in a bid to see clearly (Fig. 4.1). This mechanism is called accommodation. In it, there occurs increase in the power of the crystalline lens due to change in shape of the lens resulting from a contraction of ciliary muscle.

Far point, Near Point, Range and Amplitude of Accommodation

The nearest point at which small objects can be seen clearly is called near point or *punctum proximum* and the distant (farthest) point is called far point or *punctum remotum.* The distance between the near point and the far point is called *range of accommodation.* The difference between the dioptric power, needed to focus at near point (P) and to focus at far point (R), is called *amplitude of accommodation* (A). Thus, A = P – R.

Far point and near point of the eye vary with the static refraction of the eye:

- In a *hypermetropic eye*, far point is virtual and lies behind the eye (Fig. 4.2B).
- In *myopic eye*, far point is real and lies in front of the eye (Fig. 4.2C).
- In an *emmetropic eye*, far point is at infinity (Fig. 4.2A) and near point varies with age, being about 7 cm at the age of 10 years, 25 cm

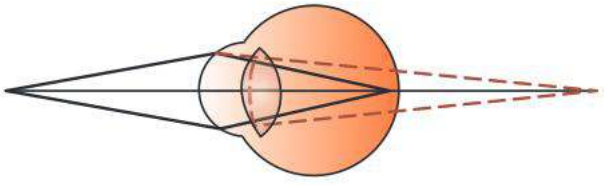


Fig. 4.1 *Effect of accommodation on divergent rays entering the eye.*

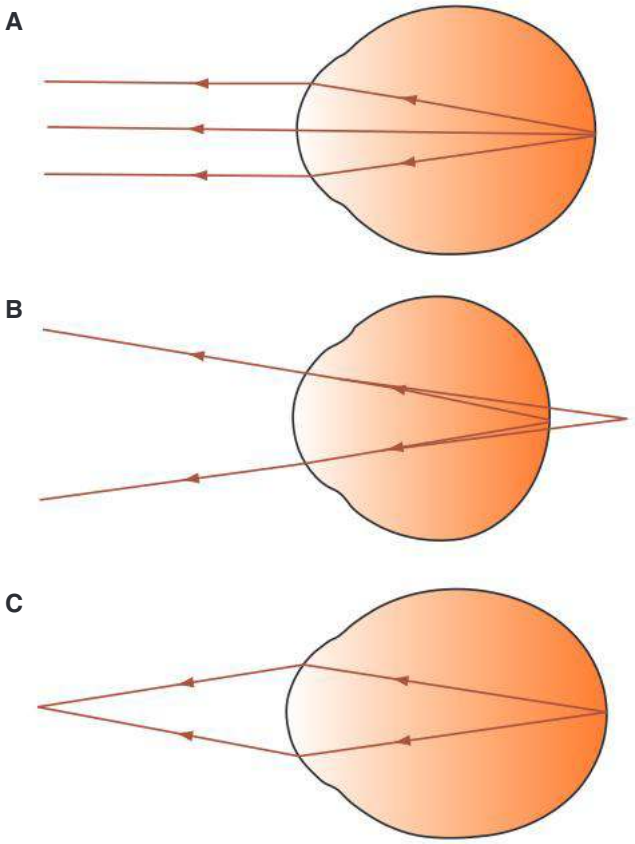


Fig. 4.2 *Far point in emmetropic eye (A), hypermetropic eye (B) and myopic eye (C).*

at the age of 40 years and 33 cm at the age of 45 years. Thus, the amount that the eye can alter its refraction is greatest in childhood and slowly decreases until it is lost in middle age. Amplitude of accommodation in dioptres as function of the age, as studied by Duane, is depicted in Figure 4.3. Duane suggested the following equation for relation of age in years to accommodation (A): A = 15 – 0.25 (age). During the second, third and fourth decades, there is gradual loss of accommodation (2 D in second decade and 2.9 D in fourth decade).

Depth of Field and Depth of Focus

When an object is accurately focused monocularly, often the objects somewhat near and somewhat farther away are also seen clearly without any change in accommodation. This range of distance from the eye in which an object appears clear without any change of accommodation is termed as *depth of field.* Depth of field reduces the necessity for precise accommodation.

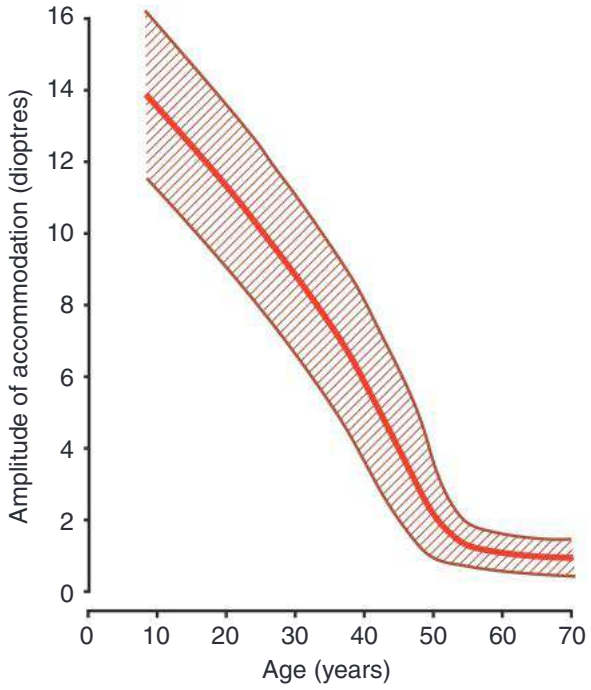


Fig. 4.3 *Decrease in the amplitude of accommodation with age in human. (From Duane, Arch Ophthalmol, 54: 566–587, 1925.)*

The range at the retina in which an optical image may move without impairment of clarity is termed as depth of focus. The depth of field and depth of focus are markedly influenced by the diameter of the pupil (Fig. 4.4). Depth of field is inversely proportional to pupil size. Size of the blur circle produced on retina is proportional to pupil size.

Depth of field should not be mistaken for accommodation. The apparent range of accommodation also includes depth of field and tolerance of blur (i.e. depth of focus).

ASSESSMENT OF ACCOMMODATION

As we know, accommodation is a unique mechanism by which our eyes can even focus the diverging rays coming from a near object on the retina in a bid to see clearly (Fig. 4.1). Assessment of accommodation is of great diagnostic value in cases of incomitant strabismus of non-paralytic origin. Assessment of accommodation faculty includes:

- Assessment of NPA and amplitude of accommodation,

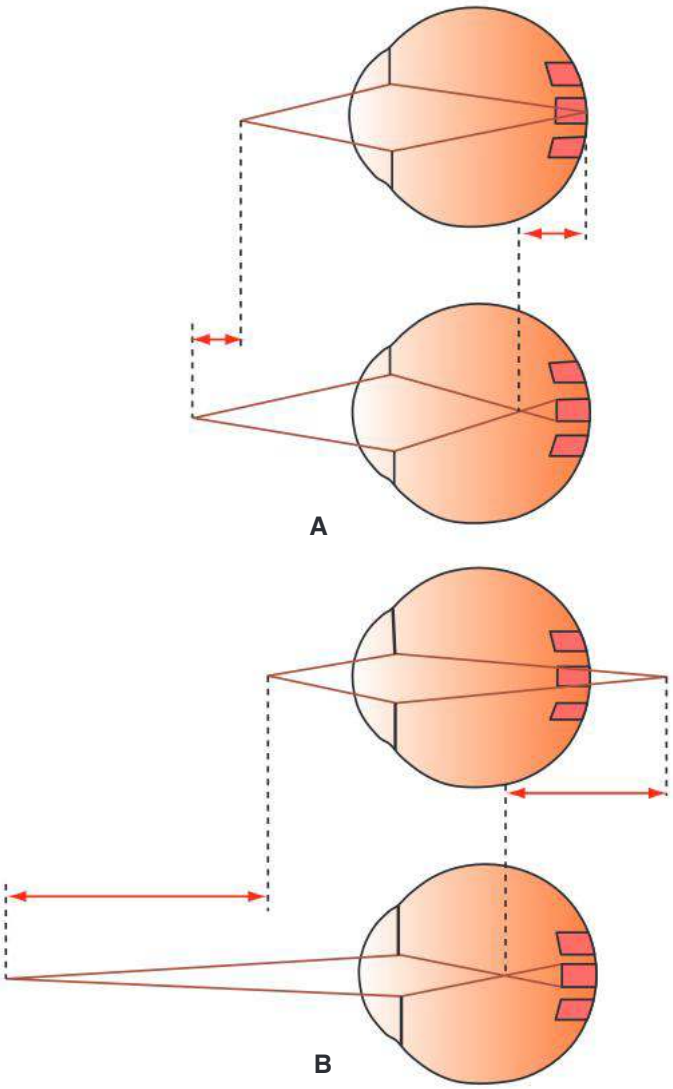


Fig. 4.4 *Effect of pupil diameter on depth of field and depth of focus: A, large pupil; B, small pupil.*

- Assessment of accommodative response and
- Assessment of dynamics of accommodation.

I. ASSESSMENT OF NPA AND AMPLITUDE OF ACCOMMODATION

Assessment of *amplitude of accommodation* (the difference between the dioptric power needed to focus at near point 'P' and far point 'R', i.e. A = P – R) in practice can be made either by measurement of NPA or by use of minus lenses. Reaction time of accommodation is 0.36 s and is increased in myopes as compared to hyperopes.

The NPA is the closest point at which small objects can be seen clearly. It is also called 'near point' or 'punctum proximum'. NPA can be measured by the following methods.

1. RAF Rule or Prince Rule

The description of such a rule has been given in the discussion on the measurement of the near point of convergence (NPC).

To determine the NPA with RAF rule (Fig. 4.5), a sliding target with 6/9 letters, numbers or fine lines is moved from or towards the eye until the closest point is found at which it still can be seen clearly. During the examination, the patient has to wear his or her full optical refractive correction. The NPA is determined first for each eye separately and then for both eyes together. The NPA is measured in centimetres marked on one side of the instrument bar. The side of the bar marked in dioptres will indicate the amplitude of accommodation in dioptres. The third side of the bar shows the age corresponding to the accommodation. For example, if the patient reports that the point appears blurred at 25 cm, the dioptric markings will show +4.0 D and the age 40 years.

If, while measuring the NPA, the patient's amplitude of accommodation is found so low that his or her near point is beyond the length of the instrument, plus lenses are added to his or her correction until the near point is brought within range. The dioptric power of these additional lenses is then deducted from the measured values of amplitude of accommodation. Conversely, in young patients with very high accommodative power, minus lenses may be added to the distance correction to move the near point away from the eyes. The dioptric power of those minus lenses is then added to

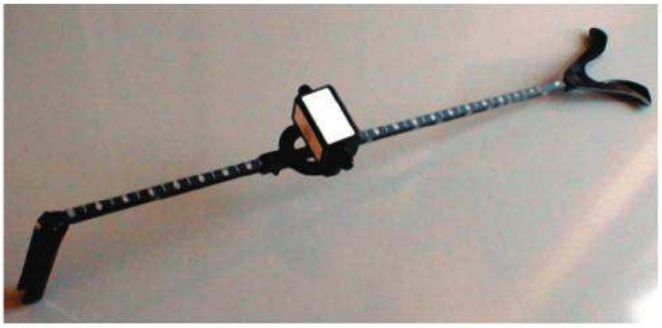


Fig. 4.5 *RAF rule.*

the measured value of amplitude of accommodation.

2. Measurement of Amplitude of Accommodation Using Minus Lenses

This test is performed for each eye separately and during examination, the patient has to wear his or her full refractive correction. The patient is asked to fixate the best corrected near vision target at 40 cm distance and minus lenses of progressively increasing power are added before the eye till the patient reports the first sustained blur. The power of this minus lens plus +2.5 D (for 40 cm distance of testing) is equivalent to the amplitude of accommodation in dioptres. For example, at 40 cm distance of testing, if the patient reports blur with –3 D spherical lens, the amplitude of accommodation would be 3 + 2.5 = 5.5 D.

3. Push-Up Test

It is a very simple test which can be done both monocularly and binocularly, with the patient wearing full refractive correction. The patient is asked to fixed it the best corrected near vision target at a distance where the target is seen clearly. The near vision chart is then moved closer till the patient reports first sustained blur. The linear distance measured between the chart and patient's spectacle plane gives the NPA.

II. ASSESSMENT OF ACCOMMODATIVE RESPONSE

The accommodative response of an individual can be assessed with dynamic retinoscopy.

Techniques of dynamic retinoscopy to measure the accommodative response are as follows:

- *Monocular estimation method (MEM) retinoscopy*. Patient is asked to fixate the near target at a distance of 40 cm and the retinoscopy is performed using streak retinoscope (Fig. 4.6). The lens power required to attain neutrality is noted.
- *Nott retinoscopy*. Dynamic retinoscopy is performed as described for MEM method, except that the retinoscopic reflex is neutralized by moving the retinoscope rather than adding the lenses. For the 'with' movement, the retinoscope is moved away from the patient and for the 'against' movement, towards the patient till the retinoscopic reflex is neutralized.

Fig. 4.6 *Monocular estimation method (MEM) retinoscopy.*

Interpretation of accommodative response is made as follows:

- *Lag of accommodation at near* refers to an accommodative response less than the accommodative demand. For example, the accommodative demand at 40 cm is +2.5 D; and if the accommodative response noted is +2 D, then there is +0.5 D of lag of accommodation. A lag of greater than +1.00 D is often found in individuals with accommodative insufficiency or infacility.
- *Lead of accommodation* refers to an accommodative response that exceeds the accommodative demand. For example, the accommodative demand at 40 cm is +2.5 D and if the accommodative response noted is +3.00 D, then there is +0.5 D of lead of accommodation. An accommodative lead of 0.5 D or more usually indicates accommodative excess.

III. ASSESSMENT OF DYNAMIC ACCOMMODATION

Dynamics of accommodation can be assessed by testing *accommodative facility*. An accommodative flipper of +2.00 DS with +2.00 DS (Fig. 4.7) is used to test accommodative facility by rapidly flipping the lenses.

- *Difficulty with plus lenses* is seen in patients with accommodative excess.

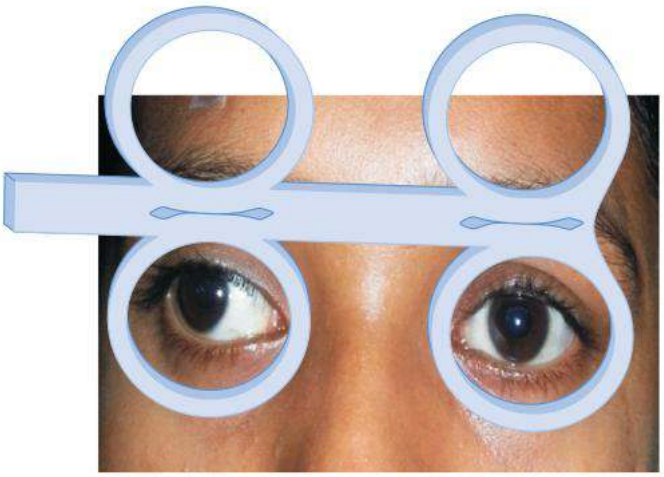


Fig. 4.7 *Testing of accommodative facility with an accommodative flipper.*

- *Difficulty with minus lenses* is seen in presbyopes and with accommodative insufficiency.

ANOMALIES OF ACCOMMODATION

As discussed earlier, the amplitude of accommodation varies with the age and has a fairly wide range which may be looked upon as normal (Fig. 4.3). Anomalies of accommodation (variations in either direction, above or below that range) are by no means uncommon and include the following:

I. *Diminished or deficient accommodation*
   1. Physiological (presbyopia)
   2. Pharmacological (cycloplegia)
   3. Pathological
      - Insufficiency of accommodation
      - Ill-sustained accommodation
      - Inertia of accommodation
      - Paralysis of accommodation

II. *Increased accommodation*
   1. Excessive accommodation
   2. Spasm of accommodation

DIMINISHED ACCOMMODATION

PRESBYOPIA

Presbyopia (eyesight of old age) is not an error of refraction but a condition of physiological insufficiency of accommodation due to reduced amplitude, leading to a progressive fall in near vision. This begins between 40 and 45 years of age.

Pathophysiology and Causes

To understand the pathophysiology of presbyopia, a working knowledge about accommodation (as described above) is mandatory. As we know, in an emmetropic eye, far point is infinity and near point varies with age (being about 7 cm at the age of 10 years, 25 cm at the age of 40 years and 33 cm at the age of 45 years). Therefore, at the age of 10 years, amplitude of accommodation (A) = 100/7 (dioptric power needed to see clearly at near point) – 1/α (dioptric power needed to see clearly at far point), i.e. A (at age 10) = 14 D; similarly, A (at age 40) 100/25 – 1/α = 4 D.

Since, we usually keep the book at about 25 cm, so we can read comfortably up to the age of 40 years. After the age of 40 years, the NPA recedes beyond the normal reading or working range. *This condition of failing near vision due to age-related decrease in the amplitude of accommodation or increase in punctum proximum is called presbyopia.*

Causes of presbyopia. Decrease in the accommodative power of crystalline lens with increasing age, leading to presbyopia, occurs due to the following:

1. *Age-related changes in the lens* which include:
   - Decrease in the elasticity of lens capsule and
   - Progressive increase in size and hardness (sclerosis) of lens substance, which is less easily moulded.
2. *Age-related decline in ciliary muscle power* may also contribute in causation of presbyopia.
   - Causes of premature presbyopia include:
   - Uncorrected hypermetropia,
   - Premature sclerosis of the crystalline lens,
   - General debility causing presenile weakness of ciliary muscle and
   - Chronic simple glaucoma.

Clinical Features

Symptoms

Symptoms of presbyopia develop when the amount of accommodation needed to focus at near exceeds more than half of the total amplitude of the eye. An uncorrected hypermetrope and a chronically undercorrected myope (who, as a result of undercorrection, never developed

full accommodative power) will both develop presbyopic symptoms earlier than an emmetropic patient. Onset of symptoms of presbyopia varies with the patient's preferred working distance, the nature of close work and the length of time for which it is done. Symptoms of presbyopia include the following:

1. ***Difficulty in near vision.*** Patients start complaining of inadequacy of vision for small print and finer objects at the usual reading distance. So, the patient begins to hold the head back and the book slightly at a greater distance. To start with, such problem occurs in the evening and in dim light, and later even in good light. Finally, the near work becomes an impossibility.
2. ***Asthenopic symptoms*** due to fatigue of the ciliary muscle are also complained after reading or doing any near work.
3. ***Intermittent diplopia*** at near may develop because of the interrelationship between accommodation and convergence.

Note. The described symptoms of presbyopia usually occur:

- *In emmetropes,* after the age of 40 years,
- *In hypermetropes,* not using distant glasses, before 40 years of age and
- *In myopic,* not using distant glasses, symptoms occur later. Myopes of about 3 D or more may not getting near vision problems as their far point matches the near point.

Note. *All symptoms of presbyopia are aggravated by* fatigue, illness, fever or other debilitating conditions.

Signs

- *Signs of presbyopia* are the result of testing for presbyopia.
- *Testing of presbyopia* should be done monocularly as well as binocularly (see page 166).

Treatment

I. Optical Correction of Presbyopia

It is done by supplementing accommodation with convex lenses of appropriate power, required for a clear and comfortable near vision. The difference between the distance correction and the strength needed for near vision is called the add.

Rough estimate for the presbyopic add for various age levels is as follows:

- 40 to 45 years: +0.5 to +1.00 D
- 46 to 50 years: +1.25 to +1.75 D
- 51 to 55 years: +2.00 to +2.25 D
- 56 to 60 years: +2.50 to +3.00 D

However, it should be estimated individually in each eye in order to determine how much is necessary to provide a comfortable range.

Adjustment for work distance. The power of the presbyopic add should be adjusted taking into consideration the working distance required by a particular patient and the remaining amplitude. For instance, in a patient in late 40s with only 3 D total amplitude left, the following adds give varying work distance and leave comfortable (50%) amount of accommodation in reserve:

- +2.5 D: 25 cm
- +1.5 D: 33 cm
- +1.0 D: 40 cm
- +0.5 D: 50 cm

Table 4.1 summarizes the range of presbyopic adds, depending upon the working distances and amplitude reserves.

Adds for intermediate distance. As the add increases and the amplitude of accommodation decreases, the range of clear near vision also decreases. Thus, unnecessarily strong reading adds, which limit the range of clear near vision to a small area very near to the patient, are a common cause of patient dissatisfaction. For example, a 45-year-old emmetropic individual works at a distance of 40 cm. His amplitude of accommodation is 3.5 D and he is given reading glasses of +0.75 D bilaterally. His range of clear vision through these glasses begins at 1/0.75 D or 1.33 m from the eye and extends to 1/(3.5 + 0.75) = 1/4.25 or 0.24 m (Fig. 4.8A). However, at the age of 60, his amplitude of accommodation is only 1 D. To read comfortably and clearly

Table 4.1 *Presbyopic adds depending upon the working distances and amplitude reserves*

Total amplitude of accommodation	Amplitude of accommodation in reserve	Add for 25 cm (4.00 D)	Add for 33 cm (3.00 D)	Add for 40 cm (2.50 D)	Add for 50 cm (2.00 D)	Add for 66 cm (1.50 D)
6.00	3.00	1.00	–	–	–	–
5.00	2.50	1.50	0.50	–	–	–
4.00	2.00	2.00	1.00	0.50	–	–
3.00	1.50	2.0	1.50	1.00	0.50	–
2.00	1.00	3.00	2.00	1.50	1.00	0.50
1.00	0.50	3.50	2.50	2.00	1.50	1.00
0.50	0.25	3.75	2.75	2.25	1.75	1.25

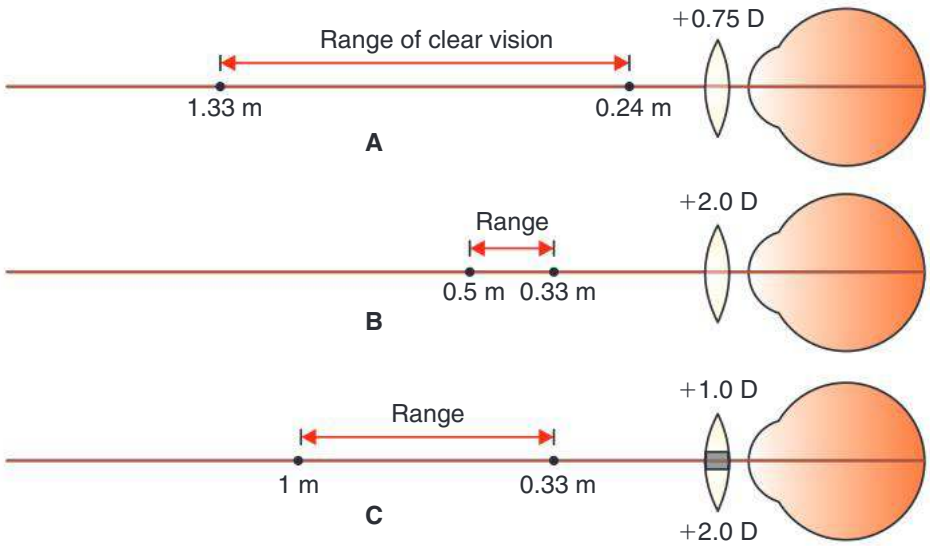


Fig. 4.8 *Use of trifocals to extend range of clear vision in presbyopia. For explanation, see text.*

at 40 cm, an add of +2.00 D is prescribed. His range of clear near vision now begins at 1/2 D or 0.5 m and extends to 1/(2 + 1) or 0.33 m (Fig. 4.8B).

Thus, this patient can see clearly in the distance without any correction and can see only close objects clearly with his reading glasses. Objects located at an intermediate distance, however, are blurred. An additional correction for this intermediate distance may be required, if it is necessary that the patient see clearly at that length. These intermediate adds are, in general, one-half the near add. Thus, our emmetropic patient would require +1.00 D and would see clearly between 1/1 D or 1 m and 1/(1 + 1) or 0.5 m as well (Fig. 4.8C).

Basic principles for presbyopic correction can be summarized as follows:

- Always find out refractive error for distance, and first correct it.
- Find out the presbyopic correction needed in each eye separately and add it to the distant correction.
- The presbyopic add prescribed should leave about 50% of the accommodation in reserve.
- Near point should be fixed by taking due consideration for profession of the patient.
- The weakest convex lens with which an individual can see clearly and comfortably with both the eyes (binocularly) at the near point should be prescribed, since overcorrection will also result in asthenopic symptoms.

- An additional correction for the intermediate distance may be required, if it is necessary for the patient to see clearly at that length. Varifocal (progressive) lenses are a good option.

Modes of prescribing presbyopic add. Correction of presbyopia can be prescribed in following ways:

1. ***Spectacles.*** Patient may need any of the following spectacles:
   - Single vision reading glasses,
   - Bifocal glasses,
   - Trifocal glasses and
   - Multifocal or varifocal glasses.

   If a patient has no significant distance refractive error, the best correction is single vision reading glasses of the proper strength. Since distant objects are blurred through this correction, the patient must either remove the glasses or look over them to see clearly in the distance. Thus, half glasses are commonly worn by these patients to alleviate this problem. If the patient has a significant distance refractive error, then two pairs of glasses are required or a bifocal or multifocal lenses may be prescribed. For details, see page 232.
   Drawbacks of reading glasses include the following:
   - Some people find it very annoying to switch between regular glasses and reading glasses, and also to put on and take off their reading glasses all day long.
   - Reading glasses need to be carried everywhere, so may be forgotten or misplaced.
   - They hide the eyes from the world and also emphasize age.
   - Even those who are used to wearing glasses, do not like the segments of bifocal.
   - The new no-line progressive addition eye glasses look better, but still these are glasses and also cause distorted vision to left and right. Also, these are expensive.

2. ***Contact lenses for presbyopia***. Bifocal contact lenses are available in many soft and RGP lens design. Bifocal contacts have two prescriptive powers for distance vision and near vision.
   - *Multifocal contact lenses* are also available now to correct intermediate distance and also to treat astigmatism.
   - *Monovision* is one other option for correcting presbyopia, where one eye wears a near vision contact lens and the other eye wears a distance vision contact lens.
   - *Also, there is a modified monovision,* where a single vision lens is in one eye and a bifocal lens in the other eye or two bifocal lenses with different near vision power.
   - *Hybrid bifocal fit* involves one contact lens with a distance zone in the centre and the other with a near zone in the centre, both lenses have an intermediate zone in the surrounding area. This is useful for people with strong presbyopia.

Note. One thing to remember is that presbyopia does progress over time and so contact lens and glass prescription have to be increased with time.

II. Surgical Treatment of Presbyopia

See page 442.

INSUFFICIENCY OF ACCOMMODATION

The term insufficiency of accommodation is used when the accommodative power is significantly and persistently below the normal physiological limits for the patient's age. Therefore, it should not be confused with presbyopia in which the physiological insufficiency of accommodation is normal for the patient's age.

So it can be labelled as pathological insufficiency of accommodation.

Causes

1. ***Premature sclerosis of lens***. It is in essence a premature presbyopia and is thus a stable condition. In other words, it is presbyopia which sets in at early age than usual.
2. ***Weakness of ciliary muscle due to systemic causes*** of muscle fatigue such as debilitating illness, anaemia, toxaemia, malnutrition, diabetes mellitus, pregnancy, mental stress, whooping cough, measles, nasal obstruction and hypopituitarism.
3. ***Weakness of ciliary muscle due to local causes***, e.g. primary open angle glaucoma and mild cyclitis as during onset of sympathetic ophthalmia.

Clinical Features

Insufficiency of accommodation is not very common before 15 and after 45 years of age. Insufficiency of accommodation may be intermittent or constant and transient or persistent. All the symptoms of presbyopia are present, but those of asthenopia are more prominent than those of blurring of vision. Patients frequently complain of the following:

- *Headache, fatigue and irritability of the eye* while attempting near work. Patient remains comfortable, if near work is not attempted.
- *Near work is blurred* and becomes difficult or impossible.
- *Intermittent diplopia* due to associated disturbances of convergence is also reported. Often accommodative failure is associated with convergence insufficiency, but sometimes the attempt to accommodate brings excessive amount of convergence. Convergence insufficiency is present in 44% of cases.

The above symptoms are stable in accommodation insufficiency of lenticular origin. However, when the condition is due to ciliary muscle weakness, with an improvement of the exciting factors, a betterment in the general health or a relaxation from over work or worry, the symptoms may considerably improve, only to relapse at a later date, if the same conditions again prevail.

Treatment

1. *Treatment of the cause*. The treatment is essentially that of the systemic causes which need to be discovered meticulously.

2. *Near-vision spectacles* in the form of weakest convex lens which allows adequate vision should be given till the power of accommodation improves and also to stimulate accommodation.

- In every case, in the first place any refractive error should be corrected.
- Where there is associated convergence insufficiency, BI prism may be added to patient's comfort.
- In cases with convergence excess, full spherical correction should be prescribed.
- As soon as recovery in accommodation takes place, the additional correction for near should be made progressively weaker from time to time.

3. *Accommodation exercises* help in recovery, if the underlying debility has passed.

- Exercises are not useful in cases with general debility and in cases where lenticular sclerosis is the cause of diminished accommodation.
- During the exercise, the patient should always wear the distance correction.
- Accommodation exercises should be undertaken simultaneously by both eyes, if there is associated convergence weakness as well; otherwise, one eye (alternately) should be covered while exercising for convergence excess cases.
- *Accommodation test-card exercise* is the most simple and commonly advised exercise. The accommodation test card consists of a black vertical line drawn on a white card. The patient is instructed to hold the card at a considerable distance from the eyes and then bring it closer until the line appears blurred and indistinct. By repeating this, the patient should be encouraged to attempt to bring his or her near point as close as possible. The patient should be encouraged to maintain the accommodative effect as large as it can be done with comfort. Patient should be advised to practise at short periods throughout the day.

ILL-SUSTAINED ACCOMMODATION

Ill-sustained accommodation, or a condition of accommodation fatigue, refers to a situation in which although the range of accommodation is normal, it cannot be sustained for a sufficient time period. This causes a tendency for the patient's NPA to recede during the close work.

Aetiology

Frequently, the ill-sustained accommodation is the initial stage of true insufficiency and so by and large, causes are the same as described above. Accommodation fatigue is

characteristically known to occur under the following conditions:

- Stage of convalescence from debilitating illness,
- Stage of general tiredness and
- When patient is relaxed in the bed.

Clinical Features

Since it is an initial stage of true insufficiency, the symptoms are largely the same. Typically, patients complain that while doing near work, they start feeling tired very soon, their near point gradually recedes and the near vision becomes blurred.

Treatment

- Curtailing the near work during the situations described in aetiology.
- General tonic measures.
- Improved visual hygiene with a particular reference to conditions of illumination and posture during the study.

■ ACCOMMODATION INERTIA

It is a condition in which there is difficulty in adjusting the accommodation according to the distance of the object of regard so as to gain clear vision.

Clinical Features

It is a comparatively rare condition. The patient typically complains that it takes some time and involves some definite effort for him or her to focus a near object after looking at the distance. Usually this condition does not assume any serious preposition, but occasionally may give rise to some trouble and annoyance.

Treatment

Treatment consists of correcting any associated refractive error and practice of accommodation exercises.

■ PARALYSIS OF ACCOMMODATION

Paralysis of accommodation, also known as cycloplegia, refers to complete absence of accommodation.

Causes

1. *Drug-induced cycloplegia* results due to the effect of atropine, homatropine or other parasympatholytic drugs.
2. *Internal ophthalmoplegia* (paralysis of ciliary muscle and sphincter pupillae) may rarely result from neuritis associated with diphtheria, syphilis, diabetes, chronic alcoholism, cerebral or meningeal diseases, including even a mild head injury. The condition is usually bilateral.
3. *Paralysis of accommodation as a component of complete third nerve paralysis* may occur due to intracranial or orbital causes. The lesions may be traumatic, inflammatory, vascular, demyelination or neoplastic in nature.

Clinical Features

1. *Blurring of near vision.* It is the main complaint in previously emmetropic or hypermetropic patients. Blurring of near vision may not be marked in myopic patients.
2. *Photophobia* (glare) due to accompanying dilatation of pupil (mydriasis) is usually associated with blurring of near vision.
3. *Micropsia.* As a more accommodative effort is required to see near object which is then perceived to be nearer than it actually is and therefore smaller.
4. *Abnormal receding of near point* and markedly decreased range of accommodation are revealed on examination.
5. *Other signs of third nerve palsy* may be seen if paralysis of accommodation is due to third nerve paralysis.

Treatment

1. *Self-recovery* occurs in drug-induced paralysis and in diphtheric cases (once the systemic disease is treated).
2. *Dark glasses* are effective in reducing the glare.
3. *Convex lenses* for near vision may be prescribed, if the paralysis is permanent.

■ INCREASED ACCOMMODATION

■ EXCESSIVE ACCOMMODATION

The term excessive accommodation is used to describe a situation in which an individual

exerts more than the normal required accommodation for performing a certain near work. It is within the voluntary control of the individual and is an intermittent process, whereas the spasm of accommodation is continuous prolonged use of excessive accommodation.

Causes

Certain degree of excessive accommodation is frequently noted under following circumstances.

1. *Young hypermetropes* frequently use excessive accommodation as a physiological adaptation in the interests of clear vision.
2. *Young myopes* performing excessive near work may also use excessive accommodation in association with excessive convergence.
3. *Astigmatic error* in young persons may also be occasionally associated with use of excessive accommodation.
4. *Presbyopes* in the beginning use excessive accommodation to accomplish near work.
5. *Use of improper or ill-fitting* spectacles may also cause use of excessive accommodation.

Precipitating factors. A large amount of near work is an important precipitating factor for this condition, especially when the work is habitually undertaken in deficient or excessive illumination. Other precipitating factors are general debility, physical or mental ill health and early presbyopia.

Clinical Features

1. *Varying degree of blurred vision* due to induced pseudomyopia.
2. *Symptoms of accommodative asthenopia* are usually present, with headaches, and a feeling of fatigue and discomfort in the eyes themselves.
3. *Far point and near point,* both are brought nearer to the eye.
4. *Near vision difficulty* may occur in more marked cases. After reading for some time, the printed page becomes blurred, an effect which clears up only after a brief rest.
5. Macropsia.
6. Miosis.

Treatment

The treatment is usually effective and so the prognosis of such a condition is good.

1. ***Optical treatment.*** Refractive error should be corrected after carefully performing cycloplegic refraction.
2. ***General treatment***. General measures are usually more important than the optical correction and should include the following measures:
   - Near work should be forbidden for a period, and thereafter its amount should be curtailed and the conditions in which it is undertaken should be supervised.
   - The general condition of the patient's health should receive special attention, for most of those subjects are ailing or overworked or neurotic. Therefore, a holiday with a change of air usually has a greater effect than anything else.

SPASM OF ACCOMMODATION

Spasm of accommodation refers to continuous exertion of abnormally excessive accommodation, which is out of the voluntary control of the individual. The condition, also called as cyclotonia, is more common in young adults, especially myopes.

Causes

1. *Drug-induced spasm* of accommodation is known to occur after use of strong miotics such as echothiophate and di-isopropyl fluorophosphate (DFP).
2. *Spontaneous spasm* of accommodation is occasionally found in children who attempt to compensate for a refractive anomaly that impairs their vision (usually uncorrected hypermetropia but also astigmatic error and sometimes even myopia). It usually occurs when the eyes are used for excessive near work in unfavourable circumstances such as bad illumination, bad reading position, lowered vitality, state of neurosis, mental stress or anxiety.
3. *Iridocyclitis* may also be associated with ciliary spasm.
4. *Spasm of near reflex* is a characteristic clinical syndrome, often seen in tense or disturbed

individuals who present with excessive accommodation, excessive convergence and miosis.

5. *Lesions of brainstem* in their irritative phase, e.g. tabetic crisis, epidemic encephalitis and meningitis may be associated with ciliary spasm.

6. *Toxic reaction of exogenous poisons*, e.g. sulphonamides and arsenic, or even smoking can also sometimes cause spasm of accommodation.

Clinical Features

1. *Varying blurred vision* due to induced pseudomyopia.
2. *Asthenopic symptoms* are more marked than the visual symptoms.
3. *Headache* and *browache* are typical features.
4. *Near point* is abnormally close.
5. *Macropsia* may occur due to optical illusion.

Treatment

1. ***Relaxation of ciliary muscle.*** The most effective method of treatment is the production of complete ciliary paralysis with atropine, and the cycloplegia should be kept up for a long time: 4 weeks or more. Even then, the spasm, not infrequently, returns whenever the influence of the drug has passed off, when a further period of atropinization must be prescribed.
2. ***Optical treatment.*** Correcting spectacles should be worn immediately when eyes are used again.
3. ***General treatment*** similar to that described for excessive accommodation is also essential.

CONVERGENCE

Convergence is a disjugate movement in which both eyes rotate inward so that the lines of sight intersect in front of the eyes. It allows bifoveal single vision to be maintained at any fixation distance. Convergence remains more or less same throughout the life. It does not deteriorate with increasing age, as does accommodation, but may deteriorate under certain abnormal conditions. The power of convergence can be increased by exercises.

TYPES OF CONVERGENCE

Convergence is a very complex process. It may be voluntary or reflex.

Voluntary Convergence

It is the convergence of visual axes, which can be produced at will. It is not a part of normal convergence movement as it occurs in everyday vision. Voluntary convergence is thus a separate phenomenon from the reflex convergence involved in normal visual activities; not everyone is capable of doing or learning this.

Reflex Convergence

It is the convergence of visual axes, which is not under complete voluntary control. Reflex convergence has four components: tonic, fusional, accommodative and proximal convergence.

1. ***Tonic convergence***. It is the convergence that results from some inherent innervational tone of the extraocular muscles when the patient is awake. It is the sum of excitatory and inhibitory influences from different sources such as cortical centres, subcortical centres and vestibular organs. It is independent of fusion or object proximity. It is very important in determining the position of a person's eyes; i.e. under the influence of tonic convergence, the eye position will be more convergent than before, but from an absolute point of view, it will still be divergent. Tonic convergence is most prominent in childhood and decreases with age. The emotional energy level of the individual may affect tonic convergence. It disappears under deep general anaesthesia.
2. ***Fusional convergence***. Fusional convergence, also called positive fusional convergence, is the convergence that is produced to ensure that similar retinal images are projected on to corresponding retinal areas. It occurs without a change in refractive state of the eye and is initiated by a bitemporal retinal image disparity. In other words, fusional convergence implies a responsiveness to disparate stimuli lying outside the Panum's fusional area. It is not a voluntary process, but one of the *optomotor reflexes* and thus forms a kind of fusion reflex or motor fusion. Fusional vergence, in general, forms an

important mechanism for the achievement of bifoveal single vision. Fusional convergence is the most important type of convergence in the study of motor anomalies. It has been found that the amplitude of fusional convergence is greater when attention is directed between the two disparate retinal images than when the attention is directed at only one of the two images. The normal fusional convergence amplitude for distance is about 18 D and for near, it is 35 D. Fusional convergence helps to control exophoria (latent divergent squint). The fusional convergence may be decreased by fatigue or illness, converting a phoria into a tropia. The amplitude of fusional convergence can be improved by orthoptic exercises.

3. ***Accommodative convergence***. It is the convergence that occurs when the eyes accommodate or when a nerve impulse to accommodate is discharged to the eyes. Thus, the stimulus for accommodative convergence is blurred retinal images rather than the retinal disparity that stimulates fusional convergence. In fact, the accommodative convergence is a part of the *triad of synkinetic near reflex complex* – other two components of this nerve synkinesis being accommodation and miosis. The quantitative relationship between the accommodative convergence and accommodation is expressed as the accommodative convergence/accommodation (AC/A) ratio. This relationship is a linear one and is thought to be relatively stable throughout life. In it, the accommodative convergence is measured in prism dioptres and the accommodation in lens dioptres. The AC/A ratio is, therefore, expressed as so many prism dioptres per 1 D of accommodation. The normal AC/A ratio is about 3–5 prism dioptres (Δ) for 1 D of accommodation.

The fact that AC/A ratio remains almost normal in presbyopic persons indicates that it is the stimulus for the accommodation that evokes the response of accommodative convergence rather than the amount of accommodation that actually takes place. The majority of myopes have a high AC/A ratio and hypermetropes have a low AC/A ratio as compared with the emmetropes. However, there is no correlation between the degree of myopia, hypermetropia and the magnitude of AC/A ratio. The pupillary distance must also be considered in the determination of the AC/A ratio, since the convergence requirement for an individual with a wide interpupillary distance (IPD) is greater than for a patient with a narrow IPD looking at the same fixation distance.

Abnormalities of the AC/A ratio are very important causes of strabismus. A high AC/A ratio may cause excessive convergence and produce a convergent squint (esotropia, ET) during accommodation on a near object. A low AC/A ratio may cause a divergent squint (exotropia) when the patient looks at a near object.

4. ***Proximal convergence***. This component of reflex convergence is induced by the proximity of the object of regard or the awareness of the proximity of a near object. It appears to be initiated by psychological factors, since it occurs also when a subject just believes that he or she is looking at a near object, although he or she actually is not. For example, while using the haploscope optically set at infinity, proximal convergence is often induced.

There exists a linear inverse relationship between proximal convergence and the changes in fixation distance, similar to accommodative convergence. Here the change in fixation distance is expressed as changes in the vergence of light, i.e. in dioptres. Thus, a change in fixation from infinity to 1 m is a change of 1 D; as is a change from 1 to 0.5 m. It has been found that for about each dioptre of change of fixation distance, an approximate change of 1.5Δ occurs in proximal convergence.

ANGLE OF CONVERGENCE

It refers to the angle that is formed between the primary lines of sight during convergence (Fig. 4.9A). Its size depends on the fixation distance and IPD, becoming smaller with increasing distance of fixation object (Fig. 4.9B) and becoming larger with increasing IPD (Fig. 4.9C).

The effect of IPD on the angle of convergence is usually negligible and so practically it

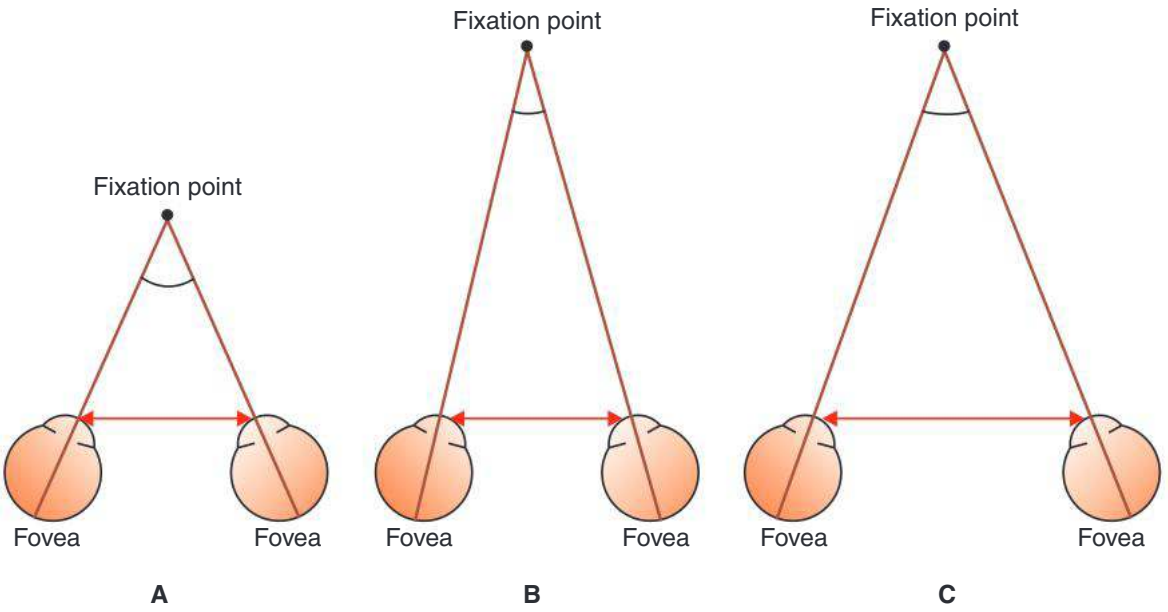


Fig. 4.9 *Angle of convergence (A) which becomes smaller with increasing fixation distance (B) and becomes larger with increasing interpupillary distance (C).*

is not taken into consideration while measuring the convergence angle. Convergence angle can be measured in metre angle or in prism dioptres.

Metre Angle

One metre angle convergence is exerted by each eye when the eyes are directed to an object at a distance of 1 m of the meridian line between the two eyes (Fig. 4.10). The convergence exerted in metre angle (ma) by each eye is inversely proportional to the distance in metres the object is in front of the eyes; i.e. it would be 0.5 ma at 2 m and 2 ma at 1/2 m (Fig. 4.10).

In an emmetropic eye, the number of dioptres of accommodation required to see an object clearly is equal to the number of metre angles through which each eye must converge to see the object singly. Thus, 1 D of accommodation is associated with 1 ma of convergence of each eye.

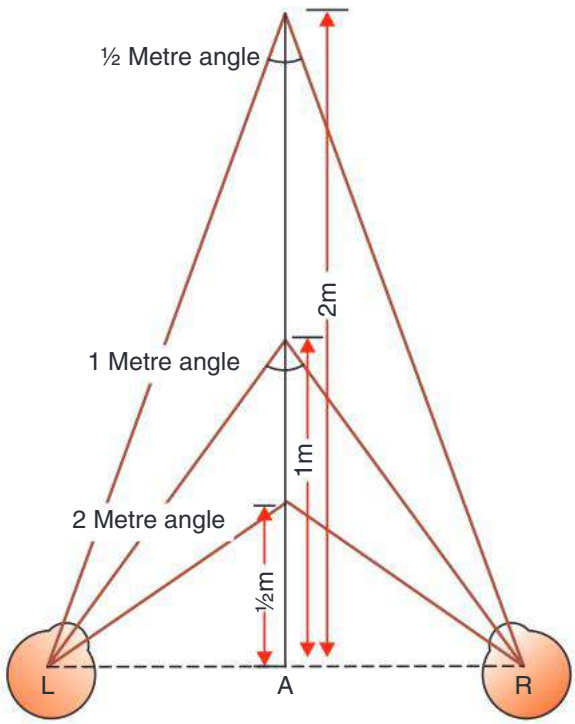


Fig. 4.10 *Convergence in metre angles.*

Convergence in Prism Dioptres

When a converging prism (base out, or BO) is placed in front of the eye, it will deviate the rays of light entering the eyeball outwards and will tend to produce diplopia. To maintain a binocular single vision, the eye will turn inwards (converged) through a corresponding degree (Fig. 4.11). The convergence required to see singly an object placed at 1 m distance from the eyes with a prism of 1Δ placed in front of one eye is called 1Δ convergence. It has been estimated that roughly 1 ma convergence is equal to 3Δ convergence.

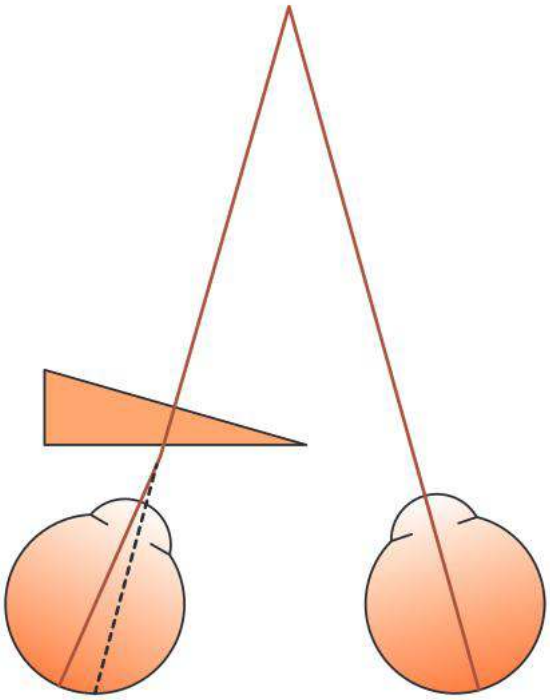


Fig. 4.11 *Convergence in prism dioptres.*

NEAR POINT, RANGE AND AMPLITUDE OF CONVERGENCE

Near point of convergence (NPC) is the closest point at which an object can be seen singly during bifoveal vision. In other words, it is the point at which the two foveal lines of sight intersect when maximum convergence is exerted. It is always closer than the NPA and is usually less than 8 cm.

Far point of convergence refers to relative position of the eyes when they are completely at rest. It is usually infinity. At rest, the eyes may be in slight divergence and so the far point of convergence may be in negative (behind the eyes).

Range of convergence is the distance between far point of convergence and NPC. The part of the range of convergence between the eye and infinity is called *positive convergence*, and the part beyond infinity, i.e. behind the eye (when eyes are in slight divergence), is called *negative convergence or divergence.*

Amplitude of convergence refers to difference in the convergence power exerted to maintain the eye in a position of rest and in a position of maximum convergence.

MEASUREMENT OF AMPLITUDE OF CONVERGENCE

1. Prism Bar Method

To perform the test for near, the patient is asked to fixate 6/12 symbol at 33 cm and the bar is used with prism base directed out (BO). By progressively increasing the amount of BO prism power, the eyes are converged to the limit of bifoveal single vision, i.e. up to the point when the patient just appreciates diplopia. This point is the end point of the test and is called the *break point*. Its reading is recorded. At this point, the power of the prism is decreased slowly until diplopia disappears. This point, called the *recovery point*, is also recorded. Theoretically, before the break point, there will be a blur point because after the exhaustion of the fusional convergence, the patient starts using his or her accommodative convergence to avoid diplopia. This, however, can only be done by accommodating in excess of the requirements for the given distance (pseudomyopia), and consequently the image is blurred. Therefore, it is important to record the *blur point* in order to know what kind of fusional amplitudes are measured.

To perform the test for distance, the same procedure is repeated at 6 m, and the blur point, break point and recovery point are recorded.

An example of a recording of fusional amplitudes as tested with the prism bar:

- *Distance*: Diverged to 12Δ BI/recovered at 9Δ BI; converged to 32Δ BO/recovered at 21Δ BO; blurred at 12Δ BO.
- *Near*: Diverged to 14Δ BI/recovered at 9Δ BI; converged to 36Δ BO/recovered at 24Δ BO; blurred at 18Δ BO.

2. Synoptophore Method

To begin with, the objective angle of deviation is determined using simultaneous macular perception slides. Then, the second-grade fusion slides (similar targets with control marks for each eye) are introduced, and if the patient fuses these targets and sees them as one with both control marks, the examiner blocks the arms at the objective angle. Then, first the

amplitude of divergence and second the amplitude of convergence is measured as discussed below.

To measure the divergence, the arms of the synoptophore are slowly diverged and the patient is instructed to report occurrence of diplopia or the disappearance of one or the other control mark of the picture (suppression). This point – the *break point* – is recorded and the arms of the synoptophore are slowly converged (i.e. brought to less divergent position) and the *recovery point* where fusion occurs is noted.

To measure the convergence, the arms of the synoptophore are further converged slowly till the fusion breaks and the *break point* is noted. Then, the arms are moved back into a less convergent position until fusion is regained and the *recovery point* is noted.

To measure the amplitude of vergences for near with synoptophore, a –3.0 DS lens is placed before each eye. In order to see clearly with –3.0 DS lens, the subject has to overcome these lenses by accommodating as if he or she were fixating an object at a distance of 33 cm. To simulate the orthoposition for near fixation, the synoptophore tubes have to be set according to the convergence requirement for a point at a distance of 33 cm which, in prism dioptres, is three times the patient's IPD in centimetres.

The procedure of testing for near is the same as that for distance.

Normal values of vergences are as follows:

Vergence	Distance (6 m)	Near (33 cm)
Convergence	14–20Δ	35–40Δ
Divergence	5–8Δ	15–20Δ
Vertical vergence	2–4Δ	2–4Δ
Incyclovergence	10–12Δ	10–12Δ
Excyclovergence	10–12Δ	10–12Δ

An example of a recording of fusional amplitudes as tested with the synoptophore:

Distance:
- 30Δ ET, objectively and subjectively
- First- and second-grade fusion at angle
- Convergence to 42Δ BO/recovery at 32Δ BO
- Divergence to 12Δ BO/recovery at 20Δ BO

Near (with –3.0 D):
- 44Δ ET, objectively and subjectively
- First- and second-grade fusion at angle
- Convergence to 56Δ BO/recovery at 44Δ BO
- No divergence past angle, suppression OD (oculus dexter)

MEASUREMENT OF NPC

The NPC is the closest point at which an object can be seen single during bifoveal vision. In other words, it is the point at which the two foveal lines of sight intersect when maximum convergence is exerted.

The NPC practically measures all types of convergence, since an object actually approaches the eyes during testing. That is, the test for NPC simultaneously stimulates fusional, accommodative and proximal convergence and during the last phase, if the patient is cooperative, there will be a strong voluntary effort to converge.

Instruments. The NPC can be measured simply with the help of a graded plastic rule placed at the outer canthus and a fixation target (e.g. tip of a sharp pencil) moved towards the eye; or by use of specially designed rule such as RAF rule (Fig. 4.7), Livingstone binocular gauge and Prince rule. These specially designed instruments basically consist of a bar or rule made from plastic, metal or wood on which a rider with the test chart can be moved back and forth (fixation target). At one end of the bar is a wing-like support that fits over the nose and rests against the lower orbital margins during the measurement. In Prince rule, the bar is 24 in long and 1/2-in square that has different markings on each of its four sides. One side is divided into centimetres (to be used for measurement of NPC and NPA), the second one into inches, the third one into dioptres (for NPA in dioptres) and the age is indicated in years on the fourth side. The sliding target contains targets for measuring NPA and NPC.

Procedure. For measurement of convergence, a dot or a vertical line may be used as the target. It is advanced towards the patient at, or slightly below, the eye level, until the patient has converged maximally and cannot sustain single

bifoveal fixation as the target is brought closer. At this break point, the subject's non-dominant eye will diverge (*objective test*) and the patient may appreciate diplopia (*subjective test*). The distance from the canthus to this point is read on the rule and the NPC is recorded in millimetres or centimetres. Some of the near point rules have the zero point of their scales at the so-called spectacle point (i.e. 27 mm in front of the baseline). Therefore, with such instruments, 27 mm must be added to the distance that is read off the scale.

Normal values. The normal values of NPC vary considerably among different persons and even in different examinations of the same person. In normal adults, its average value is 70 mm (7 cm) with a range between 50 and 100 mm (5–10 cm). A distance closer than 5 cm is excessive; however, in children, it may be as close as the tip of the nose. NPC farther away than 10 cm is defective or remote. In patients with convergence insufficiency, it may be as remote as 25 or 30 cm or more.

AC/A RATIO

The AC/A ratio is the relationship between accommodative convergence (AC), expressed in prism dioptres (Δ), and accommodation (A), expressed in lens dioptres (D). This relationship is linear one and is thought to be relatively stable throughout life. The normal AC/A ratio is about 3–5Δ for 1 D of accommodation. The concept of AC/A ratio was first clearly defined by Fry, who later with Haines introduced the abbreviation AC/A ratio. The ratio AC/A can be transiently altered by optical or pharmacological or modified by surgical means.

Methods of Measurement of AC/A Ratio

1. Heterophoria Method

To measure AC/A ratio, the deviation is measured with full optical correction at 6 m distance and at 33 cm distance in prism dioptres, and IPD is measured in centimetres. Then the AC/A ratio is calculated from the following formula:

$$AC/A = IPD + \Delta n - \Delta d/d$$

where:

- IPD is interpupillary distance in centimetres.
- Δn is deviation at 33 cm or 3 D distance in prism dioptres.
- Δd is deviation at 6 m distance in prism dioptres.
- d is the fixation distance at near in dioptres.

Note. Esodeviations are denoted by positive (+) and exodeviations by negative (–) signs.

For example, if IPD = 6 cm, Δn = 9Δ exophoria and Δd = 3Δ exophoria, then

$$AC/A = 6 + [-9 - (-3)]/3 = 4\Delta/D.$$

2. Gradient Method

This method is based on the fact that for a given fixation distance, minus lenses placed before the eyes increase the requirement for accommodation and plus lenses relax accommodation. Further, it is assumed that –1.0 D lens produces an equivalent of 1.0 D of accommodation, whereas +1.0 D lens relaxes accommodation by 1.0 D.

In practice, original deviation is found at near while the patient wears his or her optical correction and then with additional +3.0 D lens, and the calculations for AC/A ratio are made as follows:

$$AC/A = \Delta L - \Delta O/D$$

where:

- ΔL is deviation with additional lenses.
- ΔO is original deviation without additional lenses.
- D is dioptric power of the additional lenses.

For example, if original deviation (ΔO) = 2Δ esophoria, deviation with additional lenses (ΔL) = 10Δ exophoria and the power of additional lenses (D) used is +3 D, then:

$$AC/A = [2 - (-10)]/3 = 4\Delta/D$$

Alternatively, the patient's original distance phoria (ΔO) is determined while he or she wears full optical correction. A –3.0 D lens is then placed before the patient's eyes and the distance deviation (ΔL) is measured once more.

The AC/A is calculated as above. The AC/A ratio computed by the heterophoria method is usually larger than the one obtained with the gradient method, mainly because of the effect of proximal convergence. It is considered that the gradient method gives a true estimate of the AC/A ratio.

Note. The gradient method is inaccurate because it does not take into account the patient's IPD.

3. Fixation Disparity Method

This method has been used extensively by Ogle and coworkers. In this method, AC/A ratio is indirectly derived from the fixation disparity induced either by forced convergence by use of prism or by altering the accommodative stimulus by use of optical lenses. Because of its complexity, this test is not performed in routine clinical practice.

4. Haploscopic Method

In haploscopy, the visual fields of the two eyes are differentiated and a separate target is presented to each eye. Hering's original instrument was designed primarily for studying the AC/A ratio. In practice, this method is no more used. However, the haploscopic devices, such as the major amblyoscope, are of fundamental importance for the study of the sensorimotor cooperation of the eyes.

ANOMALIES OF CONVERGENCE

CONVERGENCE INSUFFICIENCY

Convergence insufficiency is the inability to obtain and/or maintain adequate binocular convergence for any length of time without undue effort. It is the most common cause of ocular asthenopic symptoms.

Aetiology

1. ***Primary or idiopathic.*** In many cases, exact aetiology of convergence insufficiency is not known. It may be associated with a wide IPD and delayed or inadequate functional development. General debility, psychological instability, overwork and worry may be the precipitating factors.
2. ***Refractive errors.*** Convergence insufficiency may be associated with uncorrected high hypermetropia and myopia. Diseases of accommodative convergence mechanism result in convergence insufficiency in such patients as follows:
   - *High hypermetropes* (more than 5 D) usually make no effort to accommodate and thus there is deficient accommodative convergence as well.
   - *Myopes* may not need accommodation and thus lack accommodative convergence.
   - Patients who have worn too full a plus spherical correction may also exert less accommodation and thus less accommodative convergence.
3. ***Presbyopia.*** With advent of presbyopia, the near point of eye recedes and so there is less use of convergence. Neglect of presbyopia may lead to fixation of this anomaly.

On the other hand, patients may also develop convergence insufficiency with the first-time use of presbyopic correction. This has been explained by the fact that the relief of sustained accommodative effort afforded by the use of presbyopic correction causes a decrease of accommodative convergence.

4. ***Muscular imbalances.*** Extraocular muscular imbalances in the form of exophoria, intermittent exotropia and vertical muscle imbalances, if neglected for a long time, may be associated with convergence insufficiency.
5. ***Consecutive convergence insufficiency*** may occur following either recession of medial recti muscles or resection of lateral recti muscles.

Clinical Features

Convergence insufficiency becomes a clinical problem in children with increased schoolwork, prolonged periods of reading, desk workers and precision workers. It is usually not a problem in farm- and manual-labour workers.

Symptoms of convergence insufficiency are similar to that of heterophoria, and in general, the term *asthenopia* is used to denote the symptom complex. Unsuitability of the glasses is the most frequent complaint of patients using glasses and having asthenopic symptoms. Such

patients change their refractionist and glasses frequently without any satisfaction. Asthenopic symptoms may be grouped as follows:

1. ***Symptoms of muscular fatigue.*** These results due to continuous use of the neuromuscular power and are usually marked with near work. These include the following:
   - *Eye strain and a sensation* of tension in and around the globes is a common complaint of such patients.
   - *Headache and eye ache* after prolonged use of eyes especially for near work, which are relieved when the eyes are closed for a while. Some patients may show even migrainous tendencies.
   - *Difficulty in changing the focus* from distant to near objects.
   - *Itching, burning and soreness* of eyes and even hyperaemia of the nasal half of the conjunctiva may occur after prolonged close work.
2. ***Symptoms due to failure to maintain binocular vision.*** These include the following:
   - *Blurred near vision* and crowding of words while reading.
   - *Intermittent crossed diplopia* for near vision under conditions of fatigue is not uncommon.
   - *Characteristically, one eye will be closed* or covered while reading to obtain relief from VF.

Diagnosis

Diagnosis of convergence insufficiency is confirmed by the following:

1. ***Remote NPC.*** Convergence insufficiency is said to exist, if NPC is more than 10 cm from the baseline.
2. ***Decreased fusional convergence for near.*** When measured on synoptophore, the convergence insufficiency is said to exist, if there is difficulty in attaining 30 degrees of convergence. Fusional convergence amplitudes less than 15–20 at near are due to convergence insufficiency.
3. ***Prism convergence*** is low but prism divergence is normal.
4. ***Exophoria*** at near with orthophoria at distance may occur. However, convergence insufficiency may be associated with orthophoria and even exophoria. It is important to measure the exodeviation in all positions of gaze to rule out any eye muscle imbalance that could make the exodeviation greater in downgaze. Measurements at near should be done in both primary position and reading position. Superior oblique overaction can cause an exodeviation greater in downgaze and can be mistaken for convergence insufficiency.
5. ***NPA*** is normal and corresponds to the age of the patient. However, measurement of NPA is essential in each case to diagnose and manage patients suffering from a combined insufficiency of convergence and accommodation. Further, rarely accommodative spasm may occur, if voluntary accommodation and convergence are stimulated in an effort to overcome the convergence insufficiency.

Differential Diagnosis

Convergence insufficiency needs to be differentiated from the following conditions presenting with almost similar symptoms.

1. ***Convergence insufficiency versus convergence paralysis***
   - In convergence paralysis, there is total lack of ability to overcome any amount of BO prism, whereas in convergence insufficiency, several dioptres of convergence amplitude can be demonstrated.
   - On receiving a convergence impulse, a patient with convergence paralysis will show pupillary constriction but inability to converge; in a patient with convergence insufficiency, pupillary constriction will occur while converging on an approaching target, followed by dilation of the pupil when convergence can no longer be maintained.
2. ***Convergence insufficiency versus accommodative effort syndrome***
   - Usually an exophoria at near is associated with convergence insufficiency, while patients with accommodative effort syndrome have esophoria.

- Convergence insufficiency is helped by the –3 D test, which compensates for the lack of good fusional convergence, whereas a patient with accommodative effort syndrome breaks into a tropia during this test.
- Plus lenses will worsen the convergence insufficiency due to relaxation of accommodative convergence, while they will improve the symptoms in the accommodative effort syndrome for the same reason.

Treatment

Convergence insufficiency has an excellent prognosis in the majority of cases. *Children* are treated when fusional vergences are poor and the patient is showing signs of becoming exotropic. *Adults* with this condition receive treatment only in the presence of symptoms. *Treatment* of convergence insufficiency includes optical treatment, orthoptic treatment, prismotherapy and surgery.

1. Optical Treatment

Proper refraction should be carried out and the correct glasses should be prescribed for any associated refractive error. Myopes are given full correction and hypermetropes undercorrection to stimulate their accommodation, which will simultaneously stimulate convergence. In adults older than 40 years, proper presbyopic correction should also be done.

2. Orthoptic Treatment

First documented by von Graefe in 1855, these orthoptic exercises' aim is to improve the binocular convergence and to increase the amplitude of fusional convergence. By and large, orthoptic treatment for convergence insufficiency is same as for exophoria and includes the following exercises.

a. Exercises to Improve NPC

i. ***Advancement exercise.*** It is a good convergence exercise, which can be done at near. In it, patient is asked to hold a target (preferably a small detailed picture or fine print) away from the nose where fusion is possible. He or she is asked to slowly advance the target towards the nose until physiological diplopia is appreciated. At this point, one is asked to stop and try to converge more and, thus, to unite the two images again. If one cannot do this, one should move the target back to a small distance to get single vision and then try to bring it closer again. This should be repeated until the patient can converge to his or her nose or at least reasonably close to it. If a patient suppresses an image from one of their eyes, then a red filter can be used over one eye as an antisuppression technique. Caution to be taken that intractable diplopia does not occur.

ii. ***Jump convergence exercise***. Jump convergence is more elaborate and more effective form of the 'picture-to-nose' convergence exercise. It trains the patient to achieve bifoveal single vision following a sudden change in the convergence requirement. This is usually possible only after convergence has been improved to some extent by other exercises and, therefore, is not used before the fourth week of convergence training, depending upon the progress. This exercise may be carried out by any of the following methods.

b. Exercises to Increase Amplitude of Fusional Convergence

i. ***Convergence exercise with prisms.*** It is similar to that described for esophoria, except that in it prisms are placed BO in front of the eyes. While the patient is performing this exercise, the orthoptist should watch the patient's eyes to make certain that he or she is converging and has not diverged and suppressed.

ii. ***Convergence exercise using synoptophore.*** It is performed as described for esophoria, except that in it the instrument arms are slowly converged, beginning at an angle at which the patient can fuse the picture.

iii. ***Exercises using convergence card.*** Convergence card consists of dots on either side; so it is also known as physiologic dot card. On one side of the card, dots are coloured red and on the other side, blue. Dots identical in size are in the same place on each side of the card and these are of three sizes: large, medium and small.

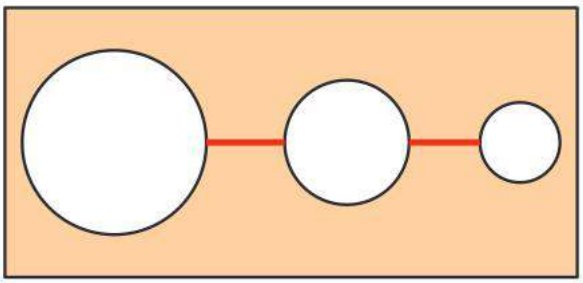


Fig. 4.12 *Convergence card.*

To perform the exercise, the card is put in front of the patient's eyes with one end of the card resting on the nose, with the large dots farthest away, so that he or she will see the red dots with one eye and the blue with the other eye. The patient is instructed to look at the large dots and to see them fused or blended together, then the middle dots and finally the smallest ones. The patient must be aware of heteronymous physiologic diplopia on those dots between his or her eyes and the fused ones, and of homonymous physiologic diplopia on those beyond the fused one.

With the use of convergence card, there is a great deal of retinal rivalry. If the patient is unable to do the exercises as instructed above, it may be easier for him, if the three dots are connected with a black line on both sides of the card (Fig. 4.12). Now, when fixating on the large size dots, he or she should see the lines as ∧. When the patient is able to fuse the large dots easily, he or she may then fixate on the middle-sized dots and see the black lines as X. Lastly, he or she should fixate the small-sized dots and see the black lines as ∧.

iv. ***Physiologic diplopia exercise using stereogram in the uncrossed position.*** To perform this exercise, the stereogram card is held at arm's length in front of the patient and a pencil (fixation point) is placed midway between the eyes and the card. When one looks at the pencil, one will notice diplopia (uncrossed) of the card and will see four instead of two pictures. The patient is trained to adjust the position of the pencil in such a way that the two central pictures are joined into one, so that now he or she sees three pictures (Fig. 4.13). The patient is trained to see

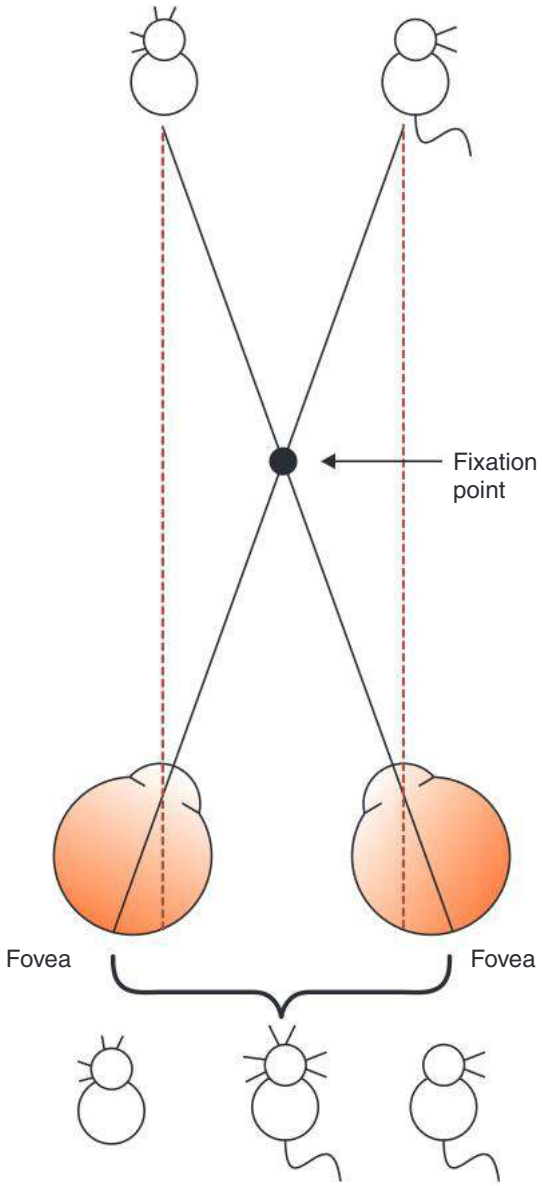


Fig. 4.13 *Physiologic diplopia exercises using stereogram in the uncrossed position.*

the fused central picture clearly. In doing so, one is converging for the fixation object and accommodating for the distance of the card; i.e. one is converging relatively more than one is accommodating. The patient can practise this exercise at home for a few minutes several times a day.

v. ***Computer-based convergence exercises.*** A computer-based orthoptic program CVS (computer vergence system). The program uses random dot stereograms to form picture that require fixation to stimulate the vergence system. The program gradually increases the amount of convergence required to appreciate the picture.

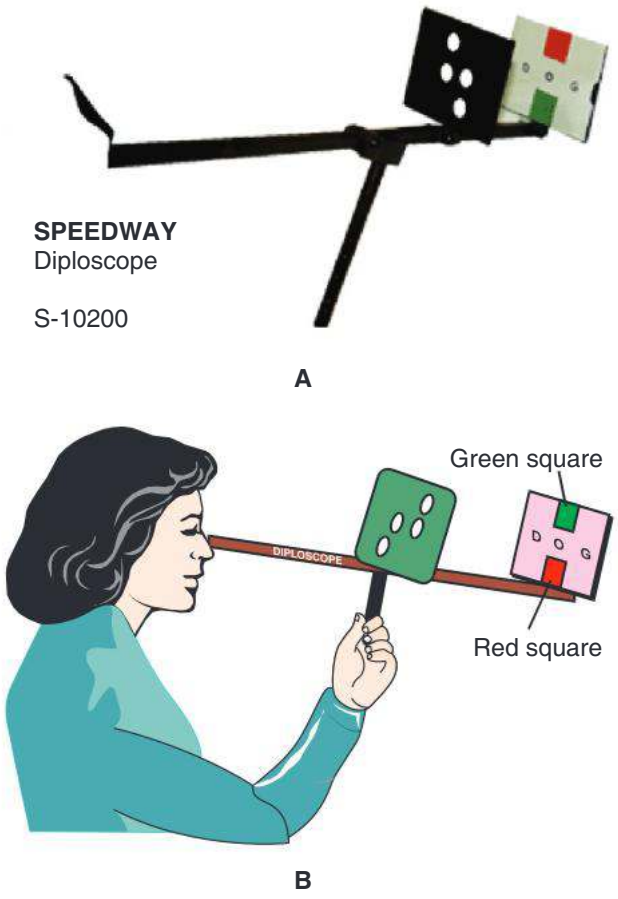


Fig. 4.14 *Diploscope (A) in use (B).*

vi. ***Convergence exercise using diploscope.*** The main use of the instrument (Fig. 4.14) is to exercise for relative convergence when binocular single vision is present. To perform exercise, the patient is asked to move his or her eyes in relation to septum and card at four different positions (described below). As the patient does so, he or she sees a change in the relative position of the letters and colours as perceived by each eye simultaneously. This movement of letters into a definite pattern is utilized in training the patient to appreciate and control the position to which his or her eyes are directed. Thus, it teaches the patient to switch easily from distant to near fixation and vice versa, thus improving the fusional amplitudes, which are essential for a comfortable binocular single vision.

Procedure. The four positions of fixation and the various kinds of physiological diplopia when practising with the diploscope are as follows (Fig. 4.15).

- ***Position 1.*** The point of fixation is central letter O on the card. In this position, letter D falls on a point temporal to the fovea in the right eye and is projected to the left of O, while G falls on point temporal to the fovea in the left eye and is projected to the right of O. Thus, the letters DO are seen with the right eye and the letters OG with the left eye and in the presence of binocular single vision, the patient will perceive three holes with the word DOG in them.
- ***Position 2.*** The second point of fixation is the centre of metal septum midway between the two horizontally placed holes (Fig. 4.15). When the patient's eyes converge on this point, the images of O no longer fall on both fovea, but on a retinal element nasal to the fovea in each eye. Consequently, the O will be seen in uncrossed (homonymous) diplopia and the patient sees DO and OG. When the patient will exert a greater amount of convergence, one may see only D G, because the D and O, and the G and O will overlap.
- ***Position 3***. The point of fixation is the tip of a pencil or other object held midway between the septum and the patient's eyes. When the patient's eyes converge on this point, the images of both D and O in the right eye and G and O in the left eye fall on a retinal element nasal to the fovea in each eye and thus will be projected temporally, and the patient will see OGDO on the card.
- ***Position 4***. The point of fixation is an object (such as a picture on the wall) situated beyond the printed card. When the patient fixates at this distant point, the images of D and O, and G and O fall on retinal element temporal to the fovea in each eye and thus will be projected nasally, and the patient will see D O G.

Note. The aim of exercise with diploscope is to teach the patient to obtain and maintain all four positions with ease, so that effortless convergence and divergence is fully established. It is advisable to practise for 2–3 min for two to three times a day. Position 4 is quite useful in

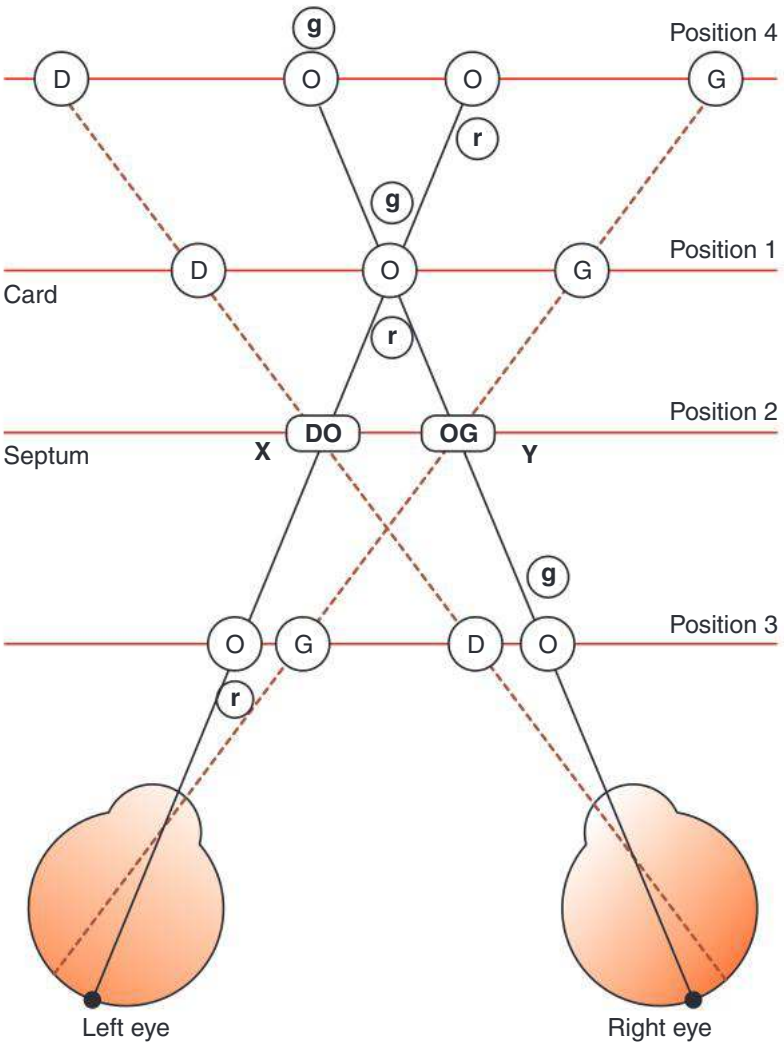


Fig. 4.15 *Principle of diploscope and observations made by the patient while in use at positions 1, 2, 3 and 4. For explanation, see text.*

improving the fusional divergence (fusional negative convergence).

c. Training of Voluntary Convergence

It is very helpful, if the patient is intelligent and cooperative. It aims at developing the control of the position of eyes. The patient is made to understand physiological diplopia which he or she practises. If a finger is brought in the field of vision while the patient is fixing a distant light, there will appear two fingers. Now, if the patient fixes at the finger, then there will appear two lights at the distance. While the finger is moved to and fro, the distance between the lights increases or decreases. Patient is asked to maintain the two lights apart as long as possible. The finger may again be brought in, if the two lights become single as soon as the finger is removed. This exercise is completed when the patient is able to double the lights without the aid of the finger. Development of voluntary convergence goes a long way in relieving symptoms.

d. Relaxation Exercises

Relaxation using relative negative convergence may be carried out after the treatment by any of the following methods:

i. ***Physiologic diplopia exercises using stereograms in the crossed position.*** To perform this exercise, the patient is first trained to appreciate

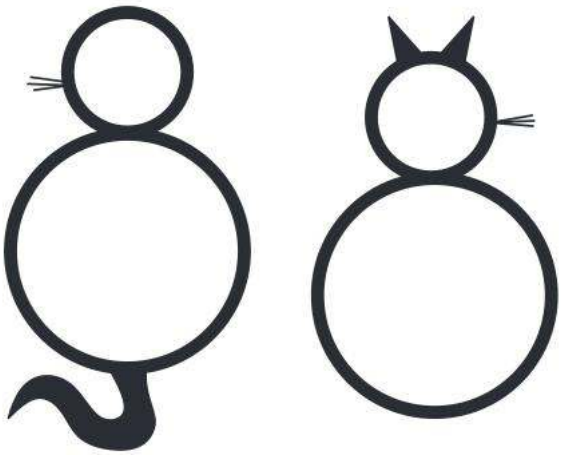


Fig. 4.16 *Stereogram card.*

crossed physiological diplopia with a flash light or pencil. Once the patient is trained, the exercise is performed as given below.

While the patient is fixating a distant object, the stereogram card (Fig. 4.16) is held about 25 cm in front of his eyes. Patient will perceive four pictures (because of crossed physiological diplopia). He or she is trained to adjust its position until the two central pictures are fused and patient perceives three pictures (Fig. 4.17). The patient is trained to maintain the joined pictures and to see it clearly. While doing so, the patient is converging for the distant target but accommodating for near (distance of the card) and thus relatively relaxing his or her convergence.

Once the patient is trained to perform this exercise, one can practise at home for a few minutes several times a day.

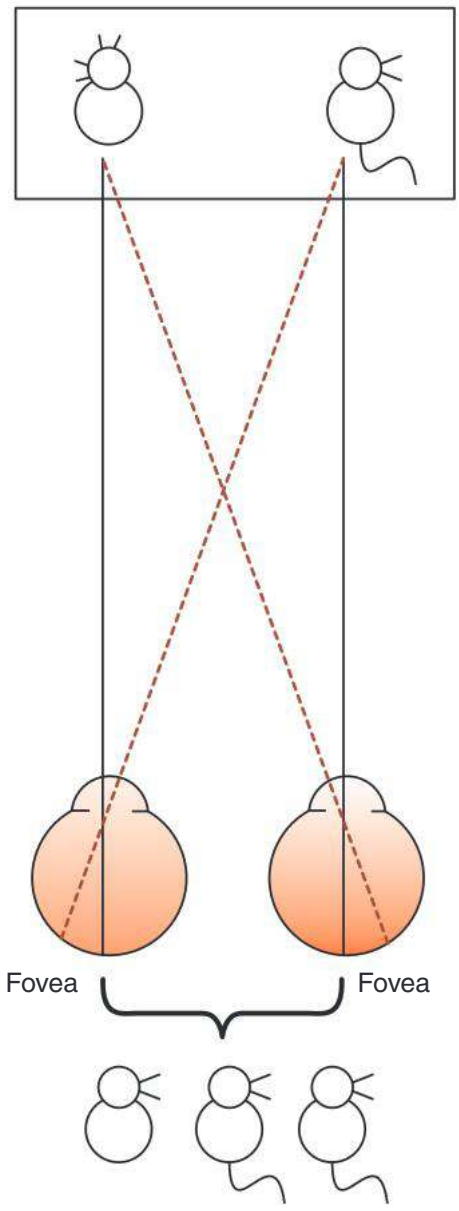


Fig. 4.17 *Physiologic diplopia exercises using stereogram in the crossed position.*

ii. ***Divergence exercises on synoptophore.*** These exercises are performed on synoptophore using stereopsis slides, because they provide the strongest stimulus to fusion. After fusing the two pictures, the patient is trained to maintain a single vision (by relaxing convergence) while the instrument tubes are diverged. These exercises should be performed for about 5 min at each weekly visit.

iii. ***Divergence exercises with prisms.*** Prisms of increasing strength are placed BI before one eye while the patient is fixating an object at any distance (preferably at a distance where the esophoria is maximum). The patient is trained to maintain a single vision by relaxing the convergence.

Loose prisms, a prism bar or rotatory (Risley) prisms may be used for this purpose. A prism bar should be preferred. Prism exercises are performed for a few minutes at each weekly visit.

Criteria for good orthoptic management:

- The patient should be symptom free.
- There should be good binocular convergence.

- Voluntary convergence should be possible easily.
- The patient should have good fusional reserves.

3. Prismotherapy

When all the exhaustive orthoptic exercises fail, then prismotherapy may be tried to relieve symptoms.

- *BI prism* reading glasses or bifocals with prism in the lower segment are useful as relieving prisms.
- *Relieving prisms and bifocals* in young age should be avoided.

4. Surgical Treatment

As a last resort, when all other measures fail, especially when convergence insufficiency is associated with a large exophoria at near vision, medial rectus muscle resection can be performed in one or both eyes. In some cases, exophoria at near fixation tends to recur.

CONVERGENCE INSUFFICIENCY ASSOCIATED WITH ACCOMMODATIVE INSUFFICIENCY

Convergence insufficiency in some patients may be secondary to accommodation insufficiency. Therefore, before treating the patient for a functional convergence insufficiency, it is important to rule out associated accommodation insufficiency.

Aetiology

Secondary convergence insufficiency associated with primary accommodation insufficiency has been reported to occur in following conditions:

1. Early Adie syndrome,
2. Sequelae to head trauma, particularly posterior occipital or whiplash injury,
3. Subclinical viral encephalopathies,
4. Infectious mononucleosis,
5. Diphtheria and
6. As a conversion reaction.

Clinical Features

1. Symptoms of the patients are similar to those of functional convergence insufficiency.
2. NPC is reduced.
3. NPA is reduced drastically.
4. AC/A ratio may be low or even absent.

Treatment

1. ***Orthoptic exercises*** alone are usually not much effective. Exercises need to be combined with reading glasses.
2. ***Plus lenses for reading and BI prism*** is the treatment of choice. The reading spectacle prescription should be titrated according to patient's need. The minimal power necessary to achieve comfortable vision should be prescribed. Fresnel membrane prisms glued on glass lenses in the lower segment of bifocals may be useful, since a frequent change may be necessary before the final adjustment is made. Alternatively, two-piece executive bifocals with decentred plus lenses for prism power in the lower half may be prescribed.
3. ***Surgery*** is usually not indicated for this condition. However, it has been reported that resection of medial rectus muscles followed by prescription of bifocal adds may be helpful in untreatable cases.

CONVERGENCE PARALYSIS

Convergence paralysis refers to a total lack of ability to overcome any amount of BO prisms. It is an uncommon entity and should not be confused with functional convergence insufficiency, which is very common.

Aetiology

Convergence paralysis occurs secondary to some organic diseases of the brain in the region of corpora quadrigemina or the nucleus of third cranial nerve. The organic brain lesions reported to be associated with convergence paralysis are as follows:

- Head injury,
- Encephalitis,
- Disseminated sclerosis,
- Tabes dorsalis,
- Narcolepsy and
- Tumours.

Clinical Features

Convergence paralysis is characterized by following features:

1. *Convergence* is completely absent. There is acute onset of convergence failure.
2. *Exotropia and crossed diplopia* occurs on attempted near fixation only.
3. *Adduction* is normal.
4. *Accommodation* is usually normal. But in some cases, it may be reduced or even absent.

Parinaud syndrome refers to convergence paralysis associated with vertical gaze paralysis.

Pretectum-posterior commissure syndrome (dorsal midbrain syndrome) which is commonly caused by tumour in the pineal region includes:

- Convergence paralysis,
- Vertical gaze paralysis,
- Pupillary areflexia to light with light near dissociation,
- Bilateral fourth nerve paralysis may be present sometimes and
- Lid retraction may also occur in some patients.

Diagnosis

Bielschowsky's criteria for diagnosis of the convergence paralysis include (1) evidence of intracranial disease, (2) history of sudden onset of crossed horizontal diplopia at near fixation, (3) reproducible findings on subsequent examinations and (4) preservation of accommodation and pupillary reaction on attempts to converge.

Differential Diagnosis

Convergence paralysis can be differentiated from functional convergence insufficiency by use of BO prisms. A patient with convergence paralysis will immediately have diplopia, while in convergence insufficiency several dioptres of convergence amplitude can be demonstrated.

Treatment

1. *BI prisms* are prescribed at near to alleviate the diplopia at near.
2. *Plus lenses with BI prisms* may be required in patients having weakness of accommodation.
3. *Occlusion of one eye* at near may be indicated in patients where it is not possible to restore comfortable single binocular vision.
4. Eye muscle surgery is contraindicated in this condition.

CONVERGENCE SPASM

Convergence spasm refers to a condition characterized by intermittent episodes of maximal convergence usually associated with spasm of accommodation.

Aetiology

1. ***Functional causes.*** It has been reported that in most of the cases, convergence spasm is functional in origin. It occurs in patients with hysteria or neurosis.
2. ***Organic causes.*** Rarely, convergence spasm may be secondary to some underlying organic lesion. It has been reported to occur after head trauma, encephalitis, tabes, pituitary adenomas, posterior fossa neurofibroma and Arnold–Chiari malformation.

Clinical Features

In most of the cases, the condition is episodic. In between the attacks, patients are normal. During the episode of convergence spasm, a patient may exhibit following clinical features:

1. *Extreme convergence.* Eyes may be fixed in a position of extreme convergence resembling bilateral abducens palsy.
2. *Homonymous diplopia* may be experienced. The patient may give history of intermittent diplopia.
3. *Blurring of vision.* During the attack, the patient may have blurred vision for near due to associated spasm of accommodation. The patient may come with a complaint of difficulty in reading.
4. *Miosis.* Pupils usually become miotic as a part of near reflex.
5. *Induced myopia* to the tune of 6 D (confirmed by retinoscopy) has been reported due to associated spasm of accommodation. Thus, during the attack, the patient may also have a reduced distance visual acuity.

Psychiatric examination may reveal the underlying hysteria and neurosis in many cases.

Management

Neurological evaluation. Organic lesions are a rare cause of spasm of convergence; however, each patient should undergo detailed neurological evaluation to rule out associated condition, if any.

Treatment of functional spasm of convergence includes the following:

1. *Prolonged atropinization with plus lenses* in lower segment of bifocals for near work may be required to break the cycle.
2. *Alternate monocular occlusion* may be considered as an alternative to atropinization.
3. *Psychiatric workup and therapy* is useful as a long-term measure.

5 Clinical Refraction: Determination of the Errors of Refraction

Chapter Outline

INTRODUCTION

The procedure of determining and correcting refractive errors is termed as *clinical refraction*. It is an art that can only be mastered by practice. The clinical refraction comprises two complementary methods:

- Objective refraction and
- Subjective refraction.

However, in clinical practice, the refraction is incomplete without the estimation and correction of associated muscle imbalance. Therefore, in this chapter, the determination of muscle balance has also been dealt along with the determination of refractive errors.

OBJECTIVE REFRACTION

In objective refraction, the examiner determines the type and degree of refractive error without the active participation of the patient. Objective refraction is not only useful but also

often essential, e.g. when examining young children and patients with poor communication due to mental or language difficulties. The findings of objective refraction should always, wherever possible, be checked subjectively, and the most comfortable lenses should be prescribed to the patient. The final refraction of the patient is much easier and is completed quickly, if it is based on an objective estimate instead of it being only the subjective technique.

Objective methods of refraction include the following:

A. Retinoscopy,
B. Autorefractometry,
C. Photorefraction and
D. Electrophysiological method of objective refraction.

A. RETINOSCOPY

PRINCIPLE

Retinoscopy, introduced by Bowman in 1859, is also known as *skiascopy* or *shadow test or pupilloscopy or korescopy*. It is an objective method of finding out the error of refraction by utilizing the technique of neutralization. It is based on the fact that when light is reflected from a mirror into the eye, the direction in which the light will travel across the pupil will depend upon the refractive state of the eye.

OPTICS

In retinoscopy, an area of the fundus is illuminated by the light reflected into the patient's eye with the help of a retinoscope. This illuminated area serves as an object and the rays which emanate from this area illuminate the pupillary area (in practice, known as reflex or shadow in the pupillary area) and form its image at the far point of the eye. When the immediate source of light is moved across the eye, the behaviour of the luminous reflex in the pupil will depend upon the refractive status of the eye.

Thus, for the purpose of understanding, the detailed optics of retinoscopy can be considered in three stages:

1. Illumination of the subject's retina (*illumination stage*),
2. The reflex imagery of this illuminated area formed by the subject's dioptric apparatus (*reflex stage*) and
3. The projection of the image by the observer (*projection stage*).

ILLUMINATION STAGE

The optics of illumination stage of retinoscopy is basically the understanding of the concept of immediate source of light and the movement of the illuminated area of the fundus with the movement of the reflecting mirror, as summarized below:

- *Immediate source of light* (S_1) refers to the image of original light source (S_0) formed by the reflecting mirror.
- *When a plane mirror is used to reflect the light,* the immediate source of light (S_1) moves against the movement of the mirror; i.e. when the mirror is moved upwards, the immediate source of light moves downwards (S'_1) and vice versa (Fig. 5.1).
- *When a concave mirror is used to reflect the light,* the immediate source of light (S_1) moves with the movements of the mirror; i.e. when the

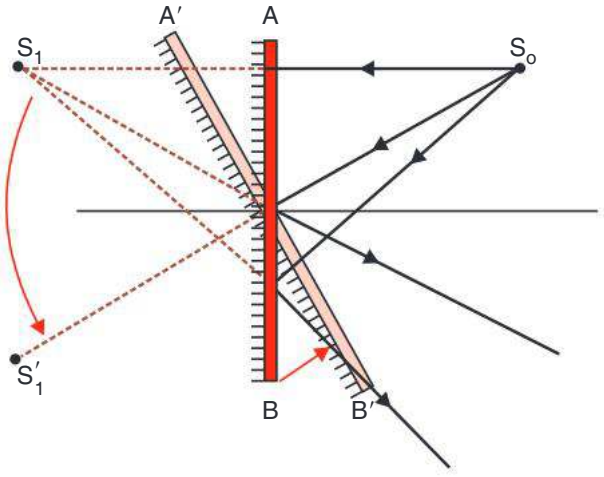


Fig. 5.1 *Movement of immediate source of light (S_1) in opposite direction to the movement of plane mirror.*

mirror is moved upwards, the immediate source of light also moves upwards (S'_1) and vice versa (Fig. 5.2).

- When the immediate source of light (S_1) moves downwards (S'_1) (with the upwards movement of plane mirror retinoscope), the illuminated spot of fundus (F_1) moves upwards (F_2) and vice versa (Fig. 5.3).

THE REFLEX STAGE AND PROJECTION STAGE

As mentioned earlier, the illuminated patch of fundus can now be considered as an object in its own right and will form an image at the far point of the subject's eye. The light rays reflected back from the illuminated area of the fundus also form a reflex shadow in the pupillary area of the subject (*reflex stage*), which is observed by the examiner by aligning his or her eye with these light rays (*projection stage*).

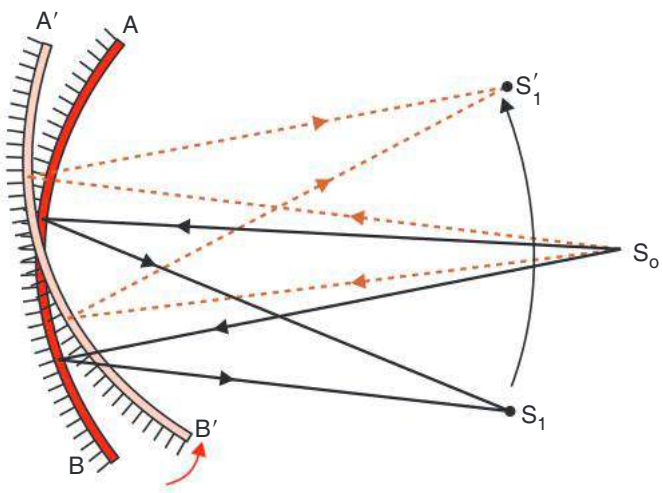


Fig. 5.2 *Movement of immediate source of light (S_1) to S'_1 in the same direction as that of concave mirror.*

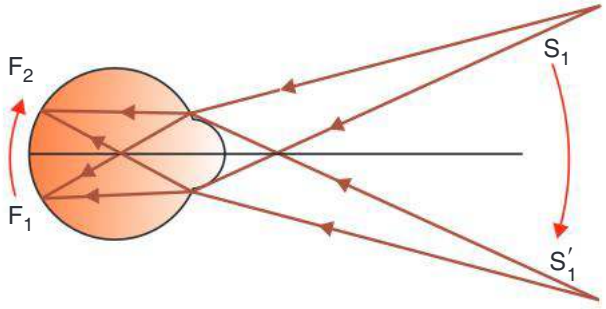


Fig. 5.3 *Movement of image of illuminated area of fundus with the movement of immediate source of light.*

The optics of reflex stage and projection stage of the retinoscopy (when performed using a plane mirror from a distance of 1 m from the subject), depending upon the refractive status of the eye, is as below.

Optics of Movement of Reflex in Emmetropia

In emmetropia, the light rays emerging out of the eye from the illuminated spot on the fundus (F_1) are parallel to each other, and so the examiner projects the image of F_1 to f_1 and that of spot F_2 to f_2 (Fig. 5.4). Thus, when the spot F_1 moves to F_2 (upwards), the image f_1 also moves upwards to f_2, i.e. along the movement of the plane mirror.

Optics of Movement of Reflex in Hypermetropia

In hypermetropia, the light rays emerging out of the eye from the illuminated spot on the fundus (F_1) are divergent and so the examiner projects the image of F_1 to f_1 and that of spot F_2 to f_2 (Fig. 5.5). Thus, when the spot F_1 moves

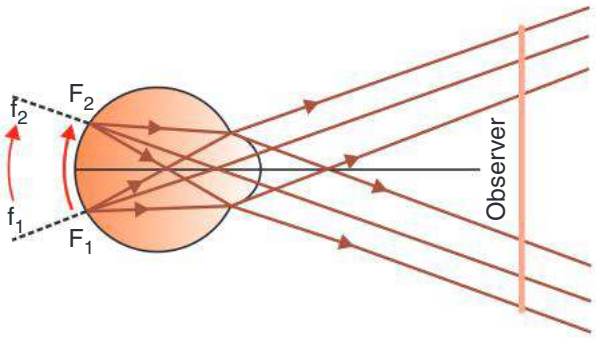


Fig. 5.4 *Movement of image of illuminated spot of fundus in emmetropia.*

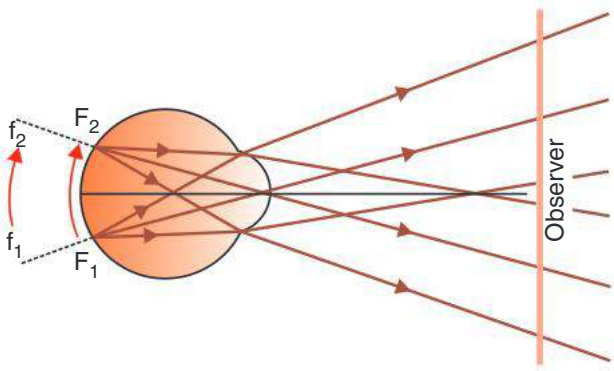


Fig. 5.5 *Movement of image of illuminated spot of fundus in hypermetropia.*

to F_2 (upwards), the image f_1 also moves upwards to f_2, i.e. along the movement of the plane mirror.

Optics of Movement of Reflex in Myopia of Less Than 1 D

In myopia of less than 1 D, the light rays emerging out of the eye from the illuminated spots on the fundus (F_1 and F_2) are convergent and meet at f_1 and f_2 behind the observer, sitting at 1 m from the patient (Fig. 5.6). Since these rays are intercepted by the examiner before they meet, so the examiner projects them along f_3 and f_4. Thus, when the spot F_1 moves to F_2 (upwards), the image f_3 also moves upwards to f_4, i.e. along the movement of the plane mirror.

Optics of Movement of Reflex in Myopia of 1 D

In myopia of 1 D, the light rays emerging out of the patient's eye from the illuminated spots on the fundus (F_1 and F_2) are convergent and meet at a point 1 m in front of the patient, i.e. at the level of pupillary plane of the observer (Fig. 5.7). Thus, when the illuminated spot F_1 moves to F_2 (upwards), its image moves from f_1 to f_2. Since in both the positions, the image is formed at the pupillary plane, so the examiner does not appreciate any movement of the shadow. In other words, there occurs no movement of the shadow with the movement of the retinoscopic mirror.

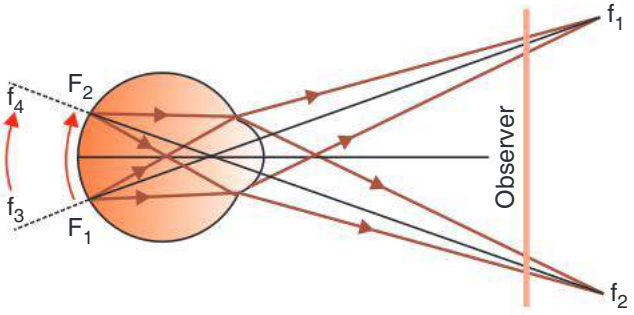


Fig. 5.6 *Movement of image of illuminated spot of fundus in myopia of less than 1 D.*

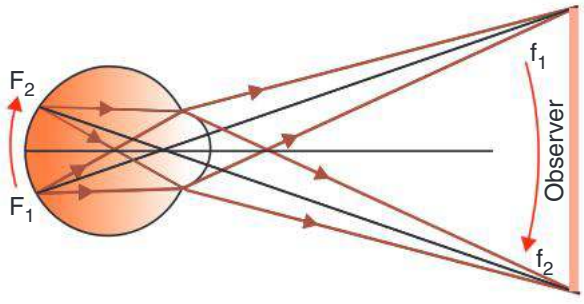


Fig. 5.7 *Movement of image of illuminated spot of fundus in myopia of 1 D.*

Optics of Movement of Reflex in Myopia of More Than 1 D

In myopia of more than 1 D, the light rays emerging out of the patient's eye from the illuminated spots F_1 and F_2 are convergent and meet at f_1 and f_2 in the space between the patient and the observer. Thus, when the spot F_1 moves to F_2 (upwards), the image f_1 moves to f_2 (downwards), i.e. opposite to the movement of the plane mirror (Fig. 5.8).

PREREQUISITES FOR RETINOSCOPY

1. ***A dark room***, preferably 6 m long, or that can be converted into 6 m by use of a plane mirror.

2. ***A trial set***. A standard trial box usually consists of the following:

- *Spherical lenses* (plus and minus) of powers 0.12 D, 0.25–4 D in increments of 0.25 D, 4.5–6 D in increments of 0.5 D, 7–14 D in increments of 1 D and 16–20 D in increments of 2 D.
  These test lenses should ideally conform as far as possible in form and thickness to the spectacle lenses to be worn subsequently. Practically this is impossible. The reduced aperture lenses (thin lenses of

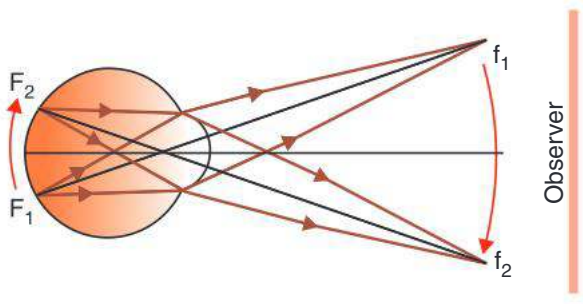


Fig. 5.8 *Movement of image of illuminated spot of fundus in myopia of more than 1 D.*

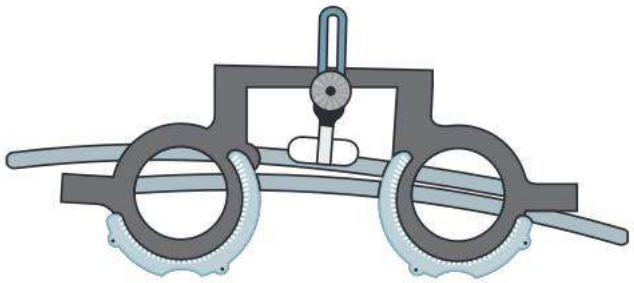


Fig. 5.9 *A trial frame.*

small size, approximately 25 mm in diameter), probably give the best approximation. These should preferably be in planoconvex or planoconcave form.
- *Cylindrical lenses* (plus and minus) of powers 0.25–2 D in increments of 0.25 D and 2.5–6 D in increments of 0.5 D.
- *Prisms* up to 10Δ with additional two of 15Δ and 20Δ.
- *Accessories* such as plano lenses, opaque discs, pinhole, stenopaeic discs, Maddox rods and red and green glasses.

3. ***A trial frame*** (Fig. 5.9), which preferably should have following features:
- Light in weight with a comfortable fitting nose rest.
- Adjustable, both horizontally and vertically.
- Fitted with at least three compartments, one each, for lodging spherical lens, cylindrical lens and the occluder or any of the accessories.
- The compartment for the cylindrical lens should be capable of smooth and accurate rotation.
- The dial indicating the axis should be properly positioned to avoid error in the prescription of axis of cylindrical lens.
- The side pieces of the frame should be joint so that it could be tilted while testing for near vision, to align the optic axes of lenses with the line of vision.

4. ***Phoropter*** or ***refractor*** (Fig. 5.10), when available, saves lot of time with ease of manipulation. In it, the entire trial set of lenses and accessories are mounted on a circular wheel so that each lens can be brought before the aperture of the viewing system by merely turning a dial.

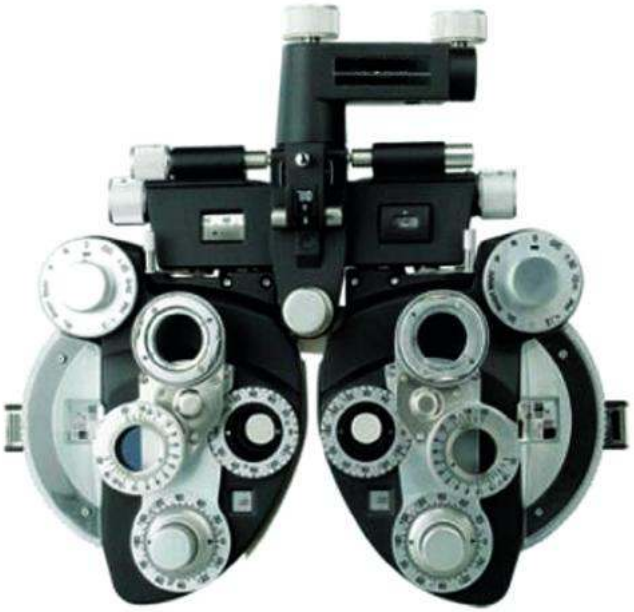


Fig. 5.10 *Phoropter or refractor.*

5. ***Distance vision chart***. A Snellen's self-illuminated vision box (Fig. 5.11A) is used commonly. The projector charts (Fig. 5.11B) and LogMAR chart (ETDRS chart; Fig. 5.11C) have also become popular nowadays.

6. ***Near vision charts***, commonly used for testing near vision, are Jaeger's chart, reduced Snellen's test types and Times Roman typeface.

7. ***Retinoscope*** is a simple device to perform the retinoscopy.

Types of Retinoscope

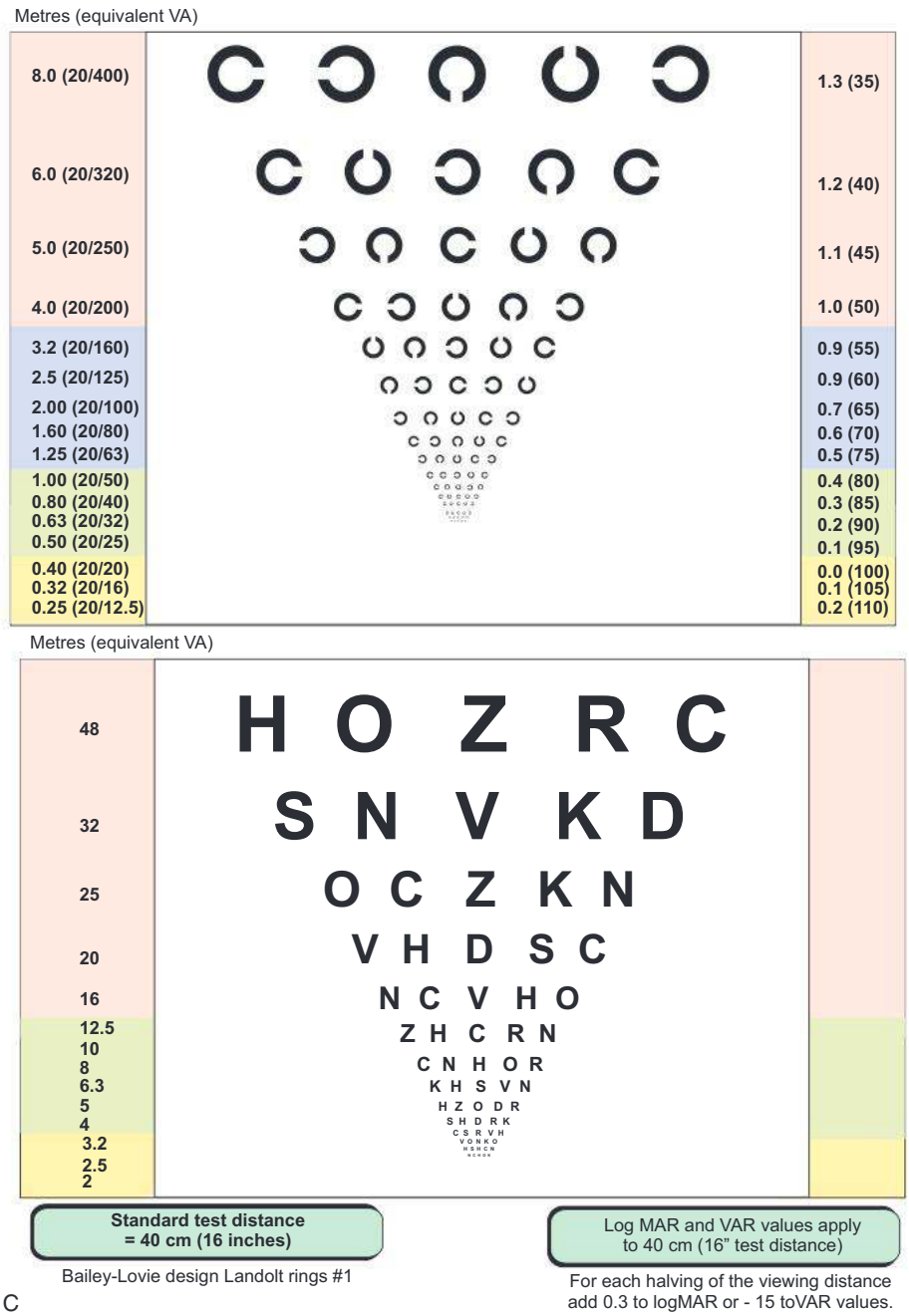
1. ***Reflecting (mirror) retinoscopes***

Reflecting (mirror) retinoscopes are cheap and at one time were the most commonly employed. However, presently these are sparingly used. A source of light is required when using mirror retinoscope, which is kept above and behind the head of the patient. The source of light used should be small, bright and enclosed; a Pointolite is ideal. A mirror retinoscope may consist of a single plane mirror (Fig. 5.12A) or a combination of plane and concave mirrors (*Priestley-Smith's* mirror; Fig. 5.12B).

Plane mirror gives comparatively more accurate results than the concave mirror. The central aperture in the mirror should be 3–4 mm in diameter so that a sufficient

A

B



C

Fig. 5.11 *Distance vision charts: A, Snellen's self-illuminated vision box; B, projector chart; C, LogMAR vision chart (ETDRS chart).*

Fig. 5.12 *Mirror retinoscopes: A, plane mirror; B, Priestley–Smith's mirror.*

amount of light can enter the observer's eye. However, the advantages of a hole of this size are counterbalanced by the appearance of a circular dark patch in the centre of reflection corresponding to the hole, which reduces the illumination in pupillary area and confuses the retinoscopy. This difficulty is overcome by using a very slightly concave mirror wherein the focal length is greater than the distance between the examiner and the patient, i.e. at least 150 cm. For all practical purposes of retinoscopy, it acts as a plane mirror.

2. ***Self-illuminated retinoscopes***

Self-illuminated retinoscopes are costly, but handy. These have become more popular nowadays. Two types of self-illuminated retinoscope available are (i) a spot retinoscope and (ii) a streak retinoscope (Fig. 5.13). The streak retinoscope is more popular, and most commonly used, since it is more sensitive than spot retinoscope in detecting astigmatism.

Fig. 5.13 *Self-illuminous streak retinoscope.*

- *Spot self-illuminous retinoscope* consists of a bulb with a tiny wired filament about 1–2 mm in size. This is imaged by a convex lens of about 20 mm focal length to give a beam of light which is reflected by a mirror (at 45 degrees) that is either totally silvered around a small circular unsilvered aperture (Fig. 5.14A) or half silvered (Fig. 5.14B).
- In *streak retinoscope,* the illumination is provided by a special bulb that has a straight filament, thus forming a 'streak' in its projection.

The filament may be moved in relation to convex lens in the system. If the light beam emerging from the lens is slightly divergent, it appears to come from a point behind the retinoscope – as if the light had been reflected off a plane mirror (*plano-mirror effect*) (Fig. 5.15A).

Alternatively, the distance between the convex lens and the bulb may be increased (by moving the sleeve on the handle), thus allowing converging light to be emitted. In this case, the image of the filament would be between the examiner and the patient – as if the light had been reflected off a concave mirror (*concave-mirror effect*) (Fig. 5.15B).

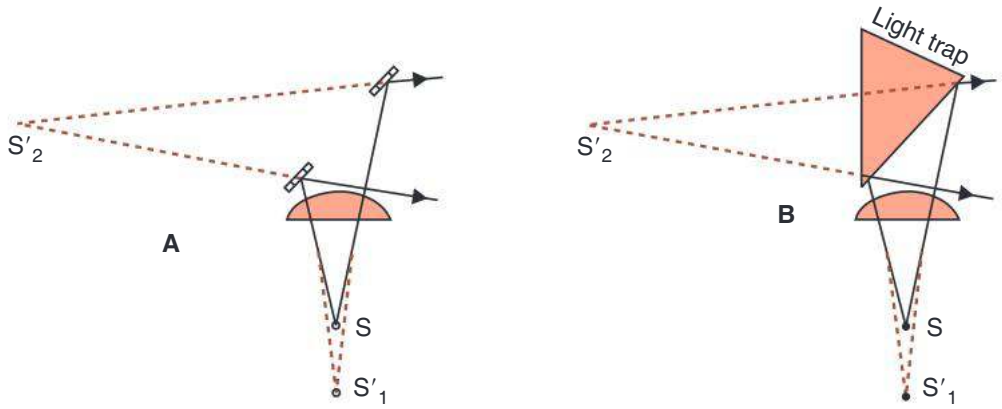


Fig. 5.14 *Ray diagram showing working principle of two types of self-illuminous retinoscopes: A, an instrument with perforated mirror and B, the instrument with a semi-silvered reflector. The immediate source of light is the bulb image S′2.*

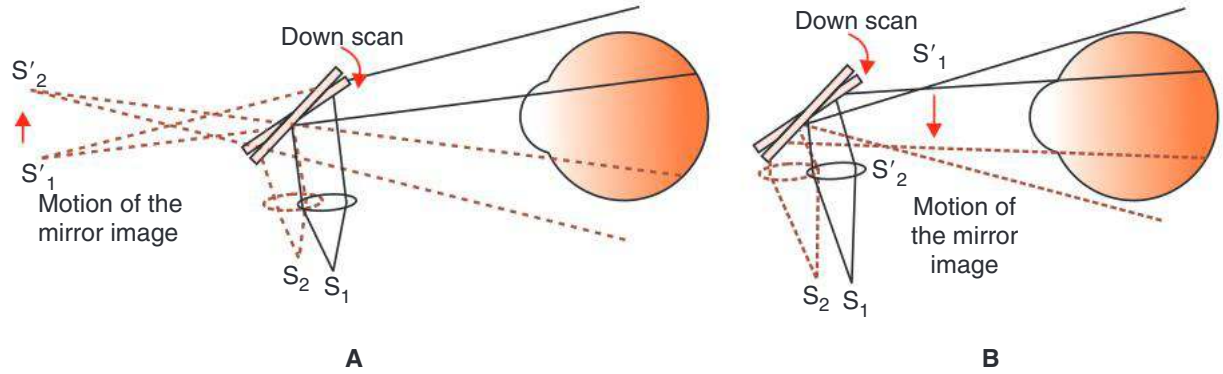


Fig. 5.15 *Illumination system of retinoscope, depicting position of the light source with plane mirror effect (A) and position of the light source with concave mirror effect (B).*

The axis of the streak of the retinoscope can be rotated by rotating the sleeve to align it with the axis of astigmatic error.

In practice, *plane-mirror effect* is used for retinoscopy. In patients with hazy media and high degree of ametropia, *concave-mirror effect* is more useful.

PROCEDURE

The patient is made to sit at a distance of 1 m (for ease of calculation) from the examiner (Fig. 5.16). However, a working distance of 2/3 m is more convenient and so is preferred in practice.

For non-cycloplegic refraction of patients who are not presbyopic (especially if they are myopic), *it is necessary to fog (blur) the fellow eye*. This involves placing a +1.50 or +2.00 spherical lens on top of the presumed refraction (estimated from their acuity, which you have just checked), so that the acuity is poorer than that of the eye being examined with the retinoscope. The reason why the fellow eye should be fogged is to reduce accommodation, which would give a false result when examining the fellow eye with the retinoscope.

This fogging induces less accommodation than simple occlusion with a black occluder, thus ordinarily occlusion should be avoided, as it stimulates more accommodation. However, *occlusion is required in the following situations*:

- When the eye being tested is densely amblyopic.
- If the patient markedly objects to fogging due to diplopia or asthenopia.
- If you are unable to estimate acuity and provide an adequate fog lens.

With cycloplegic refraction (typically in children), there is no need to fog, since the

Fig. 5.16 *Procedure of retinoscopy.*

accommodative component is removed by the cycloplegia.

To begin retinoscopy, with the help of a retinoscope, light is thrown on to the patient's eye, who is instructed to look at a far point (to relax the accommodation). However, when a cycloplegic has been used, the patient can look directly into the light and have the refraction assessed along the actual visual axis. Through a hole in the retinoscope's mirror, the examiner observes a red reflex in the pupillary area of the patient, which is seen as follows:

- *With spot retinoscope,* the whole pupil glows as red reflex.
- *With streak retinoscope,* red reflex is seen on a band of light (Fig. 5.17).

Then the retinoscope is moved in horizontal and vertical meridians, keeping a watch on the red reflex (which also moves when the retinoscope is moved). The characteristics of the moving retinal reflex are noted.

■ OBSERVATIONS AND INFERENCES

I. Direction of Movement of Red Reflex

Depending upon the movement of the red reflex (when a plane mirror retinoscope is used at a distance of 1 m), the results are interpreted as follows:

1. *No movement* of red reflex indicates myopia of 1 D (Fig. 5.17A).
2. *With movement* of red reflex *along* the movement of the retinoscope indicates either emmetropia or hypermetropia or myopia of less than 1 D (Fig. 5.17B).
3. *Against movement* of red reflex to the movement of the retinoscope implies myopia of more than 1 D (Fig. 5.17C).

The above assertions can be easily remembered from Figure 5.18.

II. Brightness and Speed of Movement of Red Reflex

- *Bright and fast* shadow (red reflex) is seen in the pupillary area, which moves rapidly with

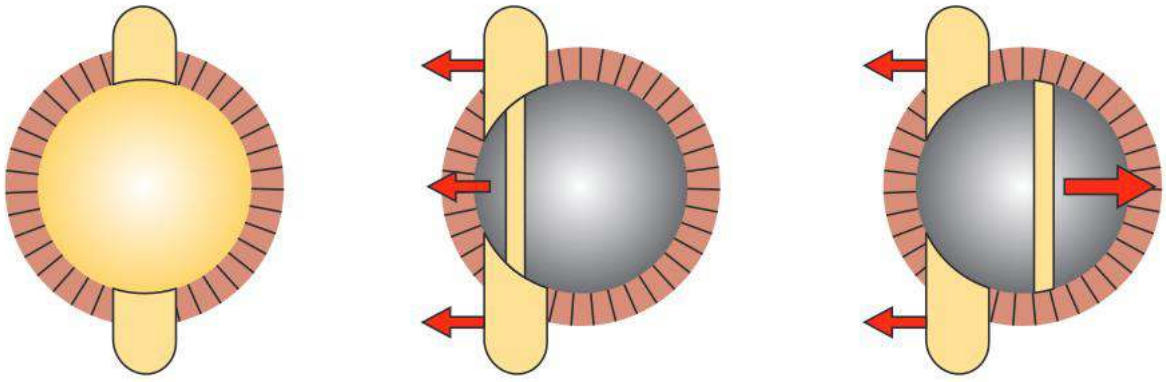


Fig. 5.17 *Red reflex during streak retinoscopy: A, neutralization point; B, with movement; and C, against movement.*

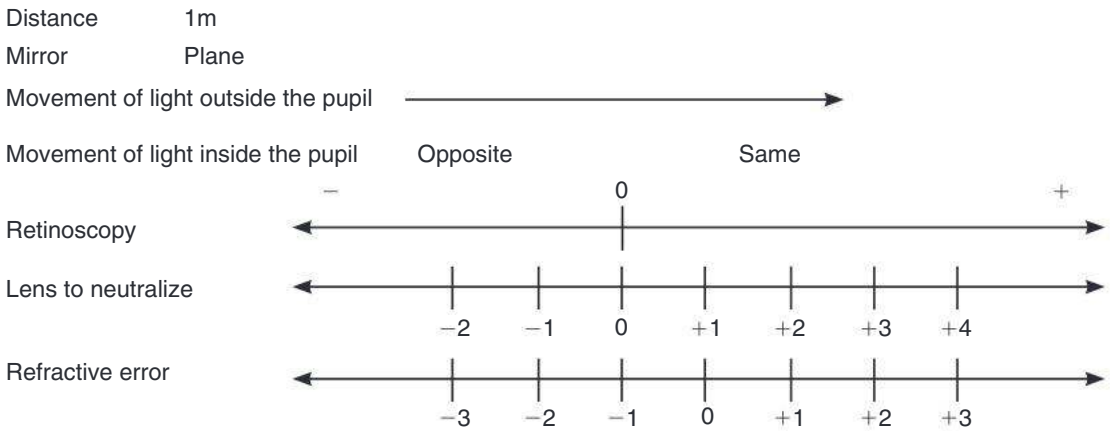


Fig. 5.18 *Diagrammatic depiction of the relation of movement of pupillary red reflex with the error of refraction.*

the movement of the mirror, in patients with low degrees of refractive errors.

- *Dull reflex,* which moves slowly with the movement of the mirror, is seen in patients with high degrees of ametropia.

III. Width of Red Reflex

Width of reflex, when using streak retinoscope, is narrow in high degree of ametropia and wide in low degrees of ametropia. At the neutralization point, the entire pupil is filled with light.

IV. Orientation of Red Reflex

In the presence of astigmatism, when the axis does not correspond with the movement of the mirror, the shadow appears to swirl around. Following types of orientation of red reflex may be noted:

1. ***Horizontal and vertical orientation*** of the red reflex is observed when either there is no astigmatism or when the astigmatism is with the rule/against the rule. In these situations, ensure the slit is first vertical and then horizontal (by rotating the slit with the help of cuff of retinoscope) to neutralize these meridians.
2. ***Oblique orientation.*** With oblique astigmatism, the principal meridians are still perpendicular but do not lie vertically and horizontally. Therefore, when a horizontal scope sweep is made with the slit orientated vertically, the orientation of the pupil reflex will be oblique and not lie vertically (it will lie between 45 and

90 degrees or 90 and 135 degrees). Similarly, if the scope slit was orientated horizontally and a sweep made vertically, the orientation of the pupil reflex will again be oblique and not be horizontal (it will lie between 0 and 45 degrees or 135 and 180 degrees). For oblique astigmatism, the scope slit should be rotated by turning the cuff slightly so the slit is parallel to the pupil reflex to aid subsequent neutralization. The perpendicular meridian can then be neutralized by rotating the slit 90 degrees (e.g. if one meridian is at 120 degrees, the other be at 30 degrees).

3. ***Scissor reflex*** or ***some other problems*** may be observed in the red reflex. These are described later (see page 145).

NEUTRALIZATION OF RED REFLEX

REFLECTING PLANE MIRROR (SPOT) RETINOSCOPY

Neutralization

To estimate the degree of refractive error, the movement of red reflex is neutralized by the addition of increasingly convex (+) spherical lenses (when the red reflex was moving with the movement of plane mirror) or concave (–) spherical lenses (when the red reflex was moving against the movement of plane mirror). When a simple spherical error alone is present, the movements of red reflex will be neutralized in both the vertical and horizontal meridians.

However, in the presence of an astigmatic refractive error, the situation is not quite so simple. The examiner has to determine not only the different neutralization points of the two meridians but also the orientation of these. The relationship of the direction of external movement to that of the reflex has an important bearing on determination of axis of cylindrical error.

Finding the Cylinder Axis

The initial examination with retinoscope is always exploratory. In the presence of astigmatism, with its principal axes, horizontal and vertical, one axis is neutralized with the appropriate spherical lens and the second axis (vertical or horizontal) still shows the movement of reflex in the direction of axis of astigmatism. In the presence of oblique astigmatism, close to neutralization point, the reflex may alter its plane of movement. In such a situation, the examiner must again explore different planes of external movement of the light until they correspond to that of the retinoscopy reflexes.

Finding the Cylinder Power

Once the two principal meridians have been identified, each should be neutralized separately to find the cylindrical power by any of the following methods:

- With a sphere and a cylinder,
- With spheres only and
- With two cylinders.

1. With a Sphere and a Cylinder

First, neutralize one axis with an appropriate spherical lens. (In order to be able to keep working using 'with reflexes', neutralize the lens plus axis first.) Then with this spherical lens in place, neutralize the other axis 90 degrees away with a cylindrical lens at the appropriate orientation. The spherical–cylindrical gross retinoscopy may be read directly from the trial lens apparatus.

The main advantage of using spherocylinder combination over the two spheres is in verifying the position of axis. For this purpose, the appropriate sphere and a slight undercorrecting cylinder should be put in the trial frame. (For example, if the neutralizing spherocylindrical combination is +2 DS and +3 DC, then put +2.0 DS and +2.5 DC in the trial frame.) In this case, on moving the retinoscopic mirror at right angles to the axis of cylinder, the reflex should move exactly at right angles to the axis of cylinder (representing the +0.5 D of uncorrected hypermetropia). If the axis of the cylinder is not proper, this reflex will not move at right angles to the cylinder, but markedly obliquely (about six times). Let us suppose, in the above example, where the correction required is +2 DS and +3 DC at 85 degrees and the examiner wrongly estimates that the

direction of axis is 90 degrees. In this case, when the cylinder is undercorrected by +0.5 D and placed at 90 degrees, on moving the mirror horizontally, the reflex will obliquely move along 150-degree axis, i.e. 30 degrees oblique. Thus, the error in axis (5 degrees) is multiplied six times. Since the obliquity of the shadow multiplies any error in the direction of the axis to such an enormous extent, a very small deviation from the true axis is easily detected. The angle that the oblique reflex now makes with the axis of cylinder should be assessed and the cylinder rotated through an angle one-sixth of this. The procedure should be repeated until the final and correct axis is obtained.

Sphere and cylinder approach can be used in two different ways:

- Using positive cylinder notation or
- Using negative cylinder notation.

i. ***Using positive cylinder notation.*** This means that your retinoscopy result will be in a plus cylinder format. Identify the orientation of the two principal meridians, which will be perpendicular to each other. The principal meridian that has an against reflex or, if both reflexes are with, the one having least with reflex (which is fastest and brightest) is neutralized first with a sphere. This will result in the other principal meridian giving a with reflex, which is then neutralized with positive cylinder (the axis on the lens in the same orientation as the scope slit). The resultant prescription will be the lenses in the trial frame.

ii. ***Using negative cylinder notation.*** This means that your retinoscopy result will be in a minus cylinder format. Identify the orientation of the two principal meridians, which will be perpendicular to each other. *First, neutralize the most with reflex with plus spheres, then neutralize the perpendicular against reflex with minus cylinder*. The lenses in the trial frame will give the retinoscopy result in minus cylinder format, which must then be corrected for working distance.

2. With Spheres Only

It is possible to obtain an objective refractive result without using any cylindrical lenses. First of all, identify the two principal meridians, then neutralize one of the meridians with a sphere and, record the result and orientation of reflex. Following this, neutralize the perpendicular meridian with an appropriate sphere and record the result and orientation of the reflex. The magnitude of the cylinder is the difference between the two spheres. It is better to use a power cross to record the results and generate the resultant prescription. For example, if the 180-degree axis is neutralized with +2.0 sphere and the 90-degree axis with +3.0 sphere, the power cross for gross retinoscopy will be (+2) + (+3).

3. With Two Cylinders

Although it is possible to use two cylinders at right angles to each other for the gross retinoscopy, there seems to be no advantage of this variant over the spherocylinder combination. Which is the most preferred technique?

End Point of Retinoscopy

The end point of retinoscopy using a simple plane mirror retinoscope is neutralization of red reflex, i.e. no movement of the reflex in any meridian with the movement of the mirror. The end point of retinoscopy can be and should be verified by following manoeuvres:

- Overcorrection by 0.25 D should cause reversal of the movement.
- On altering the working distance, i.e. by slight forward movement of the head, the examiner should observe a 'with' movement and an 'against' movement by slight backward movement.

STREAK RETINOSCOPY

With streak retinoscope, the retinoscopy is performed in the usual way and a band of light appears in the pupillary area which moves 'with' or 'against' the movement of band of light outside the pupil (Fig. 5.17). The movement of the band of light is then neutralized by adding appropriate spherical lenses as described in reflecting mirror retinoscopy.

When a simple spherical error alone is present, at neutralization, the band-shaped reflex

disappears and the pupil appears completely illuminated (Fig. 5.17A) or completely dark. However, in the presence of astigmatism, a band-shaped reflex will appear in the meridian still not neutralized.

Finding the Cylinder Axis

In a patient with regular astigmatism, two reflexes – one from each of the principal meridians – need to be neutralized. Before measuring the power in each of the principal meridians, one must determine the axes of the meridians.

***Characteristics of the streak reflex that can aid in determining the axis* are as follows:**

1. *Break in the alignment between the reflex in the pupil and the band outside*. It is observed (Fig. 5.19) when the streak is not parallel to one of the meridians. The band of light in pupillary area lies in a position intermediate between the band outside the pupil and that from axis of the cylinder. The axis, even in the case of low astigmatic errors, can thus be determined by rotating the streak until the break disappears. The correcting cylinder should be placed at this axis.

2. *Width of the streak varies as it is rotated around the correct axis*. It appears narrowest when the streak aligns with the true axis (Fig. 5.20).

3. *Intensity of the reflex band in pupil is brighter when the streak aligns with true axis.* This is a subtle finding, useful only in small cylinders.

4. *Skew (oblique motion of the streak reflex)* may be used to refine the axis in small cylinders.

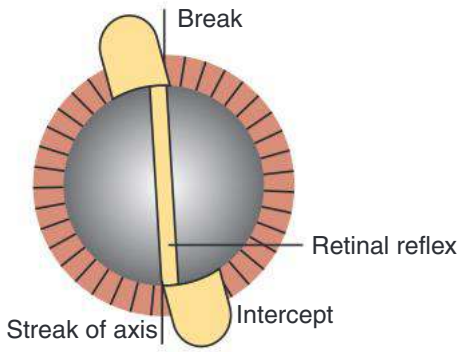


Fig. 5.19 *Break in the alignment between the reflex in the pupil and the band outside it when the streak is off the correct axis.*

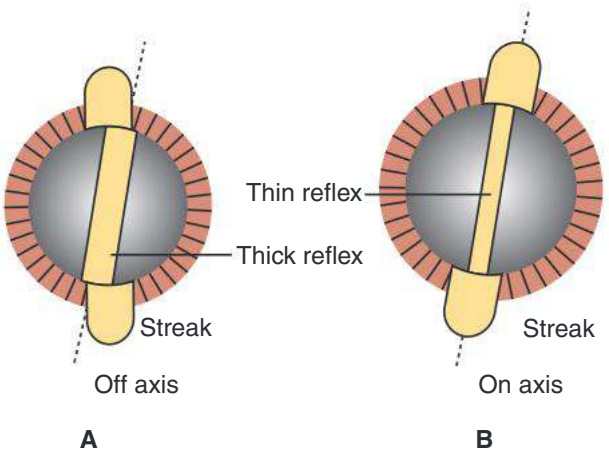


Fig. 5.20 *Width of the reflex in the pupil is narrowest when the streak is exactly aligned with the axis: A, off axis and B, on axis.*

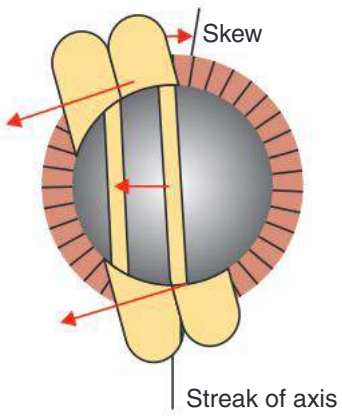


Fig. 5.21 *Skewing of the pupillary reflex and the band outside it when the streak is off axis.*

The streak and reflex will move in the same direction only when streak is aligned with one of the principal meridians. Therefore, if the streak is not aligned with the true axis, skewing will be observed on movement of the streak (Fig. 5.21).

Confirmation of the axis. Finally, the axis of cylinder may be confirmed with a technique known as *straddling*. This is performed with approximately the correct cylinder in place. The retinoscope streak is turned 45 degrees off axis in both directions. If the axis is correct, the width of the reflex should be equal in each of the two positions. If the axis is not correct, the widths will be unequal in the two positions (Fig. 5.22). In such a situation, the narrower

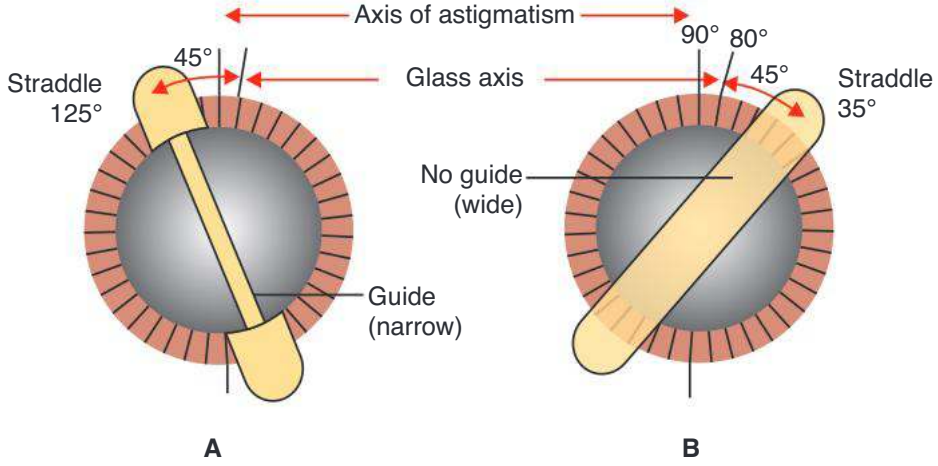


Fig. 5.22 *Technique of straddling showing narrow reflex (A) when the meridian is 45 degrees off axis towards 125 degrees from 80 degrees and wide reflex (B) when the meridian is 45 degrees off axis towards 35 degrees from 80 degrees. The narrow reflex (A) is the guide towards which cylinder's axis should be turned.*

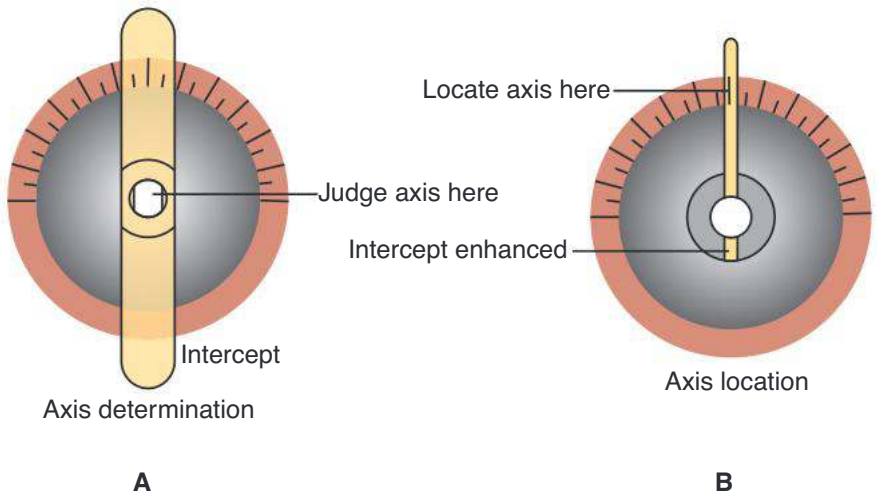


Fig. 5.23 *Final localization of the axis on protractor. First, the astigmatic axis is determined (A) and then the sleeve of the retinoscope is adjusted to enhance the intercept until the reflex is seen as a fine line pinpointing the axis (B).*

reflex serves as the guide towards which the cylinder's axis should be turned (Fig. 5.22A).

Final localization of the axis on the protractor. Once the axis of cylinder is finally confirmed (Fig. 5.23A), to pinpoint it on the protractor, the sleeve of the retinoscope is adjusted to enhance the intercept until the reflex is seen as a fine line (Fig. 5.23B).

Finding the Cylinder Power

Once the two principal meridians have been identified, the cylindrical power can be determined in a manner similar to that described in reflecting mirror retinoscopy.

End Point of Neutralization

When streak retinoscopy is performed, the width of the reflex widens progressively as the neutralization is approached, and at the end point, streak disappears and the pupil appears completely illuminated (Fig. 5.17A) or completely dark.

The end point can be verified by the same methods as described in spot retinoscopy.

USE OF CYCLOPLEGICS IN RETINOSCOPY

Cycloplegics are the drugs that cause paralysis of accommodation and dilate the pupil. These are used for retinoscopy, when the examiner

suspects that accommodation is abnormally active and will hinder the exact retinoscopy. Such a situation is encountered in young children and hypermetropes. When retinoscopy is performed after instilling cycloplegic drugs, it is termed as *wet retinoscopy* in converse to *dry retinoscopy* (without cycloplegics).

Commonly Employed Cycloplegics

1. ***Atropine*** is indicated in children below the age of 5 years. It is used as 1% ointment thrice daily for three consecutive days before performing retinoscopy. Its effect lasts for 10–20 days.
2. ***Homatropine*** is used as 2% drops. One drop is often instilled every 10 min for six times and the retinoscopy is performed after 1–2 h. Its effect lasts for 48–72 h. It is used for most of the hypermetropic individuals between 5 and 25 years of age.
3. ***Cyclopentolate*** is a short-acting cycloplegic. Its effect lasts for 6–18 h. It is used as 1% eye drops in patients between 8 and 20 years of age. One drop of cyclopentolate is instilled after every 10–15 min for three times (Havener's recommended dose) and the retinoscopy is preformed 60–90 min later, after estimating the residual accommodation, which should not exceed 1 D.
4. Only ***mydriatic*** (10% phenylephrine) may be needed in elderly patients when the pupil is narrow or media is slightly hazy.

Salient Features of the Common Cycloplegic and Mydriatic Drugs

Salient features of the common cycloplegic and mydriatic drugs are summarized in Table 5.1.

Tonus Allowance

Tonus allowance is the term used to denote the change in the refractive power brought about by the cycloplegic drug by its effect on accommodation (i.e. by relaxing effect on the ciliary muscle). The amount of tonus allowance in dioptres of various cycloplegic drugs is shown in Table 5.1.

Table 5.1 *Salient features of common cycloplegic and mydriatic drugs*

S. no.	Name of the drug	Age of the patient when indicated	Dosage of instillation	Peak effect	Time of performing retinoscopy	Duration of action	Period of post-cycloplegic test	Tonus allowance
1.	Atropine sulphate (1% ointment)	<5 years	TDS × 3 days	2–3 days	Fourth day	10–20 days	After 3 weeks of retinoscopy	1 D
2.	Homatropine hydrobromide (2% drops)	5–8 years	One drop every 10 min for six times	60–90 min	After 90 min of instillation of first drop	48–72 h	After 3 days of retinoscopy	0.5 D
3.	Cyclopentolate hydrochloride (1% drops)	8–20 years	One drop every 15 min for three times	80–90 min	After 90 min of instillation of first drop	6–18 h	After 3 days of retinoscopy	0.75 D
4.	Tropicamide (1% drops)	Not used as cycloplegic for retinoscopy; used only as mydriatic	One drop every 15 min for three to four times	20–40 min	Once pupil is dilated	4–6 h	After 24 h	0.5 D
5.	Phenylephrine (5%, 10% drops)	Used only as mydriatic alone or in combination with tropicamide	One drop every 15 min for three to four times	30–40 min	Once pupil is dilated	4–6 h	After 24 h	Nil

Note. The mydriatics should be used with care in adults with shallow anterior chamber, owing to the danger of an attack of narrow angle glaucoma. In older people, mydriasis should be counteracted by the use of miotic drug (2% pilocarpine).

STATIC VERSUS DYNAMIC RETINOSCOPY

- *Static retinoscopy* refers to the procedure performed without active use of accommodation (as described above).
- *Dynamic retinoscopy* implies when the procedure is performed for near vision with active use of accommodation by the patient. However, usefulness of performing dynamic retinoscopy has not yet been established in refraction.

ROUGH ESTIMATE OF REFRACTIVE ERROR AFTER RETINOSCOPY

Objectively, a rough estimate of error of refraction is made by taking into account the retinoscopic findings, deductions for distance (e.g. 1 D for 1 m and 1.5 D when retinoscopy is performed at 2/3 m distance) and deduction for the cycloplegic when used (e.g. 1 D for atropine, 0.5 D for homatropine and 0.75 D for cyclopentolate).

Thus, briefly,

Amount of refractive error = Retinoscopic findings − deduction for distance − tonus allowance for cycloplegic drug used

Power Cross

It is customary to do retinoscopy both vertically and horizontally and note the values separately (Fig. 5.24). In the power cross (Fig. 5.24A), X denotes retinoscopy value along the vertical meridian and Y denotes the value along the horizontal axis.

- *When retinoscopy values along horizontal and vertical meridians* are equal, then there is no

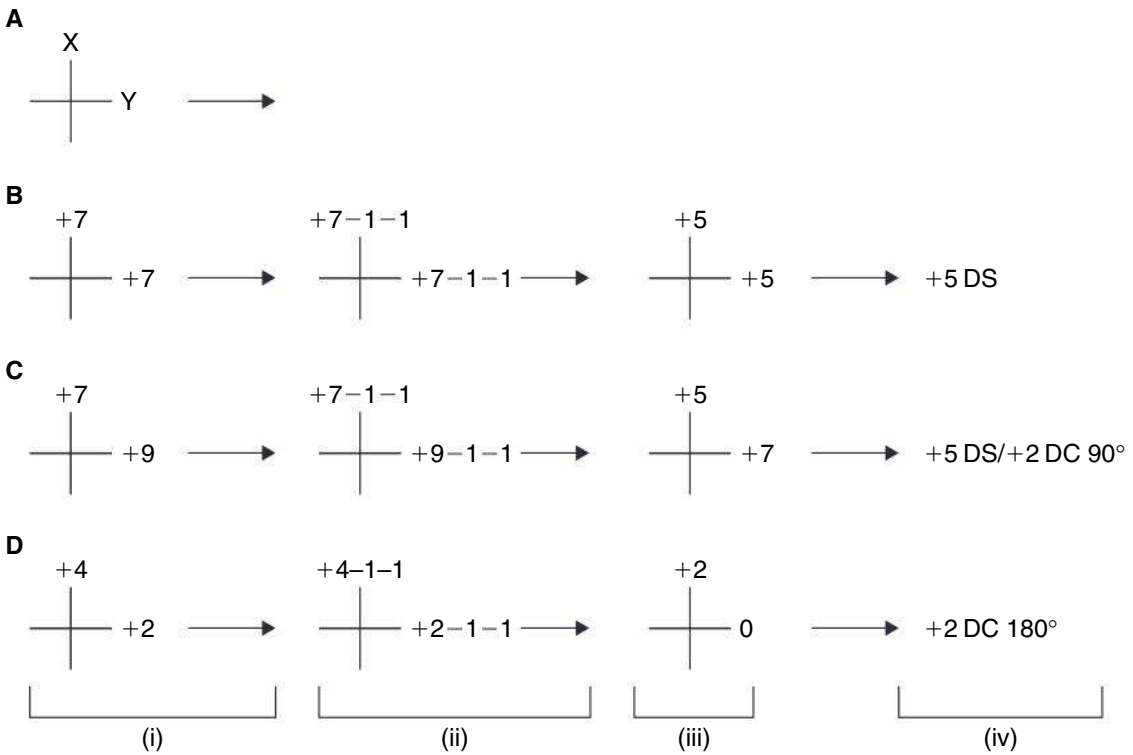


Fig. 5.24 *A, Customary way of writing retinoscopic findings. B–D, Calculation for rough estimate of refractive error: (i) retinoscopic findings, when performed at 1 m distance under atropine cycloplegia; (ii) deduction of –1 D for distance and –1 D for the atropine from the retinoscopic findings; (iii) rough estimate of refractive error along horizontal and vertical meridians and (iv) prescription required.*

astigmatism and a spherical lens is required to correct the refractive error. *For example*, when retinoscopic finding is +7 DS, with the procedure performed at 1 m distance, using atropine as cycloplegic, then appropriate refractive error will be 7 – 1 D (for distance) – 1 D (tonus allowance for atropine) = +5 DS (Fig. 5.24B).

- *When retinoscopy values along horizontal and vertical meridians* are unequal, then it denotes presence of astigmatism, which is corrected by a cylindrical lens alone or in combination with a spherical lens (Fig. 5.24C and D).

PROBLEMS IN RETINOSCOPY

Certain difficulties encountered during the procedure of retinoscopy are summarized below:

1. ***Red reflex may not be visible or may be poor.*** This may happen with small pupil, hazy media and high degree of refractive error. In most cases, this difficulty is overcome by causing mydriasis and/or use of converging light with concave mirror retinoscope.
2. ***Changing retinoscopy findings*** are observed due to abnormally active accommodation and this is corrected by following measures:
   - *Fogging retinoscopy*. In this technique, plus lenses much higher than the expected retinoscopic findings are placed in front of both the eyes. The patient is instructed to look at a far distance target, without making efforts to see clearly. Retinoscopy is performed and the plus lenses are decreased successively till neutralization is achieved. Care is taken to insert the replacing lens before the replaced lens is removed.
   - *Cycloplegic* may be required in young patients to control accommodation.
3. ***Scissoring shadows*** may sometimes be seen in patients with astigmatism (Fig. 5.25). In such a situation, two band reflexes appear which move towards and away from each other like the blades of scissors. It happens due to mixed aberration so that one-half of the reflex differs in its refractivity considerably in character from the other. The optics of this phenomenon is depicted in Figure 5.26. Mostly this difficulty is diminished with the undilated pupil.
4. ***Spherical aberrations*** lead to variation of refraction in the centre and periphery of the pupil. Such differences are accentuated with dilated pupils. The spherical aberrations tend to cause an increase of brightness at the centre or the periphery of the pupillary reflex depending on whether the aberrations are positive or negative (Figs 5.27 and 5.28). The spherical aberrations may be seen in normal eyes, but are more marked in conditions like lenticular sclerosis. The optics of spherical aberration is shown in Figure 5.29.

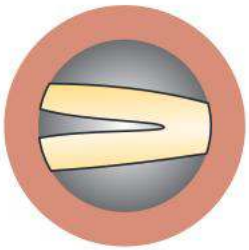


Fig. 5.25 *Scissor shadows.*

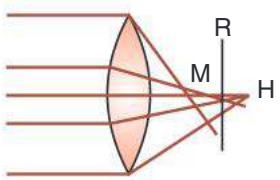


Fig. 5.26 *The optics of scissor shadows wherein at the plane of observation (R): one part of the aperture is relatively myopic (M) and the other relatively hypermetropic (H).*

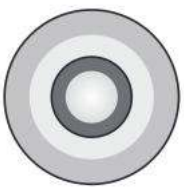


Fig. 5.27 *Positive aberration.*

Fig. 5.28 *Negative aberration.*

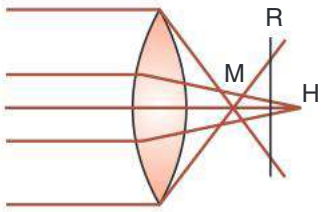


Fig. 5.29 *Optics of positive aberration. Central part shows myopic refraction (M) and peripheral part shows hypermetropic refraction (H) (R, retina).*

5. ***Conflicting shadows*** moving in various directions in different parts of the pupillary area are seen in patients with irregular astigmatism.

6. ***Triangular shadow*** may be observed in patients with conical cornea.

B. AUTOREFRACTOMETRY

Refraction being the most commonly performed optical procedure has been widely developed. Though the conventional technique of retinoscopic refraction is an excellent method of objective refraction, it is a time-consuming procedure and not every practitioner manages to accomplish it accurately.

The refractometry (optometry) is an alternative method of finding out the error of refraction by use of an optical equipment called refractometer or optometer.

OPTICAL PRINCIPLES

The present-day autorefractors (ARs) are based on the principles used in earlier attempts for automation of the refraction. Most of the autorefractometers are essentially based on the following two principles.

1. SCHEINER'S PRINCIPLE

Scheiner in 1619 observed that refractive error of the eye can be determined by using double pinhole apertures before the pupils. Following are his observations:

- *The parallel rays of light entering the eye* from a distant object, which are normally focused on a point on the retina in an emmetropic patient (Fig. 5.30A), are limited to two small bundles when double pinhole apertures are placed in front of the pupil (Fig. 5.30B).
- *In a myopic eye,* the two ray bundles cross each other before reaching the retina and two small spots of light are seen (Fig. 5.30C).
- *In a hypermetropic eye,* the ray bundles are intercepted by the retina before they meet and thus again two small spots of light are seen (Fig. 5.30D).
- These two points of light can be coalesced to a single point by moving the double pinhole to the far point of eye.
- Thus, from the far point of the eye, the refractive error of the eye can be determined.

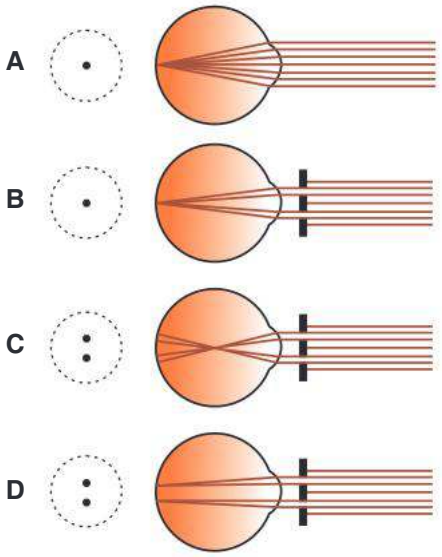


Fig. 5.30 *Scheiner's principle. Parallel rays of light entering an emmetropic eye are focused on the retina (A). Double apertures placed in front of the eye isolate two bundles of the light passing through the pupil, which are focused as a single spot on the retina in an emmetropic eye (B) and as two small spots of light in the myopic eye (C) as well as hypermetropic eye (D).*

2. OPTOMETER PRINCIPLE

Porterfield, in 1759, coined the term optometer to describe an instrument for measuring the limits of distinct vision. The optical principle on which this instrument was based is now known as *the optometer principle*. This principle permits continuous variation of power in the refracting instruments (Fig. 5.31).

- As shown in Figure 5.31A, the autorefractometers based on this principle use a single

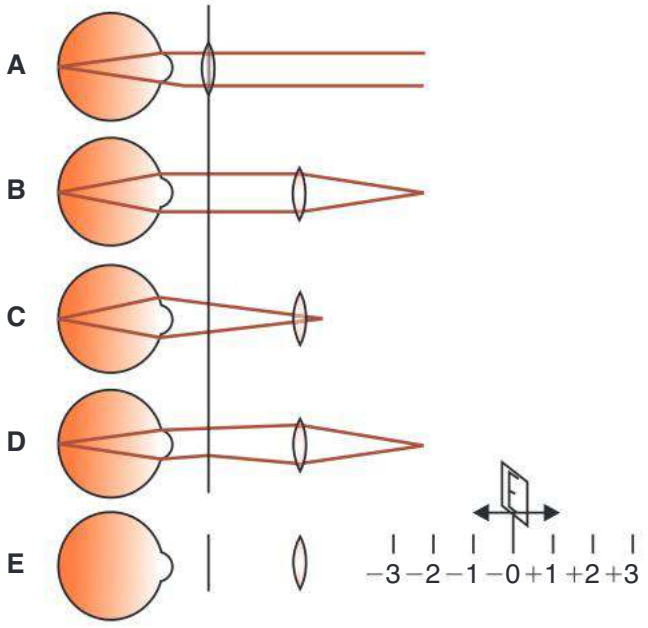


Fig. 5.31 *The optometer principle. Refractometer based on this principle uses a single converging lens (A). Light from a target on the far side of the lens may enter with zero (B), minus (C) or plus (D) vergence. The scale used in optometers would show the amount of ametropia in dioptres (E).*

converging lens placed at its focal length from the eye (or the spectacle plane) instead of interchangeable trial lenses.

- Light from the target on the far side of the lens enters the eye with vergence of different amounts (i.e. zero [Fig. 5.31B], minus [Fig. 5.31C] or plus [Fig. 5.31D]) depending on the position of the target.
- The vergence of the light in the focal plane of the optometer lens is linearly related to the displacement of the target.
- A scale with equal spacing can thus be made which would show the number of dioptres of correction (Fig. 5.31E).

DEVELOPMENT OF OPTOMETERS

The Scheiner's principle and optometer principle and their modifications have been used time and again to automate the clinical refraction. Presently, automated refraction has become a well-established technique. Numerous automated refractors have been devised during the last century. The modern electronic and computerized autorefractometers have rendered the previous optometers obsolete. However, a brief review of the overall developments will be worthwhile, because in many respects, optical systems of old optometers have been developed into those of their electronic successors and also because a reference to them is still made in the research literature.

In general, the development of optometers can be grouped as follows:

- Early refractometers and
- Modern AR.

EARLY REFRACTOMETERS

Early Subjective Optometers

The earliest optometers developed during 1895–1920 were all subjective. These optometers required the patient to adjust the instrument for best focus or best alignment of parts of the target. These subjective optometers were unsuccessful because of the instrument accommodation. Examples of early subjective optometers are as follows:

1. Badal optometer and
2. Young's optometer.

Early Objective Optometers

Objective refractometers were developed to offer an alternative means for evaluating the optical correction of the eye. However, these objective optometers were subjected to many of the uncertainties of retinoscopy with regard to accuracy of measurement. These, the so-called objective optometers, rely on the examiner's decision on when the image is clearest or in coincidence setting. Thus, they were objective only in the sense that the patient's subjective choice had been replaced by the choice of an experienced examiner.

These instruments were all based on the optometer principle, and most of them incorporated the Scheiner's principle as well. Three of these instruments that had been widely used in Europe in preference to retinoscopy are mentioned here because of their historic importance.

Limitations of the Earlier Optometers

Three basic factors responsible for the limited acceptance of optometers in clinical refraction are as follows:

1. Alignment problem,
2. Irregular astigmatism and
3. Accommodation.

1. ***Alignment problem.*** As per the requirement of Scheiner's principle, both pinhole apertures must fit within the patient's pupil. If the patient's fixation wanders or he or she moves the head even slightly, the reading is invalid. Thus, considerable patient cooperation is required.

2. ***Irregular astigmatism.*** Two small apertures of the eyes' entire optical system are used by the Scheiner's system. In a patient with irregular astigmatism, the best refraction over the whole pupil may be different in contrast to the two small pinhole areas of the pupil.

3. ***Accommodation.*** On looking into the instrument, the patient tends to accommodate. This is known as instrument myopia and this alters the actual refractive status of the patient. Factors affecting accommodation include attention, fatigue, direction of gaze, illumination, image detail, blur of the retinal image and psychological factors.

MODERN REFRACTOMETERS

With the rapid development in electronics and microcomputers, a number of innovative methods and instruments for automated clinical refraction have appeared since 1960. Efforts have been made to eliminate the limitations of old refractors.

The modern refractors can be grouped as follows:

- Objective refractometers and
- Subjective refractometers.

Both objective and subjective modern autorefractometers are available commercially (Fig. 5.32). A detailed description and comparison of the major instruments, which are currently on the market, is beyond the scope of this book. However, a general comparison of objective and subjective instruments and a brief description of some of the instruments presently in use are given.

Fig. 5.32 *Computerized autorefractometer.*

GENERAL COMPARISON OF SUBJECTIVE AND OBJECTIVE INSTRUMENTS

1. ***Source of light.*** The objective refractometers use low levels of invisible infrared light to perform the refraction, while the subjective refractors use visible light. Thus, subjective refractors are calibrated using visible light in a manner similar to calibration of lensometer. There occurs a substantial difference of about 0.75–1.50 D between the infrared refraction obtained by the objective refractometers and the visible light refraction that is desired. This difference can be explained by both the chromatic aberration of the eye and the fact that the infrared light is refracted not from the photoreceptor but from a different layer of retina.

Therefore, a bias must be built into each instrument to account for this difference.

2. ***Time required for refraction.*** The objective refractometer usually takes 2–4 min, while subjective refractometer takes 4–8 min to refract from both eyes.

3. ***Information provided.*** The subjective refractometers supply more information, and the corrected visual acuity is obtained as part of the refracting procedure. The objective refractometers do not provide this information except for the Humphrey Automatic Refractor, which provides visual acuity capability.

4. ***Patient cooperation factors.*** The objective refractometer requires less patient cooperation, since while refracting with these instruments, the patients have simply to stay reasonably still and look straight ahead at a target. On the other hand, while refracting with subjective refractometers, in addition, the patients should be able to turn a knob to focus various targets or answer simple questions about the appearance of the targets.

In general, it has been observed that children above 5 years of age can be refracted with objective refractometers, while for subjective refractometer use the child should be about 8 years of age to obtain the desirable cooperation. Regardless of the instrument being used, children should be subjected to cycloplegic refraction.

5. ***Ocular factors.*** Ocular diseases may limit the performance of the refractometers as follows:

- Objective refractors give better results than the subjective refractors in the presence of macular diseases with clear ocular media.
- Performance of objective and subjective refractometers is equal in the presence of hazy ocular media which cause decreased Snellen's visual acuity up to 6/18.
- In the presence of hazy ocular media causing a drop in visual acuity of more than 6/18, the objective refractors usually do not function properly, but rough refraction often still may be obtained with the subjective refractors.

6. ***Over-refraction capability***. The over-refraction in patients using spectacles, contact lenses or intraocular lenses is comparatively difficult with objective refractors due to reflection. On the other hand, no such problem is encountered while over-refracting with subjective refractors.

7. ***Expected results.*** The objective refractors provide only preliminary refractive findings. The practitioner has to refine these results. However, some of the subjective refractors, such as Vision Analyser and the SRN, provide refined subjective results. The 'Vision Analyser', in addition, provides binocular refraction capability for those practitioners who use binocular techniques.

OBJECTIVE AUTOREFRACTOMETERS

Over the years, automated objective refractometers, often called merely AR, have evolved as high-tech devices as a result of electronic, electro-optical, charge-coupled device (CCD) cameras and computer revolutions. Presently, combination of automated refractors and automated keratometers are also in vogue.

Common Characteristics of Autorefractors

Fixation Target and Control of Accommodation

A visible fixation target is provided in each instrument to help control the patient's fixation and accommodation. The phenomenon known as proximal accommodation confuses the determination of the appropriate refractive correction. Designers of automated refractors have often dealt with this by using visual fixation targets composed of colour photographs of outdoor scenes, with prominent central features in the distance. Accommodation is most relaxed when a prominent feature is of low spatial frequency, when the visual scene has a wide band of spatial frequencies for observation, and when the patient identifies the scene as one typically seen at distance. Natural scenes have these

characteristics, as do some other targets, such as Siemens stars or windmills. The abilities of these targets to successfully relax and stabilize accommodation when looking into an instrument under monocular or binocular conditions are suspect, and they depend greatly on the individual patient.

Primary and Secondary Sources of Electromagnetic Radiation

Primary source of electromagnetic radiation. Present-day objective autorefractometer use near-infrared radiation (NIR) at wavelength between 780 and 950 nm as primary source of electromagnetic radiation because of the following two reasons:

- NIR is efficiently reflected back from the fundus and
- NIR is essentially invisible to the patient.

Secondary source of electromagnetic radiations used by objective autorefractometers is the backscatter from the fundus. Operation of objective AR, i.e. the method on which the determination of sphere power, cylinder power and cylinder axis, depends on characteristics of the secondary source that are used by the detection systems of the instruments.

Nulling Versus Open-Loop Measurement Principle

Automated refractors find the refractive error of the eye using either a nulling or an open-loop measurement principle.

Nulling principle refractometers change their optical system until the refractive error of the eye is neutralized, i.e. until null point is reached. The nulling instruments can be designed to function with higher signal/noise ratios, as the condition can be optimized near the null point.

Open-loop principle refractometers, or the non-nulling instruments, make measurements by analysing the characteristics of the radiation exiting the eye. Open-loop instruments are generally able to more quickly arrive at the refractive states because they are not required to alter their optical systems to move to the null point.

Allowance for Ocular Refraction between Visible Light Versus NIR

Since the eye is not achromatic, an allowance has to be made for the difference in ocular refraction between visible light and whatever wavelength of IR is used. This is usually about 800–900 nm, for which the eye is 0.75–1.00 DS hypermetropic relative to 550 nm. Provided the lenses of the optometer itself are achromatic, their refractive power should not differ too greatly between visible and NIRs.

Allowance for the Plane of Reflection

The plane of reflection within the eye of visible radiation and IR may differ, and in any case, either or both of these may differ from the plane of the percipient layers of the retina. Thus, about 0.50–0.75 D allowance is to be made in addition to the effects of chromatic aberration. This suggests that the IR is either being reflected from the capillary bed of the retina, about 0.3 mm in front of receptors, or it is reflected from several layers, the mean effect being equivalent to reflection from a single plane in front of the receptors. Charman postulated that light which retains its plane of polarization on reflection by the fundus was reflected from the anterior layers of the retina, while diffusely reflected light may even be reflected from the sclera. This could give a difference between those instruments using polarized radiation, e.g. the Dioptron, and those without polarization, e.g. the Humphrey Autorefractor. Charman also points out the reflectance of the fundus increases towards the red end of the spectrum, from about 0.003 at 400 nm to almost 0.1 at 700 nm. If this trend continues into the infrared, then multiple reflections of scattered radiation within the eye, which acts as an integrating sphere, will degrade the image. It is, therefore, not possible to measure the eye's refractive error accurately by means of a simple *best-focus optometer,* e.g. an infrared conversion of the Rodenstock instrument.

Vertex Distance Consideration

ARs are constructed such that the full refractive error is determined at the plane of the cornea *(corneal plane refraction).* Most modern autorefractometers have the option to convert corneal plane refraction into desired *spectacle plane refraction* by selecting from a range of vertex distances.

Commercially Available Objective Autorefractometers

Present-day, commercially available objective autorefractometers are based on one or more of the following working principles:

- The Scheiner's principle,
- The optometric principle (retinoscopic principles),
- The best-focus principle,
- The knife-edge principle,
- The ray-deflection principle and
- The image-size principle.

Objective Autorefractors Based on Scheiner's Principle

The Scheiner's principle described in 1619, was used by Thomas Young in his research about the origin of refractive error. The principle was later used extensively in a non-automated manner, before the age of electronics, for the assessment of refractive error in the form of an optometer. The basic principle is described on page 146.

Scheiner's principle was originally conceived with the use of an opaque disc in which two peripheral circular apertures were placed. Light from a primary point source at near was collimated through a condensing lens, passed through the 'Scheiner's disc' and directed towards the eye. A modem version of Scheiner's principle is accomplished with infrared light-emitting diodes (IR-LEDs) that are optically presented in substitution for the apertures in a Scheiner's disc. To facilitate the measurement of ametropia during autorefraction using IR-LEDs, Scheiner's principle is generally used in conjunction with a Badal optometer.

Autorefractors Based on Scheiner's Principle

These are the most common automated objective refractors available. Following are a few examples:

- Acuity Systems 6600 (NA),
- Grand Seiko (RH Burton's BAR 7 in the USA; BAR 8 with AutoK),
- Nidek (Marco's AR-800 and 820 in the USA; ARK-900 with AutoK),
- Takagi (not available in the USA) and
- Topcon (NA).

Basic Working Features of Scheiner's Principle Autorefractors

- *Nulling refractors*. Scheiner's principle ARs are nulling refractors that optically substitute IR-LED for the apertures of a traditional Scheiner's disc.
- *Concept of the Badal optometer* is used to accomplish the projection of NIR into the eye, collection of the fundus reflexes emitted from the eye and determination of refractive status.
- *Specialized photodetection device* – actually a rudimentary form of robotic vision – is employed to analyse the position of fundus images created by the source optical train and imaged by the detection optical train at the photodetector.
- *Corneal reflex* is removed and the vitreoretinal reflex is likely attenuated by a corneal reflex block introduced into the path of radiation returning from the fundus.
- *Meridional refractive errors* are neutralized (nulled), and the two primary meridians of the eye are found by a second nulling process. The sensitivity (signal/noise ratio) can be brought to peak at the point of neutralization.
- *Refractive power end points.* ARs based on the Scheiner's principle can reach refractive power end points at speeds approaching 100 D/s.

Autorefractors Based on Retinoscopic Principle

ARs based on retinoscopic principle are also called *autoretinoscopes*. These refractors are

based on one of the following two characteristics of retinoscopic fundus reflex:

1. ***Direction of motion of the observed fundus reflex*** with respect to the direction of motion of incident radiation; e.g.:
   - Bausch and Lomb Ophthalmetron (no longer available in market).
2. ***Speed of motion of the observed fundus reflex*** with respect to speed of motion of *incident radion*. Examples of such refractometers are as follows:
   - Nikon NR-5500 and previous models (NRK-8000 with AutoK)
   - Nikon Retinomax (handheld; also available with AutoK)
   - Tomey TR-1000 (no longer available in the USA)
   - Carl Zeiss Meditec 'Acuitus' (NA)
   - Nidek OPD-Scan (wavefront refraction system with corneal topography system)

Basic Working Features of Retinoscopic Principle Autorefractors

- *Source optical train* of an autoretinoscope imitates the function of a streak retinoscope.
- *Motion of incident rectangular beams* is usually created by a slotted drum rotating about a source of NIR.
- *Refractors based on the analysis of the direction of motion* of the retinoscopic fundus reflex are nulling refractors. In such refractors, neutralization is achieved by the use of a *Badal optometer* placed in the detection optical train of the instrument.
- *Autoretinoscopes based on the analysis of the speed of motion* of the fundus reflex are open-loop (non-nulling) refractors. In such refractors, the Badal optometer is not required.
- *Photodetection devices* are usually composed of two or four photocells that are separated from each other by spaces that are necessary for the analysis of direction or speed of the fundus streak imaged upon them.
- *Corneal reflex* is masked from photodetection as it falls on the spaces between the photocells.
- *Vitreoretinal and corneal reflexes* can be filtered by the polarization of incoming NIR to the eye and the removal of polarized NIR returning from the eye in the fundus image. Common-path surfaces are tipped with respect to the detection train's optical axis, thereby reflecting unwanted NIR out of the detection system.
- *Autoretinoscopes are meridional refractors,* and the number of photodetectors per meridian can be increased to approach wavefront aberrometry.

Autorefractors Based on Best-Focus Principle

The 'best-focus principle' utilizes the automatic detection of a change of image contrast at the fundus by capturing the vergence of incident radiation necessary to bring about maximum contrast. Collins (1937) used this principle as *'electronic refractometer'*.

Commercially popular ARs based on best-focus principle include:

- Dioptron by coherent radiation,
- Canon autorefractor and
- Hoya autorefractor.

All these models are no longer available in the market.

Basic working features of dioptron are as follows:

- *Best-focus ARs are both nulling and meridional refractors*. They find best focus in a meridian through the analysis of the contrast of the retinoscopic image. Best focus correlates with highest contrast.
- *Neutralization is achieved with the use of a Badal optometer* placed in the common source/detection optical train of the instrument, which refers the image of the fundus reflex to the plane of a replica of the grating in a rotating drum.
- *Refractive end point* of a 'best-focus' AR is obtained when the referred image of a secondary fundus source attains highest contrast at the plane of a photodetection device.
- *Sensitivity* (signal/noise ratio) can be brought to peak at the point of neutralization. Only a single photocell is required, which allowed Collins to apply the best-focus principle before photodetectors became sophisticated.

- *Vitreoretinal reflex*, the *corneal reflex* and the *coaxial reflexes* from the extensive common optical path can be filtered by the polarization and removal of polarized NIR returning from the eye at the common beginning and end of the optical path. Coaxial optical elements may also be tipped with respect to the detection train's optical axis, thereby reflecting unwanted NIR out of the detection system.

Autorefractors Based on Knife-Edge Principle

The knife-edge principle is related to retinoscopy, and it is the basis of photorefraction. The Foucault knife-edge test is suitable for autorefraction of the eye because it is a retroreflective method using the same entrance and exit pupil of the device under test.

Basic Working Features

Humphrey instruments HARK 599 and previous model (AutoK) are based on knife-edge principle. Basic working features of such ARs are as follows:

- *Knife-edge refractors* use the *concept of optical reciprocity such that radiation from the fundus reflex is returned to the primary source.*
- *These are nulling ARs* that are not meridional. The neutralization of sphere power is achieved with the use of a *Badal optometer* placed in the common source/detection optical train of the instrument, which also returns the image of the fundus reflex to the plane of the original knife-edge targets.
- *Cylinder power and axis* are neutralized with the use of two Stokes lenses optically placed at the entrance pupil of the eye, which is optically conjugate with the photodetection device.
- *Coaxial reflexes* from the extensive common optical path can be reduced by the tipping of common-path elements. The geometry of the photodetection device is such that the corneal reflex has little, if any, impact on the refractive outcome; however, it is used to drive autocentration of the optical train with the entrance pupil of the eye.

Autorefractors Based on the Ray-Deflection Principle

Examples of ray-deflection principle ARs include:

- Canon R-30 and previous models (RK-3 with AutoK),
- Hoya (supplied by Canon),
- Welch Allyn SureSight (Hartmann–Shack handheld),
- VISX WaveScan (Hartmann–Shack wavefront refractor),
- WaveFront Sciences COAS (Hartmann–Shack wavefront refractor),
- Bausch & Lomb Zywave (Hartmann–Shack wavefront refractor),
- Alcon LADARWave (Hartmann–Shack wavefront refractor) and
- Topcon KR-9000PW (Hartmann–Shack wavefront refractor with image-size principle refractor and corneal topographer).

Basic Working Features

- *Ray-deflection ARs* are *open-loop (non-nulling) meridional refractors* that can arrive at a full refractive error almost instantaneously. Ray-deflection ARs using the Hartmann–Shack system to divide the pupil into many small areas often combine other nulling autorefraction techniques to extend the measurement range by avoiding overlap of the many CCD images. Hence, they may be considered to be *hybrid nulling and non-nulling devices*.
- *Design of a ray-deflection AR* is similar to that of an autoretinoscope and to a Scheiner's principle refractor in that discrete, fixed pupillary areas are used.
- *Instrument measures the linear deflection of the fundus image* in three or more meridians at a fixed distance from the eye, calculates the angular deflection of rays and the position of the far point in those meridians trigonometrically and computes the full refractive error.
- *Primary source and the photodetectors* are fixed.
- *Corneal reflex* may be removed from detection by placing a central aperture in a plane conjugate to the pupil in the detection path.
- *Coaxial reflexes* from the few common path elements can be filtered by the polarization

and removal of polarized NIR returning from the eye. Polarization is also used in some instruments for removing the corneal reflex. Coaxial optical elements may also be tipped with respect to the detection train's optical axis, thereby reflecting unwanted NIR out of the detection system.

Autorefractors Based on the Image-Size Principle

Examples of image-size principle AR are as follows:

- Grand Seiko (RH Burton's handheld BAR 600 in the USA),
- Grand Seiko WR-5100K (a 'see-through' instrument) and
- Topcon RM-A7000 and previous models (KR-7000S with AutoK and KR-7000P with corneal topography).

Basic Working Features

- *Size of the optical image* on the retina is a function of the refractive error. The refractive status may, therefore, be determined by measuring the size of an annular secondary fundus source and, in the case of astigmatism, the lengths and meridional orientations of the major and minor axes of the elliptical fundus reflex.
- *Detection system* consists of what is essentially a fundus camera: a CCD camera is used as the detector. A computer analyses the image to measure the digital image of the secondary source created at the detection surface of the CCD camera.
- *Design of an image-size AR* is similar to that of a Scheiner's principle refractor, although the neutralization properties of the source and detection optical trains are not used.
- *Instrument measures the size of the fundus image in three or more different meridians* (or it finds the axes and sizes along the principal meridians), and it calculates the full refractive error on the basis of ocular magnification or minification of the image relative to emmetropia.
- *Video imaging of the fundus reflex* is accomplished by what is essentially a fundus camera, and image analysis of the video image is performed by a sophisticated computer programme.
- *Refractive powers* are found by an open-loop (non-nulling) process, but an approximate nulling process is used to focus the primary target on the fundus. Image-size AR can be made compactly, and a handheld version is currently marketed.

■ SUBJECTIVE AUTOREFRACTORS

A few of the new subjective ARs, which have been available commercially, are as follows:

1. Vision Analyser

It was introduced by Humphrey in 1975. In 1977, it was combined with the Humphrey Lens Analyser to form the over-refraction system. The Vision Analyser uses an innovative optical system and equally innovative methods for subjective refraction.

2. SR-IV Programmed Subjective Refractor

This instrument uses the optometer principle, with an axially moving cylindrical lens to achieve smoothly variable spherocylindrical power over a wide range. Clinical trials of the SR-IV indicate that the Simulcross system provides results that are at least as accurate as those obtained with conventional subjective techniques. But, undoubtedly the Simulcross testing is faster and easier for both the patient and the operator.

3. Subjective Autorefractor-7

This instrument has spherical optics only. Since no refinement of the astigmatic correction is possible and because visual acuities can be determined only with spheres, the 'Subjective Autorefractor-7' can be considered only a screening instrument.

C. PHOTOREFRACTION

Over the years, there has been increasing interest in methods of objectively refracting eyes with photographic and videographic techniques. There are now several photographic and videographic refractors commercially

available that are used at distances of 0.5–2 m from the patient. Often called *photorefractors*, these devices characteristically capture images of the fundus reflexes from the two eyes of a patient, simultaneously, and these images are produced either by a flash of visible white light or IR from a source centred in or adjacent to the camera's lens. The fundus reflexes can be captured on film, digitally or by video, and they are then subjected to analysis.

At the present time, most photorefractive techniques are used in research laboratories, and only a few have found their way into clinical practice. Those that are found commercially are generally recommended for the screening of infants and children at schools or other sites away from the eye care practitioner's office, although traditional retinoscopy remains more accurate and informative when a professional takes the time to do screenings with a retinoscope.

Two different overall principles of photorefraction can be distinguished:

1. Photorefractors based on a point-spread method and
2. Photorefractors based on a retinoscopic-like method.

POINT-SPREAD METHOD OF PHOTOREFRACTION

Two point-spread methods are available for photorefraction. The advantage of these methods is the very short time required for taking a measurement, i.e. the time required by a single flash exposure.

Howland and Howland Method of Point-Spread Photorefraction

The first method introduced by Howland and Howland (1974) uses a photographic method to deduce the refractive or accommodative state of the patient's eyes. Since the photographs can be taken immediately, the patient appears to be looking at the camera. This method can be used with young infants whose span of attention is too short for retinoscopy. In such cases, an automated objective optometer is equally unsuitable because the eye has to be positioned accurately in relation to the instrument. Atkinson and Braddick recommended photorefraction as a screening test for significant refractory errors in young infants.

The photorefractor consists essentially of a small source of light mounted in front of a suitable camera. The source is formed by an electronic flash, illuminating one end of a fibreoptic light guide, the other end being mounted centrally in front of the camera lens. It illuminates the patient's face and is imaged on the fundus of both the eyes. The retinal image may be regarded as a secondary source giving rise to a fundus image in the plane conjugate with the retina.

If the eye is in focus for the source, the light leaving the eye returns to the source and is thus occluded from the camera lens. As a result, the pupil appears dark in the photograph. When the eye is out of focus, a blur circle or ellipse is formed on the fundus, producing in turn an illuminated zone around the source. The size of this zone varies with the ocular focusing error relative to the source.

Grolman's Method of Point-Spread Photorefraction

The second method, introduced by Grolman, is more accurate than the first. As shown in Figure 5.33, this method uses an array of point

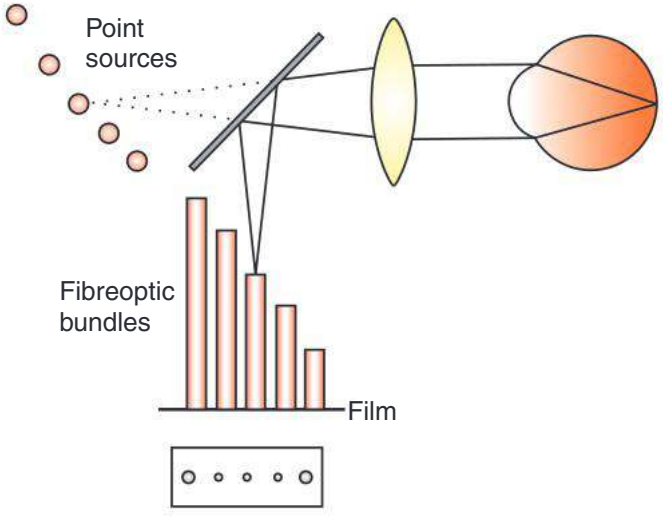


Fig. 5.33 *Grolman photographic system for objective refraction.*

sources of light spaced at varying dioptric distances from the patient's eye and flashed simultaneously. One end of a separate fibre-optic bundle is conjugate to each point source and receives the image point source as reflected from the patient's fundus. The image received by all fibre-optic bundles are recorded in a common plane on a strip of photographic film. The refractive error is judged by identifying the two sharpest ellipses and their orientation on the film.

RETINOSCOPIC-LIKE METHODS OF PHOTOREFRACTION

Synonyms of photoretinoscopy are eccentric photorefraction, photoskiascopy and paraxial photorefraction. In photoretinoscopy, a light source close to the aperture of the camera is directed into the subject's eyes. The camera, which is focused on the subject's entrance pupils, records the pupils illuminated by their respective fundus reflexes. The light returned from the fundus returns into the camera aperture in a manner similar to that described in static streak retinoscopy.

- *Stationary equivalent of retinoscopic 'against motion'* occurs when the eye is focused myopically relative to the camera. In this case, the pupil appears illuminated on the same side as that of the light source.
- *Stationary equivalent of 'with motion'* occurs, if the eye is hyperopically focused relative to the camera. The pupil will appear to be illuminated on the opposite side relative to the light source.

Techniques of Retinoscopic Photorefraction

Following techniques are there:

1. ***Visible-light photoretinoscopy.*** In visible-light photoretinoscopy, an exposure of the subject's pupils is achieved with a visible light source that is slightly eccentric (usually inferior) to the camera aperture. This results in an illumination of the pupils with red backscattered light from the fundi, which are the glowing 'red eyes'. When the radius of the point-spread image exceeds the eccentricity of the light source, a bright orange/yellow crescent appears in the periphery of the pupil as the red reflex becomes non-uniform in illumination.
2. ***Infrared videoretinoscopy.*** An IR source, consisting of a row or several rows of IR-LEDs, can be located below a knife-edge aperture similar to that of a visible light photoretinoscope. The IR-LEDs are mounted in front of a video camera, and the apparatus is called an infrared videoretinoscope. When the various rows of IR-LEDs are illuminated sequentially, a retinoscopic-like IR fundus reflex can be detected at the video screen as the fundus reflexes appear to move across the pupils of the subject's eyes. The optical principles of the infrared videoretinoscope are virtually the same as that of an ordinary retinoscope. As the eccentricity of the IR source is increased (i.e. as the IR-LED rows illuminate sequentially away from the knife-edge of the aperture), the size of the crescent detected in the subject's eye decreases. The crescent appears to move in a direction opposite to that of the IR source (in relative hyperopia) or in the same direction as the IR source (in relative myopia).
3. ***Computer-assisted infrared videoretinoscopy.*** The videoretinoscopy images could be captured in a computer frame store and processed by a computer. Although there are only three well-described instruments for this purpose, it appears likely that the next decades will see a proliferation of this technology as a result of steady improvement within the video and computer fields.

D. ELECTROPHYSIOLOGIC METHODS OF OBJECTIVE REFRACTION

This uses the visually evoked response for estimating automated clinical refraction. An advantage of this method is that it tests the entire visual system, from the cornea to the visual cortex. Spherical correction to the nearest 0.25 D is relatively easy to obtain. However, it does not measure the astigmatism very effectively.

SUBJECTIVE REFRACTION

Subjective refraction is meant for finding out the most suitable lenses to be prescribed. It can be carried out after objective refraction or even without that. However, preferably, it should always be carried out after getting a rough estimate of the refractive error by the objective refraction as described above. This practice is not only time-saving but more accurate method of testing as well. However, in some instances, where it is impossible to obtain a satisfactory retinoscopy, usually on account of hazy media, the examiner may have to limit himself or herself to subjective testing only. When a cycloplegic has been used, the subjective refraction (post-mydriatic test) should be carried out preferably after 3–4 days (when homatropine or cyclopentolate is used) and 14 days (when atropine is used).

The technique of subjective refraction requires patient's cooperation in arriving at the proper estimation of the refractive error. Therefore, it may not be possible in very young children and in patients with lack of comprehension. Therefore, in such cases, the examiner has to prescribe on the basis of objective refraction (e.g. retinoscopy) alone.

Instrumentation for subjective refraction are as follows:

- *Phoropter* or the so-called manual refractor (Fig. 5.10) should be the preferred unit.
- *Trial frame and loose lenses from the trial box* (Fig. 5.16) are, however, still the most frequently used in practice.

Steps of subjective refraction include:

A. Monocular subjective refraction,
B. Binocular balancing and
C. Correction for near vision.

A. MONOCULAR SUBJECTIVE REFRACTION

AIMS

Aims of monocular subjective refraction are to find out the following for each eye separately:

- Cylindrical lens with exact power and axis and
- The best vision sphere.

PROCEDURE

Many methods of monocular subjective refraction have been described. The widely accepted protocol, described here, includes the following steps:

- Selection of baseline starting point lenses,
- Refining the sphere,
- Refinement and finalization of cylindrical lens axis and power and
- Finalization of spherical lens.

I. SELECTION OF BASELINE STARTING POINT LENSES

The patient is seated at a distance of 6 m from the Snellen's vision chart. A trial frame is properly centred and adjusted on the face of the patient and the visual acuity is tested for both the eyes, separately.

Although a totally subjective refraction is possible, it is always better to first estimate the refraction objectively.

Baseline starting point lenses for objective refraction can be obtained from:

- Retinoscopy,
- Autorefractometry,
- Evaluation of the patient's old glasses or
- From the level of visual acuity: While performing totally subjective refraction, a clue for the baseline starting point can be made from the relationship between the unaided vision and the approximate amount of ametropia (Table 5.2).
  - *The visual acuity* does not, however, suggest whether the patient is myopic or hypermetropic. For example, if the patient's unaided vision is 6/36, the estimated refractive error can be either around –2 DS or +2 DS.
  - *To know whether the patient is myopic or hypermetropic,* compare the unaided distance acuity and unaided near acuity. A myopic patient (–2 DS) will have poor distant vision but good near vision, while a hypermetropic patient (+2 DS) will have poor vision for distance as well as near. This concept, however, is more useful in presbyopic patients, since otherwise the effect of accommodation confounds the estimation.

Table 5.2 *Expected vision in various ametropic states*

Vision	Refractive error (D)	
	Spherical[a]	Astigmatic[b]
6/6 (20/20)	Small	Small
6/9 (20/30)	0.50	1.00
6/12 (20/40)	0.75	1.50
6/18 (20/60)	1.00	2.00
6/24 (20/80)	1.50	3.00
6/36 (20/120)	2.00	4.00
6/60 (20/200)	2.00–3.00	High

[a]Myopia or absolute hypermetropia.
[b]The predicted vision in astigmatism is on the assumption that the circles of least confusion lie on or close to the retina.

II. REFINING SPHERE

In subjective refraction, spherical lenses should be verified first. This technique employs use of trial of different spherical and cylindrical lenses as based on the baseline starting point mentioned above. As with retinoscopy, during subjective refraction, it remains important to fog the fellow eye or, if appropriate, occlude the fellow eye. This not only reduces accommodation in non-cycloplegic refraction but also ensures that the patient's answers to your subjective refraction questions are based entirely on the eye being examined. In addition, as with retinoscopy, when changing a lens, always put the next lens into the trial frame before taking a lens out, to minimize the accommodation. The '*best vision sphere*', i.e. the strongest convex lens and the weakest concave lens providing best vision should be chosen in patients with hypermetropia and myopia, respectively.

The procedure of finding best vision sphere can be made easy by having a mounted row of weak spheres of power +0.25, +0.5, –0.25 and –0.5 (Fig. 5.34) which can quickly be moved over the front of the trial lenses. Myopic patients are advised to choose the lens that makes the letters more clear and note the one which makes the letters smaller and darker.

Note that when the –0.25 sphere is offered, only hold this up for a couple of seconds. If the patient does not make a decision quickly, remove the 0.25 sphere and reoffer them the lens in question. Do not simply hold the lens up waiting for a decision, since the quality of the decision will decrease with time and, in the case of this minus lens, the patient will accommodate. At this stage, do not panic if the acuity is poor and cannot be improved. It may be that the patient has a large cylinder (a high degree of astigmatism). Therefore, move onto refining the cylinder when an end point is reached, rather than persevering only with spheres in the pursuit of perfect acuity.

Fig. 5.34 *Weak spherical lenses mounted in a row used for easy manipulation.*

III. REFINEMENT AND FINALIZATION OF CYLINDRICAL LENS AXIS AND POWER

An accurate determination of the spherical component is predicated on having fully corrected the astigmatic error to ensure that a point focus is obtained with the final correcting cylindrical lens. Therefore, in the presence of astigmatic error, it is mandatory to refine and finalize the cylindrical component before the spherical component.

The cylindrical lens can be finalized by using any one or more of the following techniques:

- Astigmatic clock dial and fogging technique,
- Jackson's cross-cylinder technique and
- Astigmatic fan and block technique.

1. Astigmatic Clock Dial and Fogging Technique

Steps of astigmatic clock dial and fogging technique are as follows:

i. Obtain best visual acuity using sphere only in one eye, with other being occluded.

ii. Fog the eye (make artificially myopic) to about 20/50 by putting enough plus sphere before the eye to focus all meridians anterior to the retina, i.e. to bring forward compound, simple or mixed hyperopic meridians and thus create a state of compound myopic astigmatism (Fig. 5.35).

With the eye fogged, accommodation can only blur the lines more, and the patient, therefore, tends to relax accommodation, thus stabilizing the refractive error of the eye.

iii. The patient is asked to look at the astigmatic dial and identify the 'darkest and sharpest' line. Let us suppose it is 3–9-o'clock line, i.e. 180-degree axis line (Fig. 5.36).

iv. Add minus cylinder of progressively increasing power with axis perpendicular to the blackest and sharpest line (i.e. at 90 degrees as per above example) till all lines appear equal. A rotatable cross-dial (Fig. 5.37) is often used for this step, aligned with principal meridian, for easy comparison of the two meridians. The '*rule of 30s*' may be used to calculate the axis of the minus cylinder; i.e. multiply the lower number of the astigmatic dial clock with 30 to find the axis. If in the above example, blackest line was that in 3–9-o'clock position, then the axis of minus cylinder was $3 \times 30 = 90°$. Similarly, if the darkest line seen is in 6–12-o'clock position, the axis of minus cylinder will be $6 \times 30 = 180°$. If the axis of darkest line falls between hours on the clock, multiply by lowest member plus half, i.e. between 1- and 2-o'clock position $= 1.5 \times 30° = 45°$.

As shown in Figure 5.38, by adding minus cylinders, the vertical focal line has been moved back to the position of the horizontal focal line. Thus, as the interval of Sturm is collapsed, the focal lines disappear into a point focus.

v. Now all the lines of the astigmatic dial appear equally black (since astigmatism has been neutralized), but still are not in perfect focus (blurred), for eye is still fogged. At this juncture, switch to a distance-vision chart and reduce plus spheres (and add minus spheres, if required) until the patient achieves maximum clarity of vision; i.e. focus is now on the retina (Fig. 5.39).

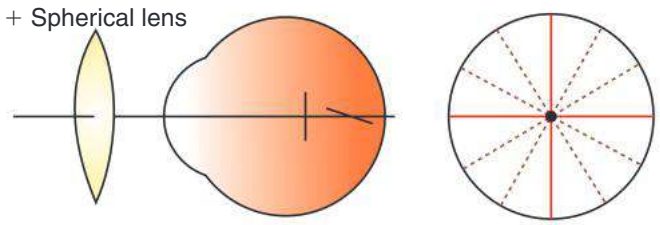


Fig. 5.35 *Fogging by plus spherical lens to create compound myopic astigmatism.*

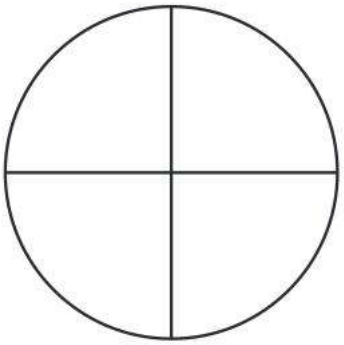


Fig. 5.37 *Two-line rotating dial is set at 3–9 position. Axis of correcting minus cylinder is 90 degrees (3 × 30).*

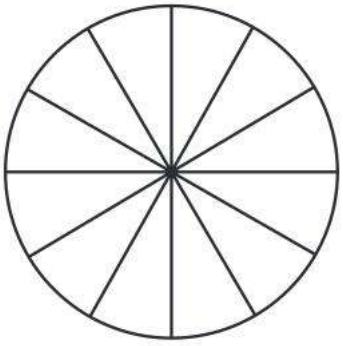


Fig. 5.36 *Clock dial as seen by 'fogged' patient with astigmatic error, 3–9 axis appears darker.*

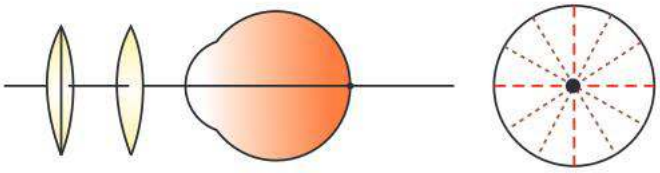


Fig. 5.38 *The vertical focal line has been moved back to the position of the horizontal focal line and collapsed to a point by adding a minus cylinder with axis at 90 degrees.*

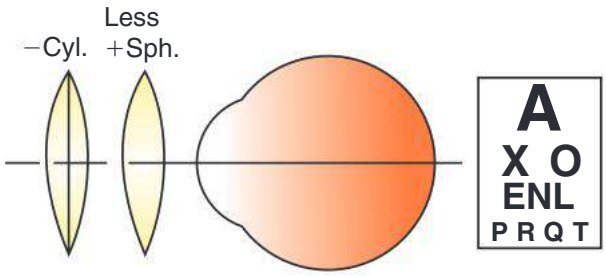


Fig. 5.39 *Focus is on the retina after defogging.*

Fig. 5.40 *Jackson's cross-cylinder.*

2. Jackson's Cross-Cylinder Technique

The cross-cylinder is a combination of two cylinders of equal strength, but with opposite sign placed with their axis at right angles to each other and mounted in a handle (Fig. 5.40). The commonly used cross-cylinders are of ±0.25 and ±0.5 D. The Jackson cross-cylinder, in Edward Jackson's words, is probably 'far more useful and, far more used' than any other lens in clinical refraction. Every ophthalmologist should be familiar with the principles involved in its use. Although the cross-cylinder is usually used to refine the cylinder axis and power of a refraction already obtained, it may also be used for the entire astigmatic refraction.

Steps of cross-cylinder refraction are as follows:

- ***Adjust sphere to the most plus or least minus*** that gives best visual acuity. This is done by fogging the eye (adding plus sphere before the eye), while viewing a visual acuity chart, and then decreasing the fog until best visual acuity is obtained. The goal, if astigmatism is present, is to place the circle of least diffusion of the conoid of Sturm on the retina, thus creating mixed astigmatism.
- ***Baseline cylindrical lens***, discovered on retinoscopy and/or autorefractometry, is then placed in the trial frame at the axis discovered. Refinement of the axis and then of the power of the cylindrical lens is done with Jackson's cross-cylinder.
- ***Refinement of the axis*** is always done first. This is because the correct axis can be found in the presence of an incorrect power, but the full cylinder power will not be found in the presence of an incorrect axis. To refine the axis, cross-cylinder (±0.5 D) is placed before the eye with its handle parallel (along the same line) to the axis of the cylindrical axis in the trial frame, i.e. with its axis at 45 degrees to the axis of cylinder in the trial frame (first with –0.5 D cylinder in and then +0.5 D cylinder or vice versa in Fig. 5.41) and the patient is asked to tell about any change in the visual acuity. If the patient notices no difference between the two positions, the axis of the correcting cylinder in the trial frame is correct. However, if the visual improvement is attained in one of the positions, a 'plus' correcting cylinder should be rotated in the direction of the plus cylindrical components of the cross-cylinder (and vice versa). The test is then repeated several times until the neutral point is reached.
- ***Refinement of cylinder power.*** To check the power of the cylinder, the cross-cylinder of ±0.25 D is placed, with its axis parallel to

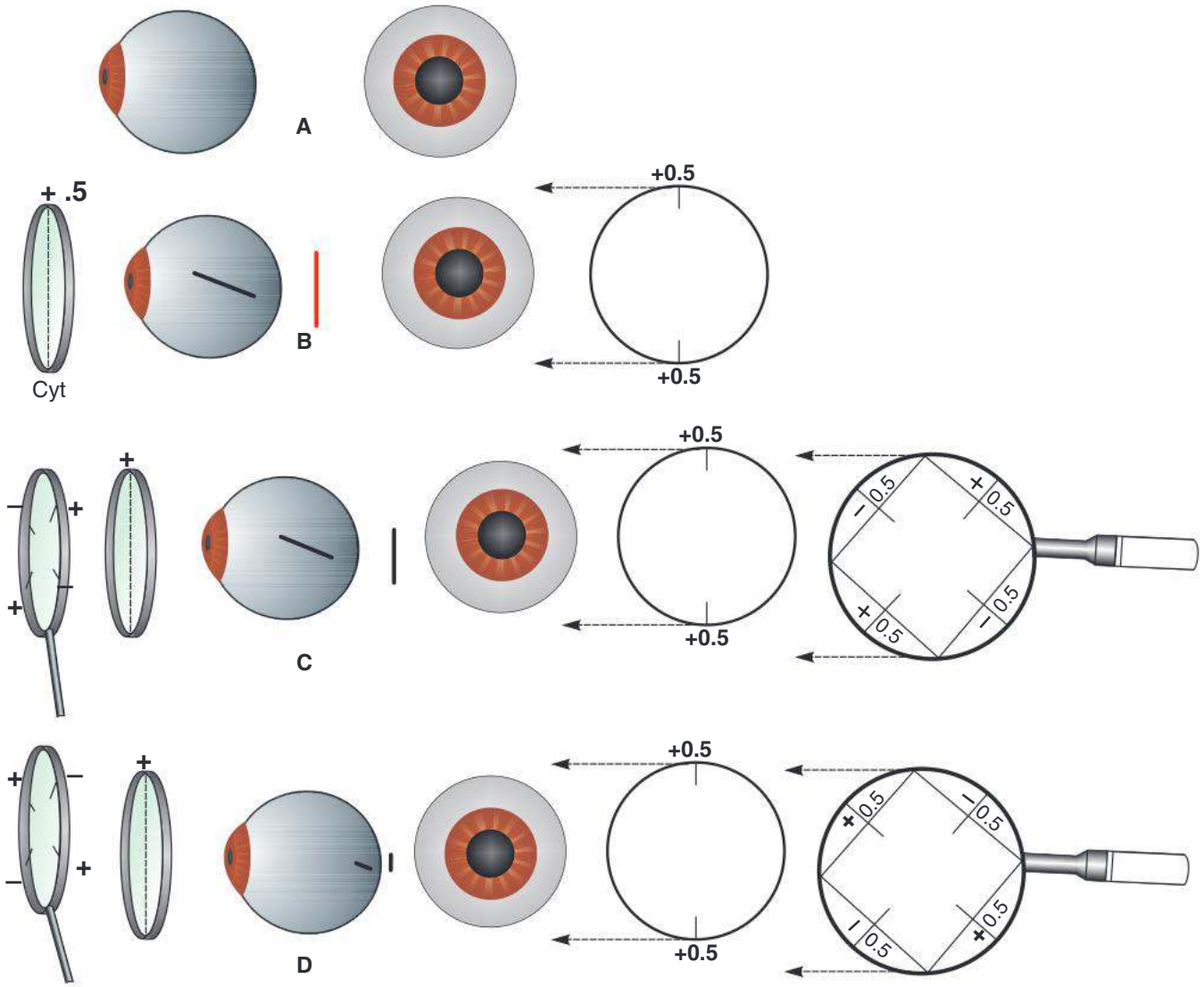


Fig. 5.41 *Use of Jackson's cross-cylinder (JCC) to refine the axis of astigmatism: A, side and front view of patient's eye; B, correcting cylindrical lens (say +0.5 DC at 90 degrees) is placed in front of the patient's eye; C, JCC is placed with –0.5 DC at 45 degrees to the axis of correcting cylindrical lens; and D, JCC is placed with +0.5 DC at 45 degrees to the axis of correcting cylindrical lens.*

the axis of the cylinder in the trial frame, first with the same sign in Figure 5.42 and then with the opposite sign in Figure 5.42. In the first position, the cylindrical correction is enhanced by 0.25 D and in the second, it is diminished by the same amount. When the visual acuity does not improve in either of the positions, the power of the cylinder in the trial frame is correct. However, if the visual acuity improves in any of the positions, a corresponding correction should be made and reverified till final correction is attained.

3. Astigmatic Fan and Block Technique

It is not always easy for the patients to respond satisfactorily with cross-cylinder testing. Therefore, it is useful to employ the older technique of fan and block method, or the so-called Maddox V test.

The fan and block consists of a series of radiating lines spaced at 10-degree interval and arranged after the manner of the rays of a rising sun around a central panel carrying a V and two sets of mutually perpendicular lines (the blocks) (Fig. 5.43). The V and the block simultaneously can be rotated through 180 degrees.

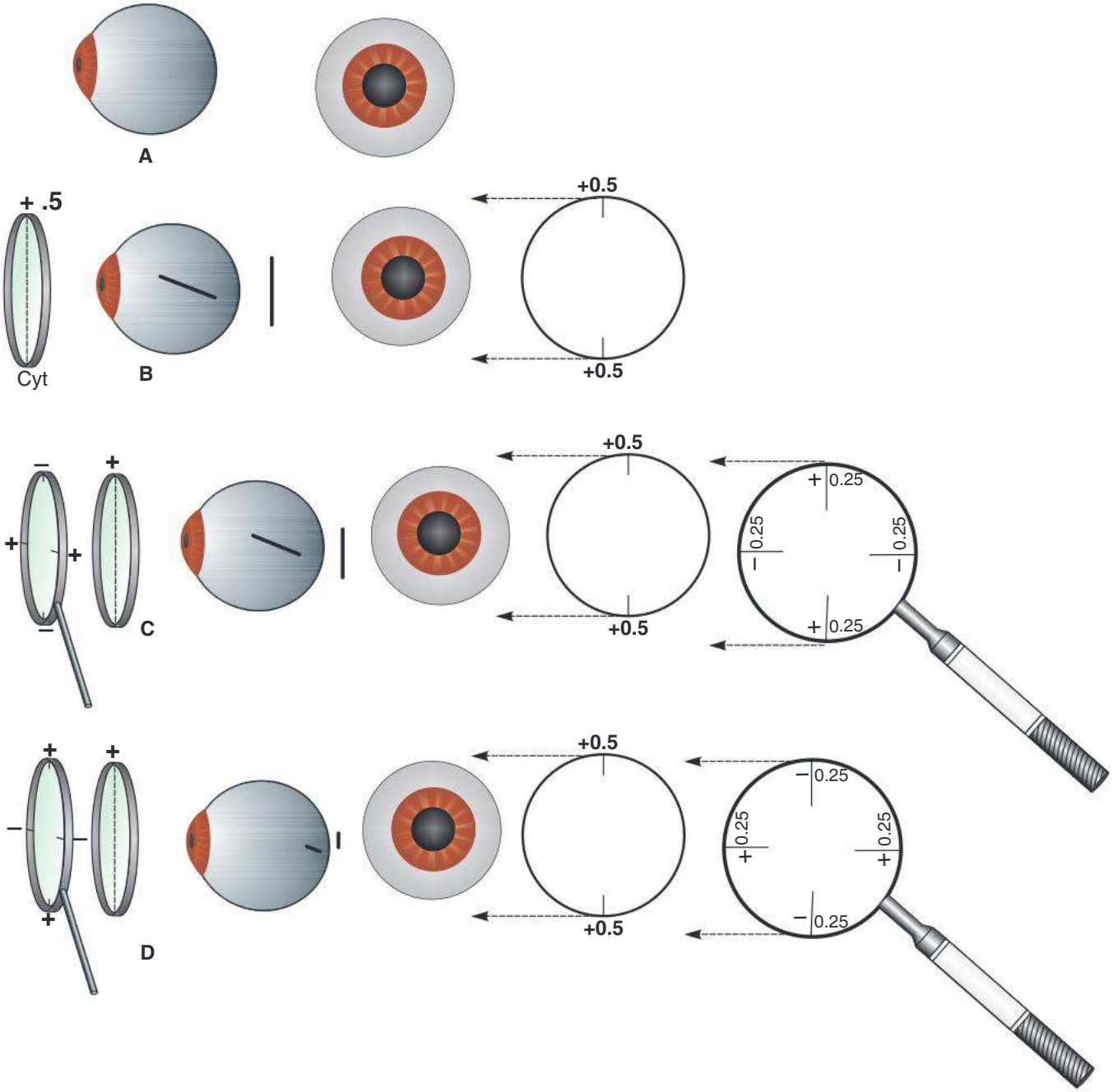


Fig. 5.42 *Use of Jackson's cross-cylinder (JCC) to refine power of the astigmatic cylinder: A, side and front view of patient's eye; B, correcting cylindrical lens (say +0.5 DC) at 90 degrees is placed in front of patient's eye; C, JCC of 0.25 DC is placed with axis parallel to the axis of correcting lens; D, JCC of –0.25 DC is placed with axis parallel to the correcting cylindrical axis.*

Steps of the fan and block technique are as follows:

1. ***Obtain the best visual acuity using sphere only (best vision sphere).*** It is assumed that the best vision sphere puts the circle of least diffusion on the retina.

2. ***Add a positive sphere*** equal to half of the estimated amount of astigmatism in order to bring the eye into a state of simple myopic astigmatism.

3. ***Refer the patient to the fan chart and ask which line or group of lines appear clearest and darkest.*** This gives the approximate direction of

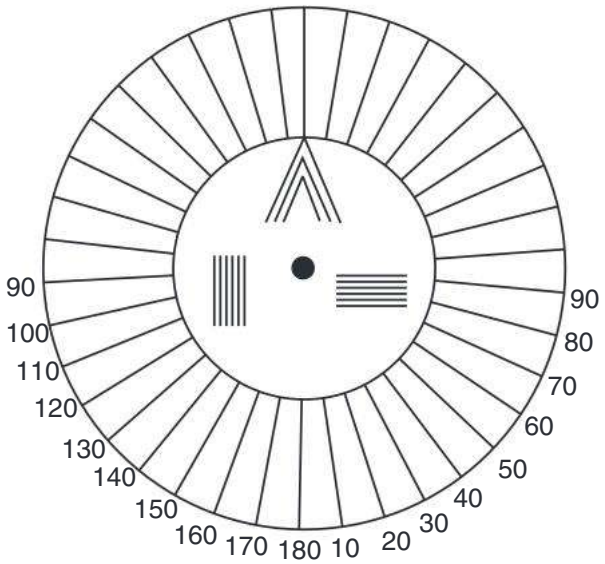


Fig. 5.43 *Fan and block dial (Maddox V test).*

the astigmatic error. However, a simple check test should be made by temporarily adding an extra +0.50 DS in order to confirm that the eye is in a state of simple myopic astigmatism. The blackest lines should blur, but if not, more positive sphere should be added until they do. (In some cases, the clearest lines will change through 90 degrees, indicating that the eye had been in a state of simple hypermetropic astigmatism, with the anterior focal line near the retina. In this case, continue adding positive sphere until this new set of lines just begins to blur.)

4. ***Direct the attention to the Maddox arrow*** and rotate it away from its blacker limb until both limbs appear equally blurred. This gives the axis of the astigmatism, but care must be taken to ensure that the patient's head is upright.

5. ***Directing attention now to the blocks, add negative cylinder*** at the appropriate axis until the second becomes as clear as the first. If this is not quite possible, it is better to just undercorrect than overcorrect the astigmatic error, i.e. leaving the first group of lines, the clearer or blacker of the two.

6. ***Make a second check test by again adding*** +0.50 DS, or, if the patient is a critical observer, +0.25 DS. Both blocks should blur equally, but if the blackest lines change over, the astigmatism has been overcorrected. If the originally darker block again becomes blacker, the original sphere from step 3 was wrong and must be rechecked. Return to the letter chart and determine the sphere giving best acuity, the cylindrical element remaining as just determined. As usual, a positive lens should be tried first, but a weak minus lens will most frequently be required.

If in step 3, no lines appear blacker than the other, there may be no astigmatism present, but other possibilities are that the eye is excessively fogged, has the circles of least diffusion on the retina or is in a state of compound hypermetropic astigmatism. The +0.50 DS check test will show up either of these last two conditions, by making some lines darker. On the other hand, if the eye is already fogged, extra positive power will blur the lines even more, whereas the addition of minus power will make some lines blacker in the presence of astigmatism, or all equally black, if there is no astigmatism.

IV. FURTHER REFINEMENT AND FINALIZATION OF THE SPHERICAL LENS

After the cylinder power and axis have been refined, the final step in monocular refraction is refining of the sphere which can be done by fogging technique using Snellen's visual acuity chart and can be verified by duochrome test and pinhole test.

1. Finalizing Sphere with Fogging Technique Using Snellen's Visual Acuity Chart

A simple criterion for initially establishing the end point for the spherical correction is to fog the eye after the cylindrical correction has been finalized and then unfog by reducing every time +0.25 DS till the best Snellen's visual acuity is attained. Some doubt, however, may exist at the very end point because the steps from one line of acuity to the next are rather large, particularly in the smaller letters. Thus, one lens may result in 6/6 acuity, and unfogging another 0.25 D may still only record 6/6 because the vision is unable to reach the 6/5 line. It may not be possible to determine by the Snellen's chart which

lens truly represents *best acuity*, and the examiner may face the quandary of either slightly fogging the eye with one choice or undercorrecting with the other. At this juncture, attempts to verify the best end point or ultimate correction point of the spherical component can be made by duochrome test.

2. Duochrome Test

It is based on the principle of chromatic aberration. It has been found that in emmetropes, yellow light (570 nm) is focused on the retina, while red (620 nm) and green lights (535 nm) are focused 0.24 D behind and 0.20 D in front of the retina, respectively (Fig. 5.44). In duochrome test, the patient is asked to read the letters graded from 6/18 to 6/5 with red and green background (Fig. 5.45) and inform whether the letters on red background are more sharp or on green background, or both appear equally sharp. As in an emmetropic eye, the green rays are focused slightly anterior and red rays slightly posterior to the retina. Therefore, to an emmetropic patient, letters with both colours background look equally sharp. When the patient tells that he or she sees letters with red background more clear than the green, it indicates that one is slightly myopic. His or her spherical lenses should be adjusted such that one sees letters of both colours with equal clarity.

Note that, although the duochrome test is easily and rapidly performed, it has the inherent weakness that it does not relax accommodation. This test should always be introduced, therefore, with the patient slightly fogged. The letters on the red side should appear clearer and minus sphere should be added until the letters with red and green background are equally clear.

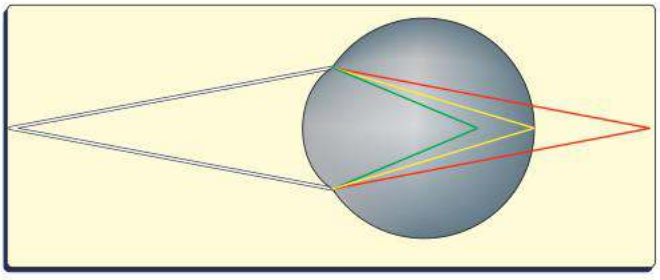


Fig. 5.44 *Optical principle of duochrome test (for explanation, see text).*

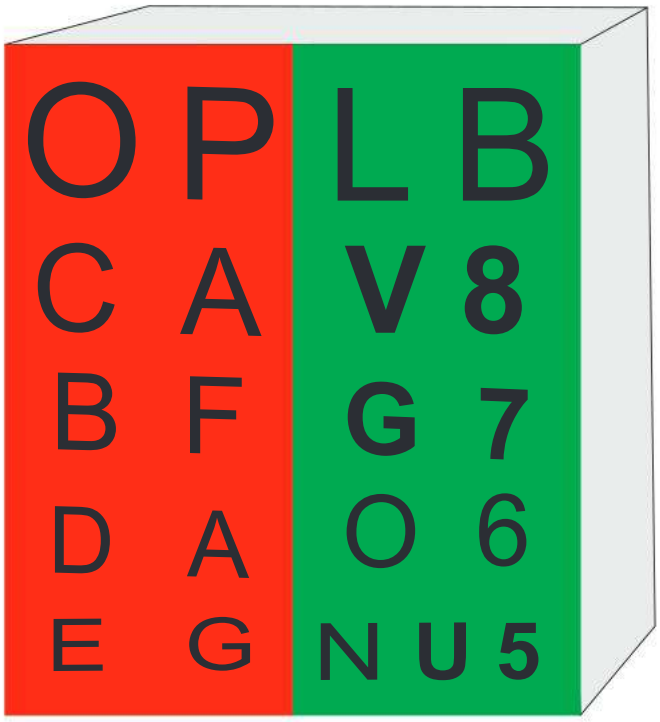


Fig. 5.45 *Duochrome test box consisting of Snellen's 6/18 to 6/5 visual acuity letters with red and green background.*

The duochrome test is not much useful with visual acuities worse than 6/9 (20/30), for the 0.5 D difference between the two sides becomes difficult to distinguish.

3. Pinhole Testing

A pinhole test at this juncture helps in confirming whether the optical correction in the trial frame is correct or not. An improvement in visual acuity while looking through a pinhole (Fig. 5.46) indicates that optical correction in the trial frame is incorrect. The pinhole allows only central rays of light which are not refracted and are directly focused on the fovea.

SPECTACLE PRESCRIPTION: NOTATION AND TRANSPOSITION

Notation

After subjective refraction, the writing of spectacle prescription is known as notation.

Types of notation. The spectacle/contact lens prescription can be written in any of the two equivalent notations in which any single

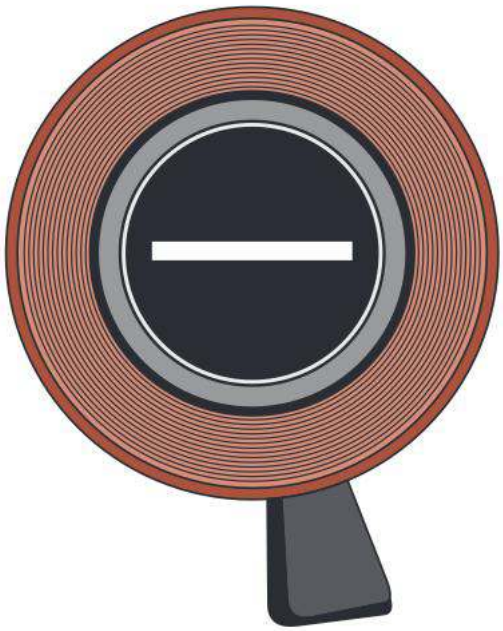


Fig. 5.46 *Pinhole.*

refractive error can be corrected. These notations are as follows:

- *Plus cylinder notation*, e.g. –2 DS/+1 DC 180°.
- *Minus cylinder notation* of the above prescription will be –1 DS/–1 DC 90°.

Note:

- Both plus and minus cylinder notations are acceptable, so either may be used and is correct.
- However, always ensure that for any single patient, both eyes are prescribed in the same cylinder notation, i.e. both eyes in either plus or minus cylinder notation.

Transposition of Notation

To obtain equivalent notation, one form has to be transposed to the other form, i.e. plus cylinder notation can be changed to minus cylinder notation or vice versa.

Steps of transposition. Transposition involves three steps:

- Add the cylinder to sphere to give new sphere.
- *Change the sign of cylinder* to give new cylinder power.
- *New axis of cylinder* is perpendicular to the old axis.

Examples of transposition are given below.

Example 1: Transposition of plus cylinder notation will be as follows:

Plus cylinder notation: –2 DS/+1 DC 180°

- *New sphere* = –2 + 1 = –1 DS
- *New cylinder* = –1 DC
- *Axis of new cylinder* = 90°

Minus cylinder notation, so, will be: –1 DS/–1 DC 90°.

Example 2: Plus cylinder notation: +1 DS/+1 DC 180°

- *New sphere:* +1 + 1 = +2 DS
- *New cylinder:* –1 DC
- *Axis of new cylinder* = –1 DC 90°

Minus cylinder notation, so, will be: +2 DS/–1 DC 90°.

Example 3: Minus cylinder notation: +2 DS/–1 DC 180°

- *New sphere*: (–2) + (–1) = –3 DS
- *New cylinder* = +1 DC
- *Axis of new cylinder* = +1 DC 90°
- *Plus cylinder notation*, so, will be: –3 DS/+1 DC 90°.

Example 4: Minus cylinder notation: +2 DS/–1 DC 180°

- *New sphere*: (+2) + (–1) = +1 DS
- *New cylinder*: +1 DC
- *Axis of new cylinder*: +1 DC 90°
- *Plus cylinder notation*, so, will be: +1 DS/+1 DC 90°.

Example 5: Minus cylinder notation: +2 DS/–4 DC 180°

- *New sphere*: (+2) + (–4) = –2 DS
- *New cylinder*: +4 DC
- *Axis of new cylinder*: +4 DC 90°
- *Plus cylinder notation*, so, will be: –2 DS/+4 DC 90°.

B. BINOCULAR BALANCING

The final step in the subjective refraction is 'binocular balancing' – a process sometimes known as 'equalizing the accommodative effort' or 'equalization of vision'. This allows both eyes to have the retinal image simultaneously in focus. An imbalanced correction often leads to asthenopia because of unstable accommodation.

Several methods have been described for binocular balancing. Most of the methods require that correctable visual acuity be essentially equal in the two eyes. A few commonly used methods are described here.

1. FOGGING AND ALTERNATE OCCLUSION METHOD

With the best accepted lenses in trial frame, both eyes are fogged with +1.0 DS, reducing the vision. Then a rapid alternate cover test is performed and the patient is asked to tell about the eye showing comparatively clearer image. If the eyes are in balance, the patient will report equal blur in both eyes. If the eyes are not in balance, +0.25 D sphere should be added to the better seeing eye until balance is achieved and both eyes are equally blurred. Now slowly defog both eyes simultaneously until patient can read the 6/6 line.

2. DUOCHROME TEST WITH FOGGING

With the best correcting lenses in trial frame, each eye observes the vision chart in turn while its fellow eye is fogged with a +1.0 DS. The sphere before the observing eye is then adjusted to give equally red preference or green preference as felt appropriate by the refractionist.

3. PRISM DISSOCIATION METHOD

With the best correcting lenses in trial frame, both eyes are fogged with +1.0 DS and a vertical prism of 3Δ or 4Δ is placed with base down in front of right eye and base up in front of left eye. Then a single line, usually 6/12, is projected on the chart. The patient will be able to see the same line with both eyes simultaneously. If the patient reports difference in the clarity between the upper and lower line, seen as two separate images, then +0.25 sphere is placed before the eye with better vision. This is done until the two lines are equally distinct for the two eyes. Having established a balance between the two eyes, the prism is removed and the fog is then reduced binocularly until maximum vision is reached with the highest plus or lowest minus spheres.

It is considered the most sensitive method of binocular balance and so is practised more commonly.

4. TURVILLE INFINITY BALANCE TECHNIQUE

A set of letters is seen with a septum in the middle, which masks some letters from each eye. If all the letters are seen clearly and equally, this implies a binocular balance.

5. POLAROID FILTERS

With a set of letters visible to one eye and the other set through the other eye, these also help in binocular balancing.

C. CORRECTION FOR NEAR VISION

Correction for near vision is indicated usually after the age of 40 years. When the distance vision has been satisfactorily corrected, the visual acuity at working distance of the patient should be estimated using any of the near-vision charts (Jaeger's chart, Snellen's reading test types or number points types standardized by the faculty of ophthalmologists N5 to N48). In case near vision is defective, further testing should proceed as follows:

1. Determination of Near Point of Accommodation and Amplitude of Accommodation

The near point should always be determined with the distance correction in place. Determination of amplitude of accommodation is essential for presbyopic corrections. For details of assessment of accommodation, see page 105.

Average accommodative amplitudes for different ages are summarized in Table 5.3. In general, the following must be remembered:

- From the age of 8 years onwards, the accommodation decreases by 1 D for every 4 years till the age of 40 years.
- From 40 to 48 years of age, accommodation decreases by 1.5 D for every 4 years.
- From age 48 years onwards, the accommodation decreases by 0.5 D for every 4 years.

Table 5.3 *Average accommodation amplitude for different ages*

Age (years)	Average accommodative amplitude (D)
8	14 ± 2
12	13 ± 2
16	12 ± 2
20	11 ± 2
24	10 ± 2
28	9 ± 2
32	8 ± 2
36	7 ± 2
40	6 ± 2
44	4.5 ± 1.5
48	3.0 ± 1.5
52	2.5 ± 1.5
56	2.0 ± 1.0
60	1.5 ± 1.0
64	1.0 ± 0.5
68	0.5 ± 0.5

2. Determination of Near Point of Convergence

While correcting near vision, the assessment of convergence is essential and needs consideration. For details, see page 116.

3. Dynamic Retinoscopy

The dynamic retinoscopy (see page 144) provides an objective basis for the optical condition when the eye is focused for near vision. In other words, it is an attempt to give an objective accuracy to measurement of accommodation. However, in practice, this matter has been left entirely to subjective testing.

4. Determination of Near Add

A suitable convex lens addition should be made over the distant correction. The presbyopic spectacles should never be prescribed mechanically by ordering an approximate addition, varying with the age of the patient. Each patient should be tested individually (and each eye separately), for the individual, variation is large. The near adds ordered should give the most serviceable and comfortable (not necessarily the clearest) vision for the particular work for which the lenses are intended.

Rule of thumb, that has gained wide acceptance, is that the near add at a given distance should allow half of the patient's accommodative amplitude to remain in reserve.

For details of presbyopic correction, see page 107.

DETERMINATION OF THE MUSCLE BALANCE

Before the final prescription is given, it is always desirable to test for the oculomotor balance, both for distant vision and near vision, with and without the correction in front of the eyes.

For details of the workup of a patient for oculomotor balance, the readers are referred to the manuscript on 'Squint and Orthoptics'. However, it must be emphasized that before dispensing, one must ascertain for the presence of the following:

- Any manifest deviation,
- Heterophoria, type and degree,
- Convergence insufficiency and
- Fusional reserves.

The oculomotor imbalance, when discovered, should be given a due attention, since it can be a potent cause of the symptoms of eye strain.

MODIFICATIONS IN THE PRESCRIPTION

Modifications in the prescription, which may sometimes be required to take care of the associated oculomotor imbalance, are as follows:

1. ***A full cycloplegic correction,*** without making any tonus allowance for the cycloplegic used, should be given in children having refractive error with associated manifest deviation.
2. ***An undercorrection of hypermetropic*** error is recommended to reduce the degree of consecutive exotropia. However, this should not be at the cost of asthenopic symptoms.

3. ***A slight overcorrection of myopia*** may sometimes help in controlling the intermittent exotropia.
4. ***An overcorrection by*** +1 to +3 D of the amblyopic eye has been advocated by some workers as penalization treatment.
5. ***Bifocal glasses*** are quite useful in controlling deviation of patients having non-refractive accommodative esotropia.
6. ***In exophoria,*** both eyes may be undercorrected by an equal amount of spherical plus power. This forces the patient to accommodate constantly and accordingly induces accommodative convergence. However, it should be kept in mind that constant accommodation itself may lead to eye strain.
7. ***In esophoria,*** the patient should receive as much spherical plus correction as is compatible with his or her best visual acuity. Bifocal glasses decrease or eliminate the need for accommodation during near vision and thus may be useful in patients having esophoria of convergence excess type. Bifocals should be used as a temporary aid to orthoptic treatment aiming to reduce the focal segment as soon as possible.
8. ***In hyperphoria,*** if feasible, the lenses of the patient's optical correction may be decentred to achieve a prismatic effect, thus relieving the stress on patient's vertical vergence control.
9. ***In cyclophoria,*** best possible efforts should be made to discover and correct the associated astigmatic refractive error.
10. ***Prisms*** may need to be incorporated in glasses sometimes in the presence of phorias as follows:
    - *Role of prisms as a permanent correction in horizontal phorias is debatable.* They should be considered only after other measures have failed to relieve the symptoms. For exophoria, base-in prisms and for esophoria, base-out prisms are incorporated into the glasses.
    - *Prisms are quite useful as a permanent correction in the treatment of comitant vertical phorias*. A vertical prismatic correction of 10Δ is the maximum amount that can be tolerated. There is no fixed rule as to the amount of prism correction to be given in a particular patient. However, in practice, prisms are prescribed with apex towards the phoria to correct only half or at the most two-thirds of total heterophoria.

SUMMARY OF CLINICAL REFRACTION

The technique of determination of errors of refraction described in this chapter may give the impression that, perhaps, clinical refraction is a cumbersome and lengthy procedure. On the contrary, it is not so. In fact, the technique takes longer to describe than to perform. However, it does emphasize that the refractionist must be fully aware of the theory as well as art of performing refraction.

Steps of Clinical Refraction

Steps of clinical refraction can be summarized as follows:

1. *History* of visual symptoms complained of by the patient should be elicited quickly and meticulously.
2. *Visual acuity* should be tested, uniocularly and binocularly, both with and without any correction, for distance as well as near.
3. *External examination*, preferably with a slit lamp, should be carried out, especially to rule out diseases of cornea and lens.
4. *Ophthalmoscopic examination* should be carried out to rule out opacities in the media and diseases of fundus responsible for low vision.
5. *Cover tests* to detect latent and manifest deviations may best be done at this stage, before the trial frames are put on. A manifest deviation may account for marked loss of vision in that eye.
6. *Retinoscopy*, and its verification with the spherocylindrical combination, provides the best objective refraction. Alternatively, *autorefractometry* observations may be used as objective refraction.
7. *Subjective refinement of sphere* should be carried out first.
8. *Subjective refinement and finalization of cylindrical lens,* axis first and then power, should be

carried out using either astigmatic dial clock fogging technique or cross-cylinder, or astigmatic fan and block method. Most practical and thus common approach is the use of Jackson's cross-cylinder.

9. *Further subjective refinement and finalization of sphere* should then be done using fogging technique, duochrome test and pinhole test.

10. *Equalization of vision (binocular balancing)* should always be carried out to avoid asthenopic symptoms due to unstable accommodation. Prism dissociation method of binocular balancing is perhaps the most sensitive one.

11. *Near vision correction* should be carried out in patients with presbyopia. It should always be verified by evaluating the range.

12. *Muscle balance* should be tested with full correction, both for distance and near vision. Adjustment in trial frame correction, if required, may be made accordingly.

6 Keratometry, Corneal Topography and Aberrometry

Chapter Outline

Wavefront Aberrometry

- Hartmann–Shack aberrometry
- Tscherning aberroscope
- Ray-tracing aberrometry
- Intraoperative, real-time wavefront-guided aberrometry
- Clinical applications of aberrometry

CORNEAL OPTICS

Cornea is the most powerful refractive element of the eye, contributing about 43 D (70%) of refractive power to the eye out of the total 58.64 D. Since the shape of the corneal surface determines its refractive power, even a minor modification on its surface can lead to a significant alteration of the images formed on the retina. Consequently, efforts have been made to detect and monitor this important refractive surface of cornea. The techniques frequently used to measure the anterior corneal curvature are keratometry and corneal topography. Before discussing the basic and applied aspects of these techniques, it will be worthwhile to have a brief review of the optical aspects of cornea.

DIMENSIONS OF CORNEA

- The *anterior surface* of cornea is elliptical with an average horizontal diameter of 11.5 mm and vertical diameter of 10.6 mm.
- The *posterior surface* of cornea is circular with an average diameter of 11.5 mm.
- *Thickness* of cornea varies from 0.52 mm at centre to 0.8 mm peripherally and about 1.2 mm (1200 µm) at the limbus.
- *Radii of curvature.* The normal human corneal surface is both aspherical and variable in curvature. It has got different radii of curvature at different points along the same meridian with central steepening and peripheral flattening. Asphericity varies even among different meridians of the same cornea. The anterior and posterior radii of curvature of the central optic zone of cornea are approximately 7.8 and 6.70 mm, respectively.

OPTICAL POWER OF CORNEA

Refractive power of the cornea is about 43 D, which is approximately 70% of the total refractive power (58.64 D) of the eye. The cornea has the largest dioptric power because the largest index difference is between air (1.000) and cornea (1.376). The other interface differences are minor.

OPTICAL ZONES OF CORNEA

For practical and functional purposes, the surface of the cornea can be divided into two general regions: the central optical zone and peripheral zone (Fig. 6.1A). The central zone (4 mm) is responsible for forming the image at fovea. Peripheral zone may be further divided into paracentral (4–8 mm), peripheral (8–11 mm) and limbal zones (11–12 mm).

1. ***Central zone.*** It is approximately 4 mm in diameter and has been called the *apical* zone or the corneal cap or the central spherical zone. It is more spherical, symmetrical, optically important area of cornea where the radius of curvature does not vary by more than 1 D or 0.05 mm. This may also be defined as the area where refraction differs by less than 0.25 D.
2. ***Paracentral zone.*** It is approximately 4–8 mm in diameter, is flatter than the central zone but is still generally spherical. The central and paracentral zones together constitute the *optical zone*, the term more frequently used by contact lens fitters. After radial keratotomy (RK), there is a marked change in the curvature of this zone.
3. ***Peripheral zone.*** It is about 8–11 mm in diameter. It is the area in which the normal cornea flattens the most and becomes more aspheric.
4. ***Limbal zone.*** It is the rim of cornea, approximately 0.5 mm wide, which abuts the sclera.

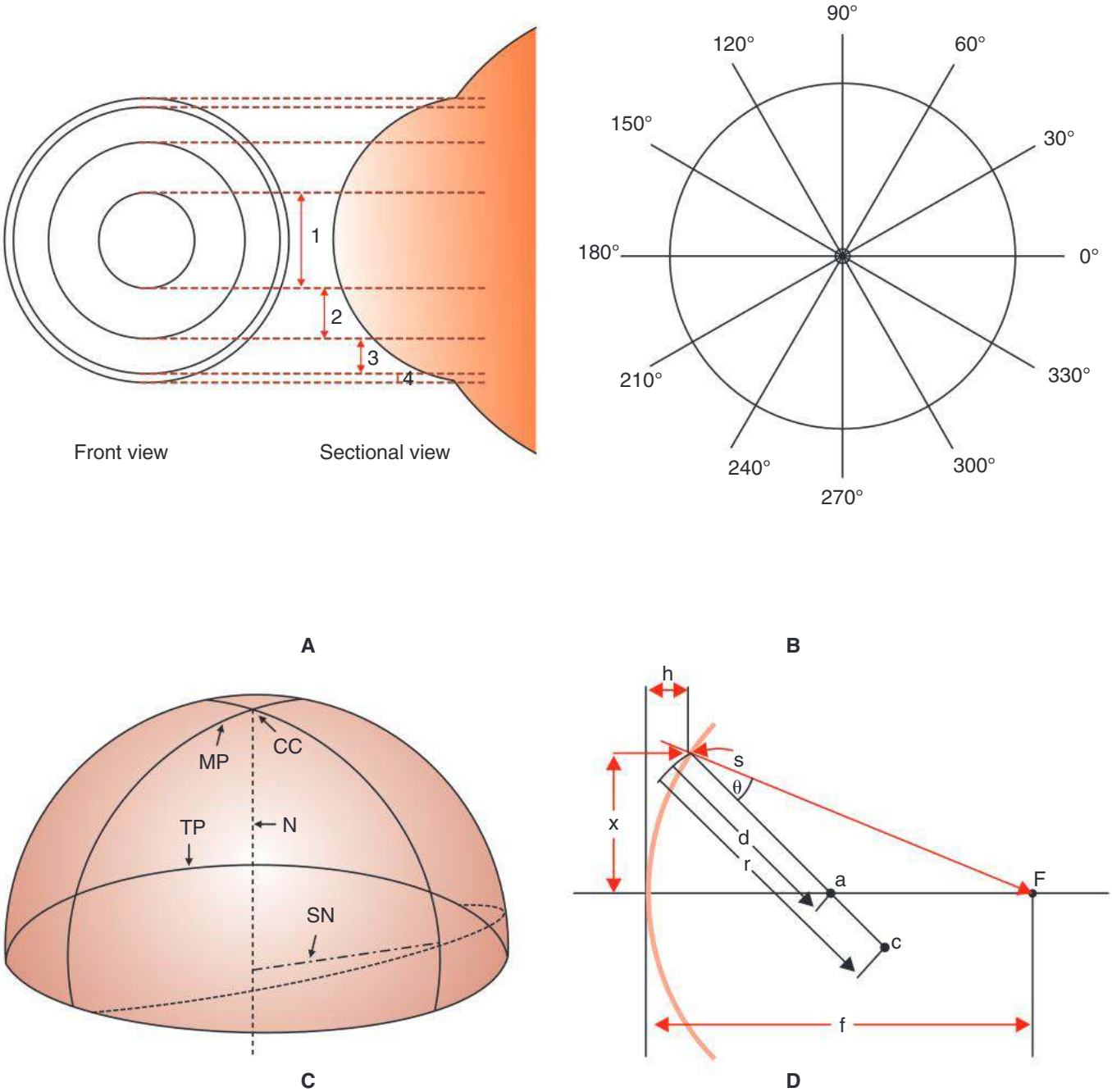


Fig. 6.1 *Optical zones and planes of cornea. A, Optical zones of the cornea: (1) central zone (diameter 4 mm), (2) paracentral zone (between 4 and 8 mm), (3) peripheral zone (between 8 and 11 mm) and (4) limbal zone (between 11 and 11.5 mm). B, Meridional planes of cornea, a top-down view of the cornea in a polar coordinate system. All meridian planes include the centre where the lines intersect, defined as the system origin. C, Three-dimensional illustration of corneal surface showing transverse plane (TP) and meridional plane (MP). The intersection of two MPs defines the corneal centre (CC) and the vertical dotted lines represent the normal (N) at that point. The line intersecting the TP represents the surface normal (SN) at that point. D, Drawing depicting axial distance (d), surface height (h) and the reference axis intersected at (a) by a normal to the surface point (s) of the cornea. Other points shown are centre of curvature (c), radius of curvature (r), perpendicular distance between the surface point and the reference axis (x) and the focal distance (f).*

PLANES AND MERIDIANS OF CORNEA

For the ease of interpretation and description, the three-dimensional corneal surface can be reduced to two dimensions by passing multiple planes of intersection through it. Various definitions adopted are as follows:

Meridional plane (Fig. 6.1B). A plane through the centre of the cornea is called a meridional plane (MP) or tangential plane. MPs are specified in polar coordinates, with the origin at the centre, the angular position of 0 degrees at the 3-o'clock position and angles increasing in a counterclockwise manner.

Corneal meridians. These are the intersection of MPs with the corneal surface and cover angular positions from 0 to 180 degrees.

Hemimeridia or semimeridia are defined from the centre outwards and cover angular positions from 0 to 360 degrees.

Sagittal planes (Fig. 6.1C). The transverse plane (TP) or the sagittal planes are defined to complete the three-dimensional description. A transverse or sagittal plane of intersection at a surface point is perpendicular to the MP through that point and contains the surface normal (SN).

AXIAL DISTANCE, SURFACE HEIGHT AND REFERENCE AXIS

Axial distance, surface height and reference axis are important terminologies that help in understanding the corneal topography. These are described in brief here (Fig. 6.1D).

Axial distance. It refers to the distance from a point on a curve to the reference axis along the SN at that point. For a circle or sphere, the axial distances and radii of curvature are all identical. Similar to the radius of curvature, axial distance converted to a dioptric value is topographic data display using the keratometric formula:

$$Da = \frac{n - 1}{d}$$

where Da is axial dioptres, d is axial distance, n is the keratometric index of refraction (1.3375) and 1 is the index of refraction of air.

Axial-distance–based display used in corneal topography is useful for refractive power maps.

Surface height. It refers to the actual elevation of the corneal surface relative to a reference. The reference can be a plane tangent to the apex or a best-fit reference sphere. Topographic display of surface height (sagittal height or sag) relative to a reference sphere provides much more clinically useful information. For creation of colour-coded map based on surface height, an intermediate colour is chosen to correspond to the neutral position, or match with the sphere, and elevation above and below the sphere are shown.

Reference axis. It defines the centre of topographic display and thus the MPs in which axial shape and curvature are determined. The most appropriate axis to be used for centring corneal topography should preferably depend on the application for which corneal topography is used. For example, for refractive surgery where relationship between the shape and optical performance is crucial, it is logical to centre on the line of sight, while for a contact lens fitting, a reference axis through corneal apex might be more appropriate.

OPTICAL PRINCIPLES AND NOMENCLATURE OF TECHNIQUES TO STUDY CORNEAL SHAPE AND CURVATURES

Most of the techniques employed to study the shape of corneal surface are based on the fact that the anterior surface of the cornea acts as a convex mirror and that the size of the image formed varies with its curvature. Various techniques that have been employed from time to time to study the shape of corneal surface can be broadly grouped into two:

I. *Reflection-based techniques and*
II. *Projection-based techniques.*

I. REFLECTION-BASED TECHNIQUES

These calculate the slope of the corneal surface, then the curvature and power. They include:

1. Keratometry and
2. Keratoscopes (Placido disc keratoscope, photokeratoscopy and videokeratoscopy).

1. KERATOMETRY

Helmholtz was the first to devise an instrument named ophthalmometer to measure the shape of the cornea. Later on, the term keratometer was found more appropriate and thus was preferred over ophthalmometer. As discussed in detail, the keratometer helps to measure the radius of curvature of the anterior corneal surface from four reflected points approximately 3 mm apart (Fig. 6.2A). This device is limited by the fact that it provides no useful information regarding corneal surface central or peripheral to these points.

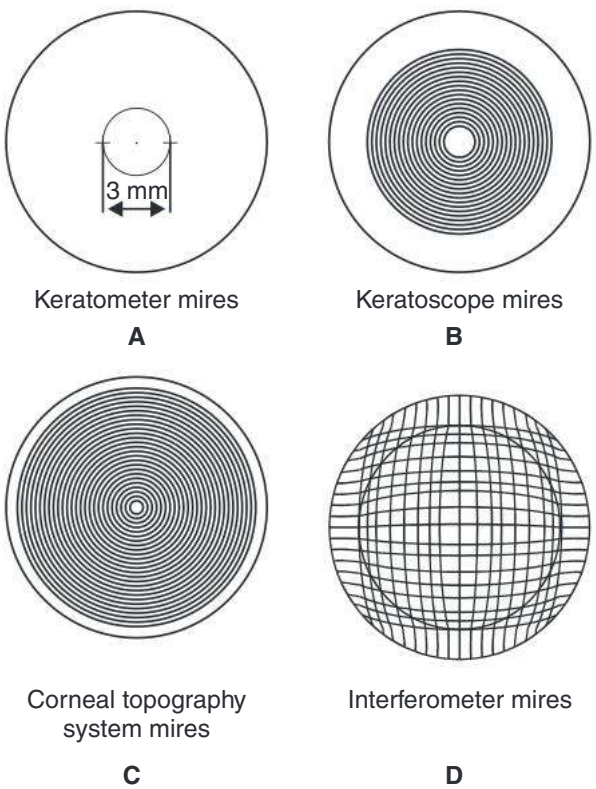


Fig. 6.2 *Surface area of the cornea covered by mires of A, keratometer – note that it measures only two points approximately 3 mm apart; B, keratoscope – note that the 12-ring corneascope mires cover approximately 70% of the surface, omitting the central and peripheral zones; C, corneal topography system – note that the mires cover approximately 95% of the surface; D, interferometer – note the fringes cover the entire cornea and limbus.*

2. KERATOSCOPY

Keratoscopy is a general term that refers to the evaluation of topographic abnormalities of the corneal surface by direct observation of images of mires reflected from the surface of the cornea (Fig. 6.2B). The evolution and advances in the field of keratoscopy can be described as follows:

i. ***Placido disc keratoscope.*** In 1880, Antonio Placido developed the first keratoscope, popularly known as *Placido disc*. It consists of equally spaced alternating black and white rings with a hole in the centre to observe the patient's cornea (Fig. 6.18A). Distortions in corneal shape appear as deviations from evenly spaced concentric circles.

Disadvantages include the following:

- Small degrees of abnormalities of corneal shape are not easily identifiable.
- It cannot be used in corneas with epithelial defects and stromal ulcers, etc. because of non-reflection of the target by the cornea.

  Thus, Placido disc is used only as a gross method of qualitative assessment of the corneal surface.

ii. ***Photokeratoscopy.*** When a photographic film camera is attached to a keratoscope, the instrument is called photokeratoscope. A record or portrayal of corneal surface produced by the photographic film is called a *keratography*. Despite Placido's invention of the photokeratoscope in 1880, quantitative analysis of the eye was not possible until 1896 when Gullstrand provided precise methods for analysing corneal topography. In this technique, keratoscopic image is photographed and the size of the images on the photographic film can be varied to change the size of the corneal image. The corneal curvature is then measured by utilizing the distance of the keratoscopic rings from the cornea, the magnification of the virtual image formed by the anterior surface of the cornea and the focal length of the objective of the camera.

The image of most photokeratoscope rings covers the paracentral area, overlapping into the central and peripheral zones, but leaving the optically important central 2–3 mm as well as the peripheral cornea. Current photokeratoscopes (e.g. Nidek PKS-1000 or Keracorneascope) have 9–15 rings, which cover 55%–75% of the corneal surface. In these photographs, the closer the line, the steeper is the corneal surface; and the further apart the lines, the flatter is the corneal surface. However, corneal cylinders of up to 3 D can escape detection by use of photokeratoscopy.

iii. ***Videokeratoscopy/videokeratography***. When a television camera is attached to a keratoscope, it is called a videokeratoscope. Tremendous advances have occurred in the field of videokeratoscopy. With the advent of computers, the videokeratoscopy has been computerized. A portrayal of the video recording of the corneal surface is called videokeratograph. All videokeratoscopes use the same reflection mechanism, but they may vary in the size of cone – large or small cone-based placid projection system. The large cone Placido can be used slightly away from the patient's face, whereas the small cone device needs to be very near to the patient's eye. The advantage of the small cone devices is more complete coverage of the cornea and avoidance of data loss due to the varying nasal bridge anatomy. These areas of absent data are seen as data gaps in final printouts in some devices and may be interpolated in others to give a complete coverage. This is the biggest disadvantage with large cone placid device while more focussing errors are seen with small cone devices. The usual coverage of corneal surface with large cone Placido devices is 70%–95%. Some devices have also introduced blue-coloured mires (Nidek OPD Scan 3) to facilitate accurate edge detection by computer. The data points on the mires of a videokeratograph can be resolved with either manual or automated digitalization.

In fact, presently the computer-assisted videokeratoscopy has become synonymous with the corneal topography and thus will be discussed in detail in the ensuing text. It covers approximately 95% of the corneal surface (Fig. 6.2C).

II. PROJECTION-BASED TECHNIQUES

Projection-based systems project an image on the corneal surface and measure the true shape of the cornea by calculating the height or elevation, above a reference plane. This data can be used to calculate slope, curvature and power. These include rasterstereography, laser interferometry and Moiré interference.

1. RASTERSTEREOGRAPHY

It uses a direct image on the corneal surface. It projects a calibrated grid (a grid pattern of horizontal and vertical lines spaced 0.2 mm apart is used) on to the fluorescein-stained tear film, takes a photograph and uses computer algorithms to analyse the pictures. The accuracy of the system is 0.3 D for a diameter of 7 mm. The contour plots of cornea appear like keratographs, but actually, each line is an isopter, representing areas of equal height on the corneal surface.

The advantage of this system over the keratoscopic one is that it includes information across the whole of the cornea and even includes part of the sclera. Furthermore, the projected nature of the test does not allow interference due to corneal surface or stromal defects.

2. INTERFEROMETRY

It uses the technique of light wave interference. The interference fringes can cover the entire anterior ocular surface, not just the cornea (Fig. 6.2D). This includes both holography and Moiré fringe techniques. This method is not in widespread clinical use.

KERATOMETRY

Keratometry is measurement of curvature of the anterior surface of cornea across a fixed chord length, usually 2–3 mm, which lies within the optical spherical zone of the cornea.

PRINCIPLE

Keratometry is based on the fact that the anterior surface of the cornea acts as a convex mirror and the size of the image formed varies with its curvature. The greater the curvature of cornea, lesser is the image size. Therefore, from the size of the image formed by the anterior surface of the cornea (first Purkinje image), the radius of curvature of the cornea can be calculated as below.

In Figure 6.3, consider an object AB that forms an image A′B′ after reflection at the anterior surface of the cornea. Ray AC passing towards the centre of curvature C of the cornea is reflected back on itself. Ray AQ is reflected towards QS and seems to meet the ray AC at A′, forming the image A′B′. Now, if the object AB is at infinity then A′B′ will be very small and situated at the focus F. Therefore, B′P will be the focal distance or 1/2 of the radius of curvature of the mirror.

$$\text{Thus, if } AB = O,\ A'B' = I,\ BP = u$$

$$\text{and } CP = r, \text{ then } \frac{r}{2} = u \times \frac{I}{O}$$

$$\text{or } r = \frac{2uI}{O}$$

$$\text{where } O = \text{Object and } I = \text{image}$$

The distance BP denoted by u is kept constant for any instrument by using a short-focus telescope in order to view the reflected image. From this, it is clear that for known object size, measurements of image size will allow us to determine r, the radius of curvature.

The accurate measurement of such an image, however, raises a problem since it is impossible to immobilize the living eye completely while the image is under observation. This has been overcome by devices using the *principle of visible doubling*. In one type of instrument, the image is doubled by refraction through two rotating glass plates which are then adjusted so that the lower edge of one image coincides with the upper edge of the other. If the eye moves during the process, both the images move together, and so difficulties in adjustment are avoided. From the amount of rotation of the glass plate necessary just to double the image, its size can be calculated.

In other types of keratometers, the amount of doubling is fixed but size of external object can be varied. Helmholtz (1854) utilized this principle to devise the first keratometer. He gave the name ophthalmometer to it, but later on keratometer was found to be the more appropriate term.

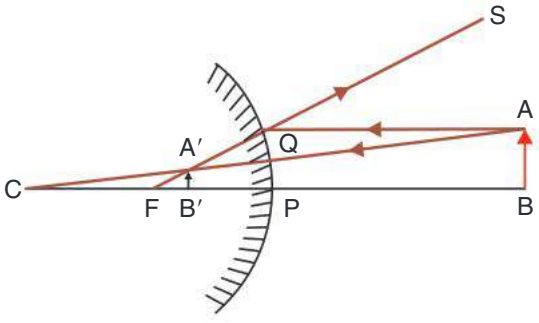


Fig. 6.3 *Principle of keratometry.*

HELMHOLTZ KERATOMETER

Though presently not in use, the Helmholtz keratometer is described here as a tribute to the inventor. Helmholtz keratometer consists of two plates. Each plate displaces the image through half its length and the total displacement gives the size of the image. The doubling of image dispenses with the necessity of immobilizing the living eye. If the eye moves during the process, both the images move together and, therefore, difficulties in adjustment are avoided. The glass plates are of known thickness and index of refraction, placed side by side, so that each covers half of the object of a short-distance telescope. The axis of telescope coincides with the plane of separation of glass plates. These plates can be inclined one to the other at known angles, and the angle of incidence of light falling on them from a point in front can be varied and measured.

Optics of Helmholtz Keratometer

As shown in Figure 6.4, rays from point O meet the plates at U and E and undergo lateral

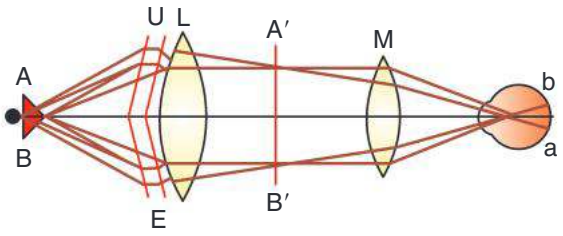


Fig. 6.4 *Optics of Helmholtz keratometer.*

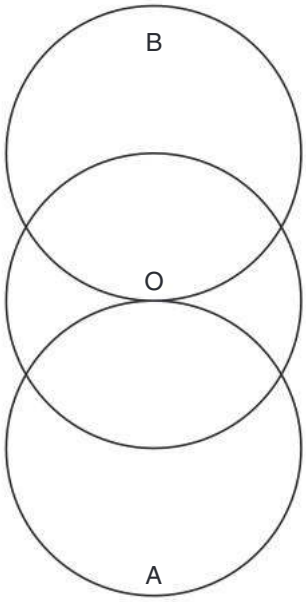


Fig. 6.5 *Measurement of the size of image in Helmholtz keratometer (observer's view).*

Fig. 6.6 *Bausch and Lomb keratometer.*

displacement after refraction. As viewed through L, the two objects appear at A and B. The eyepiece M is so arranged that its principal focus coincides with the images A′ and B′ and receives parallel rays which come to the focus without accommodation on the retina at a and b. As shown in Figure 6.5, if the position of plates is such that the two images A and B just touch at O, then each plate has displaced the image through half its length and the total displacement gives the size of the image. The original instrument has undergone several modifications and nowadays several keratometers are in use.

An ideal keratometer must be able to measure the radii in various meridians about the axis of the cornea. Thus, instruments are designed that can be rotated with respect to a particular axis. The objects are called mires. In order to avoid the error due to constant motion of eyes, a doubling device has been introduced.

■ BAUSCH AND LOMB KERATOMETER

Principle

The working of Reichert (Bausch and Lomb) keratometer (Fig. 6.6) is based on the principle of *constant object size and variable image size*.

Optical System and Other Parts

The functioning of the optical system (Fig. 6.7) and the other parts of this keratometer are as follows:

1. ***The object*** is a circular mire with two plus and two minus signs (Fig. 6.8). As shown in Figure 6.7, a lamp illuminates the mire by means of a diagonally placed mirror. Light from the mire strikes the patient's cornea and produces a diminished image behind it. This image becomes the object for the remainder of optical system.
2. ***The objective lens*** focuses the light from the image of the mire (new object) along the central axis.
3. ***Diaphragm and doubling prisms***. A four-aperture diaphragm is situated near the objective lens. Beyond the diaphragm are two doubling prisms, one with its base up and other with its base out. The prisms can be moved independently, parallel to the central axis of the instrument. Light passing through the left aperture of diaphragm is made to deviate above the central optical axis by a base-up prism. Light passing through the right aperture is deviated by the base-out prism, placing the second image to the right

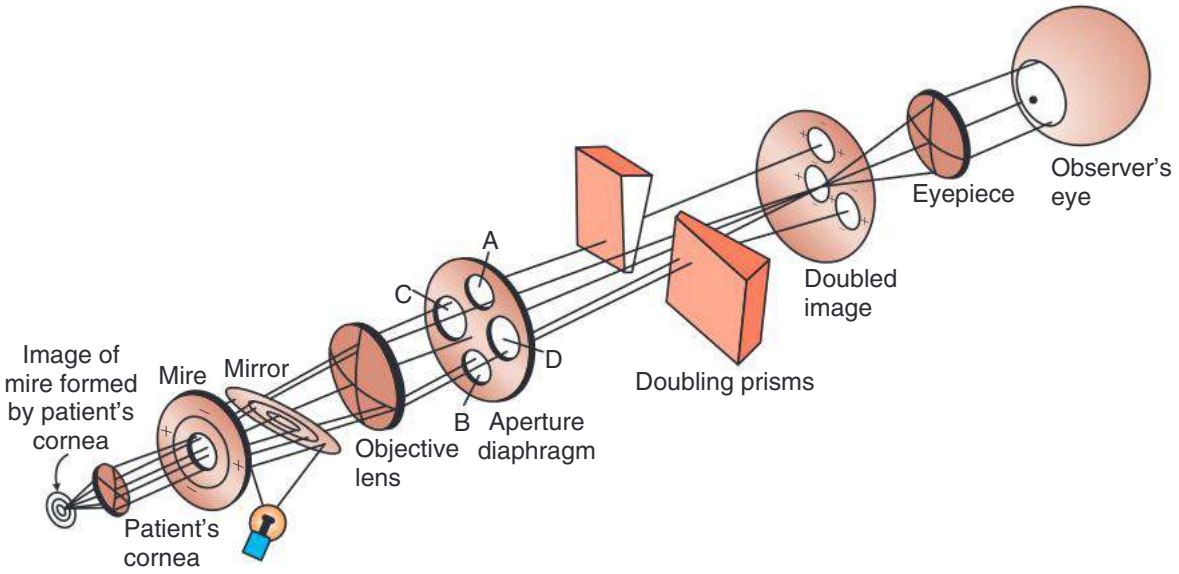


Fig. 6.7 *Optical system of Bausch and Lomb keratometer.*

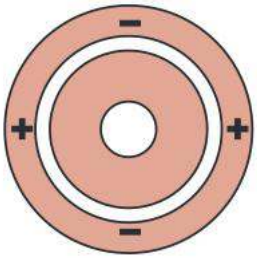


Fig. 6.8 *Configuration of the mires used in Bausch and Lomb keratometer.*

of the central axis. Light passing through upper and lower apertures does not pass through either prism and an image is produced in the axis. The total area of upper and lower apertures is equal to the area of each of the other two apertures. Thus, brightness of the images is equal. The upper and lower apertures also act as Scheiner's disc, doubling the central image, whenever the instrument is not focused precisely on the central mire image. So, continuous monitoring of correct focus can be done. Thus, the image-doubling mechanism is unique in Bausch and Lomb keratometer, in that double images are produced side by side as well as at 90 degrees from each other. This allows the measurement of the power of cornea in two meridians, without rotating the instrument. Therefore, it is also known as *'one-position keratometer'*. The doubling device also moves parallel to the control axis of the instrument so that the amount of separation can be raised.

4. *The eyepiece lens* enables the examiner to observe the magnified view of the doubled image.

Procedure of Keratometry

1. *Instrument adjustment.* The instrument is calibrated before use. A white paper is held in front of the objective piece and a black line is focused sharply on it. The keratometer is then calibrated with steel balls. A steel ball of known radius of curvature is placed before the keratometer and its value is set on the scale or dial. The mires are focused by clockwise and anticlockwise movement of the eyepiece through trial and error. When mires are in focus, the calibration is complete.

2. *Patient adjustment.* The patient is seated in front of the instrument with chin on the chin rest and head against the headrest. The eye that is not being examined is covered with the occluder. Then the chin is raised or lowered till the patient's pupil and the projective knob are at the same level.

3. *Focusing of mire.* After adjusting the instrument and the patient, the mire is focused in the

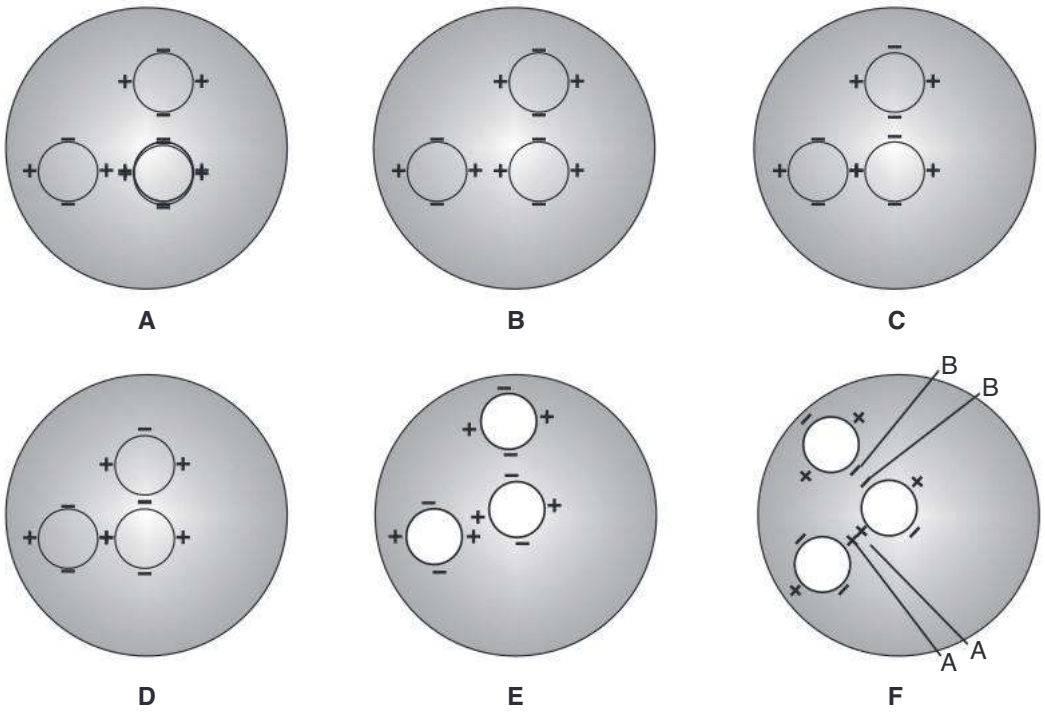


Fig. 6.9 *Examiner's view of the A, mires when not focussed properly; B, mires focussed properly but not aligned; C, alignment of mires when measuring horizontal meridian; D, vertical alignment of mires; E, nonaligned mires in oblique astigmatism and F, alignment of plus signs in oblique astigmatism.*

centre of the cornea. Figure 6.8 shows the patient's view of mire and Figure 6.9A shows the view first seen by the examiner. Note that the central image is doubled, indicating that the instrument is not correctly focused on the corneal image of the mire.

4. ***Measurement of corneal curvature.***

- *The instrument is correctly focused* on the corneal image so that central image is no longer doubled (Fig. 6.9B).
- *To measure the curvature in horizontal meridian*, the plus signs of the central and left images are superimposed using the horizontal measuring control and the reading is noted (Fig. 6.9C).
- *Then to measure the curvature in the vertical meridian*, the minus signs of the central and upper images are coincided with the help of vertical measuring control and the readings are noted (Fig. 6.9D).
- *Regular astigmatism.* For each eye, the difference between horizontal and vertical dioptre readings gives the approximate amount of corneal astigmatism. Normally horizontal and vertical dioptre readings are 90 degrees apart.
- *In the presence of oblique astigmatism,* the two plus signs will not be aligned (Fig. 6.9E). The entire instrument is then rotated till the two plus signs are aligned (Fig. 6.9F). A scale associated with the instrument rotation indicates, in degrees, one meridian of the oblique astigmatism. Corneal radius of power is then measured in this meridian and in the meridian 90 degrees to it as described above.

Interpreting the Findings

Spherical cornea is characterized by:

- No difference in the power between two principal meridians and
- The mires seen as perfect sphere.

Astigmatism is characterized by the following:

- Difference in the power between two principal meridians.
- Horizontally oval mires are seen in with-the-rule astigmatism.
- Vertically oval mires are seen in against-the-rule astigmatism.

- In oblique astigmatism, the principal meridians are between 30 and 60 degrees and 120 and 150 degrees.

Irregular anterior corneal surface is characterized by the following:

- Irregular mires and
- Doubling of mires.

Keratoconus is characterized by the following:

- Inclination and jumping of mires is seen while attempting to adjust the mires. When an attempt is made to superimpose the plus mires, they will jump above and below each other (*pulsating mires*).
- Minification of mires is seen in advanced keratoconus (K > 52 D) due to increased amount of myopia.
- Oval mires are seen due to large astigmatism.
- Irregular, wavy and distorted mires also indicate advanced keratoconus.

Fig. 6.10 *Javal–Schiotz keratometer.*

JAVAL–SCHIOTZ KERATOMETER

Principle

The working of Javal–Schiotz keratometer (Fig. 6.10) is based on the principle of *variable object size and constant image size.*

Optical System and Parts

The functioning of optical system (Fig. 6.11) and other parts of this keratometer are as follows:

1. ***The object*** in this system consists of two mires (A and B), mounted on an arc on which they can be moved synchronously (Figs 6.11 and 6.12). Since the two mires together form the object, the variable size is attained by their movement.

One mire is stepped and has a green filter and other mire is rectangular and has a red filter. The mires are divided horizontally through the centre (Fig. 6.13). The mires are illuminated by small lamps. The image of these mires formed by the patient's cornea (first Purkinje

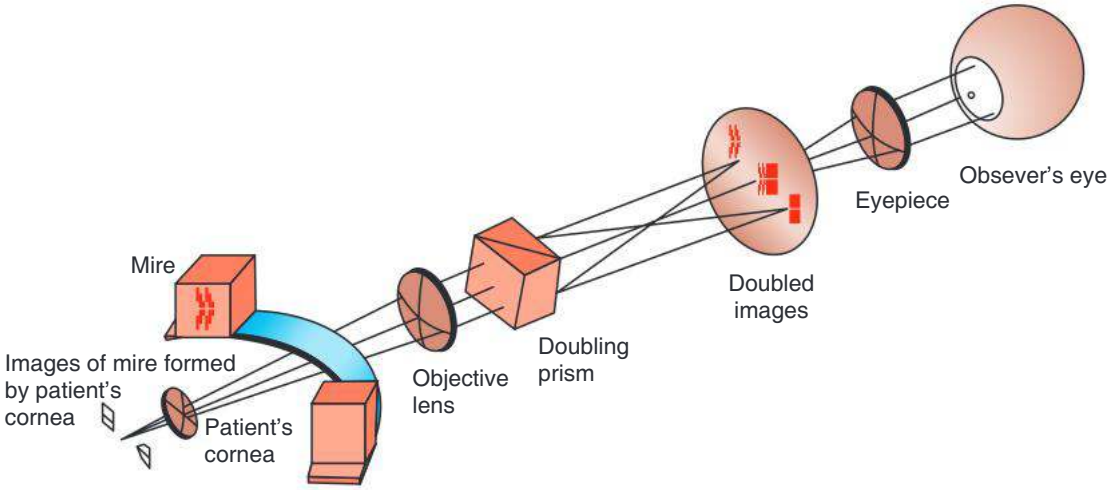


Fig. 6.11 *Optical system of Javal–Schiotz keratometer.*

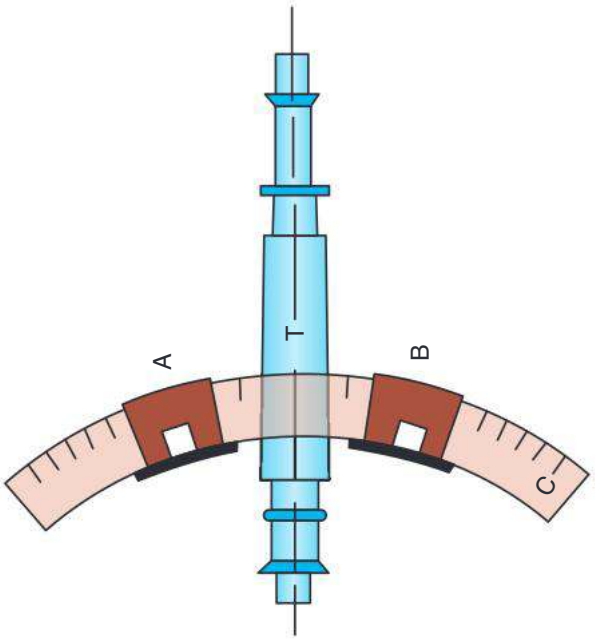


Fig. 6.12 *Basic structure of Javal–Schiotz keratometer showing placement of mires A and B on the arc.*

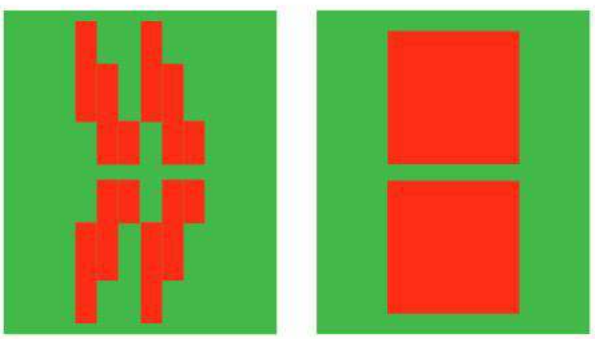


Fig. 6.13 *Patient's view of the mires.*

image) acts as *an object for the rest of the optical system* of the keratometer.

2. ***Objective lens and doubling prism*** form the *doubled image* of the new object (image of the mires formed by cornea). The doubling prism used in this instrument is a Wollaston type. It produces a fixed image doubling by the birefringent (double refracting) characteristic of the material of which it is made.

3. ***The eyepiece lens*** enables the examiner to observe the magnified view of the doubled image.

Procedure of Keratometry

1. ***Instrument adjustment.*** A white paper is held in front of the objective piece and a black line is focused on it. Then the instrument is calibrated to make it ready for use.

2. ***Patient adjustment.*** The patient is seated in front of the keratometer with chin on the chin rest and forehead against the forehead rest. The chin rest is adjusted to bring the eye at the level of the telescope (T) of the instrument (Fig. 6.12). The eye not being examined is covered with an occluder provided with the instrument.

3. ***Adjustment of mires***. The mires are adjusted in such a way that they are focused in the centre of the patient's cornea. Figure 6.13 shows the patient's view of mires and Figure 6.14 shows the view of the doubled mire image as seen by the examiner through the instrument's eyepiece.

4. ***Recording of keratometric readings***. Only the central pair of images is used when measurements are made. By changing the separation of mires, the separation of these two images can be changed. When the two control images just meet, the scales associated with the mire separation indicate the correct corneal radius and the dioptric power of the cornea.

The radius of curvature is first found in one meridian. Then the entire optical system is rotated by 90 degrees about its central axis. The measurement of the radius of curvature in the second meridian, which is perpendicular to the first one, is then made in the similar way. When the corneal astigmatism is present, there may occur overlapping of the mires (Fig. 6.15) or they may move further apart. Since the stepped mire (staircase pattern) is green and the rectangular mire is red, the area of overlap appears whitish. Each step of the mire corresponds to 1 D of corneal power and thus the number of steps overlapped gives the approximate degree of astigmatism.

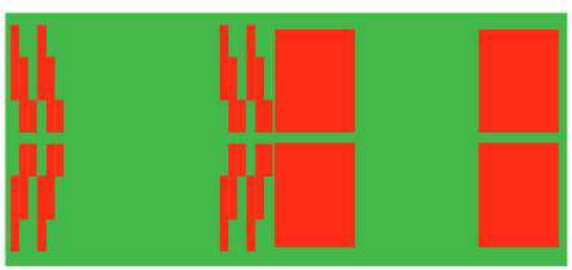


Fig. 6.14 *Examiner's view of doubled mire image.*

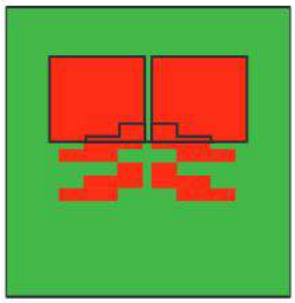


Fig. 6.15 *Overlapping of mires in corneal astigmatism.*

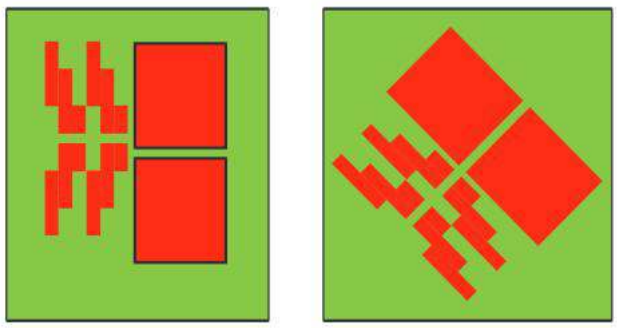


Fig. 6.16 *Appearance of images in oblique astigmatism when mires are horizontal before (A) and after alignment (B).*

When *oblique astigmatism* is present and the mires are horizontal, the central bisecting lines of the images are not aligned (Fig. 6.16A). In such cases, the instrument is rotated until the control lines are aligned (Fig. 6.16B). A scale associated with the instrument rotation indicates, in degrees, one meridian of the oblique astigmatism. Corneal radius or power is then measured in this meridian and also in the meridian 90 degrees to it as usual.

SURGICAL/OPERATING KERATOMETER

The surgical keratometer is attached to the operating microscope. It is helpful in monitoring the astigmatism during corneal/limbal surgery. The accuracy of surgical keratometer is limited due to the following factors:

- Difficulty in aligning the patient's visual axis and the keratometer's optical axis.
- Keratometers are calibrated for a fixed distance from the anterior cornea. The different microscope objective lenses result in different focal lengths and, therefore, different working distance.
- Air in the anterior chamber results in a second target reflection.
- External pressure on the globe results in a change in the corneal curvature.

AUTOMATED KERATOMETER

Essentially, an autokeratometer is similar to manual keratometer. In it, the reflected image of target is focused on to a photodetector which measures image size, and radius of curvature is computed. The target mires are illuminated with infrared light, and an infrared photodetector is used.

Advantages of autokeratometers:

- A compact device.
- Very less time-consuming.
- Comparatively easy to operate.

Precision of autokeratometry. Almost all the studies have found exceptionally high precision with autokeratometry.

Availability of autokeratometer. Autokeratometers are available alone and more commonly in association with autorefractometers as *autokeratorefractometers* (e.g. Nidek ARK 2000-S autokeratorefractometer).

Automated keratometry option is also available in the following equipment:

- The IOLMaster (see page 348),
- Pentacam (see page 201),
- Orbscan (see page 199) and
- Corneal topographer (see page 184).

Handheld autokeratometers are also available, e.g. PalmScan P2000 and HandyRef-K (uses synchroscan technology) (Fig. 6.17).

Fig 6.17 *Handheld autokeratometer.*

RELATIONSHIP BETWEEN RADIUS OF CURVATURE AND DIOPTRIC POWER OF CORNEA

The following equation gives the relationship between radius of curvature and dioptric power of the cornea:

$$D = \frac{n-1}{r}$$

where D is the dioptric power of the cornea, n is the index of refraction of the cornea and r is the radius of cornea in metres.

Since the invention of ophthalmometer by Helmholtz, the index of refraction of the cornea has been taken 1.3375 for calibrating the instrument. Therefore,

$$r = \frac{1.3375-1}{D} \text{ m}$$

$$\text{or } r = \frac{337.5-1}{D} \text{ mm}$$

Usually, the keratometers are calibrated both for radius of curvature and corresponding dioptres. Otherwise, the conversion can also be made by using the above-described equation. For a ready reference, conversion table is also available.

Range of keratometer is 36–52 D (6.5–9.38 mm). Its lower limit can be extended up to 30 D (5.6 mm) and upper limit up to 61 D (10.9 mm) by interposing a lens of –1.0 D and +1.25 D, respectively, in front of the objective of telescope.

CLINICAL USES OF KERATOMETERS

The various uses of keratometer in day-to-day ophthalmic practice are as follows:

1. It helps in measurement of *corneal astigmatic* error.
2. It helps to estimate the radius of curvature of the anterior surface of the cornea. So, it is of great use in *contact lens fitting*.
3. Keratometer is used to monitor the shape of the cornea in keratoconus and keratoglobus.
4. We may be able *to assess the refractive error* in cases with hazy media (rough estimate on the basis that the normal measurement is 43.5 D – comparison of the two eyes in these cases is useful).
5. Keratometry has gained a special place in *intraocular lens (IOL) power calculation*. The K readings are taken with the help of keratometer and along with axial length; these are utilized to calculate IOL power in Sanders–Retzlaff–Kraff (SRK) formula for IOL power calculation.
6. It is used to monitor pre- and post-surgical astigmatism.
7. It is used for differential diagnosis of axial versus curvatural anisometropia.
8. It is used to detect rigid gas-permeable lens flexure.

LIMITATIONS OF KERATOMETRY

1. The measurements of keratometer are based on a false assumption that the cornea is a symmetrical spherical or spherocylindrical structure, with two principal meridians separated from each other by 90 degrees, whereas the cornea in reality is aspheric.
2. It measures the refractive status of a very small central area of cornea (3–4 mm), ignoring the peripheral corneal zones.
3. It loses its accuracy when measuring very flat (<40 D) or very steep (>50 D) cornea.
4. Finally, small corneal irregularities would preclude the use of keratometer due to irregular astigmatism.
5. Assumed index of refraction in radius to dioptre conversion.
6. One-position instruments assume regular astigmatism.
7. Distance to focal point is approximated by distance to image.
8. The use of para-axial optics to calculate surface power.
9. It cannot describe corneal asphericity.

SOURCES OF ERRORS IN KERATOMETRY

- Improper calibration
- Faulty positioning of the patient
- Improper fixation by the patient
- Accommodative fluctuation by examiner
- Localized corneal distortion
- Excessive tearing
- Abnormal lid position
- Improper focusing of the corneal image

CORNEAL TOPOGRAPHY

GENERAL CONSIDERATIONS

Corneal topography refers to study of shape of corneal surface. The term corneal topography system (CTS), or videokeratography, implies computerized, video-assisted technique that provides detailed information about the shape of the corneal surface. Present day technologies allow three-dimensional evaluation with cross-sectional images and are thus referred to as ***corneal tomography systems.***

WORKING PRINCIPLES

Present day available corneal topography and tomography systems are based on one or combination of more than one below given working principles:

- Placido disc principle-based corneal topography/tomography systems,
- Slit-scanning principle corneal tomography system (e.g. Orbscan 3),
- Scheimpflug imaging principle-based systems (e.g. Pentacam, Sirius, Galilei),
- High-speed anterior segment optical coherence tomography (AS-OCT),
- Digital rasterstereography-based topography systems,
- Laser halographic interferometry-based topography systems and
- Very high frequency (VHF) ultrasound-based system.

COMMONLY USED CORNEAL TOPOGRAPHY/ TOMOGRAPHY SYSTEMS (CTS)

Commonly used CTS and aberrometry systems are listed in Table 6.1.

Table 6.1 *Commonly used corneal topography systems and aberrometry systems*

System	Working principle
A. CORNEAL TOPOGRAPHY AND TOMOGRAPHY SYSTEMS	
I. *Placido disc-based systems*	
1. EyeSys Desktop (*EyeSys Vision, Inc., USA*)	Placido ring/cone
2. Tomey TMS-4 (*Tomey Corp, Japan*)	Placido disc based
3. CA-200F Corneal Analyzer (*Topcon Medical Systems, Inc., Japan*)	Placido disc-based topography system (with 24 rings measuring over 10,000 data points and eight blue LED lights for fluorescein images to aid in contact lens simulation)
4. AstraMax (*LaserSight Technologies, Florida*)	Placido disc-based, 3D corneal topography
5. Keratron (Opticon 2000) – Arc step mapping	Placido disc-shaped 3D corneal topography
II. *Scheimpflug rotating imaging-based systems*	
1. Pentacam AXL (*OCULUS, Germany*)	Dual Scheimpflug and Placido disc imaging
2. Oculyzer (*WaveLight AG, Germany*)	Dual Scheimpflug and Placido disc imaging
3. Preciso (*iViS Technologies, Taranto, Italy*)	Dual Scheimpflug and Placido disc imaging
4. Galilei G6 (*Zeimer, Switzerland*)	Dual Scheimpflug and Placido disc imaging
5. TMS-5 (*Tomey Corp., Japan*)	Dual Scheimpflug and Placido disc imaging
6. Sirius (*CSO, Italy*)	Dual Scheimpflug and Placido disc imaging
III. *Horizontal slit scan-based system*	
1. Orbscan IIIz (*Bausch & Lomb, Rochester, New York*)	Dual horizontal slit scan and Placido disc imaging
IV. *Rasterstereography-based system*	
1. PAR corneal topography system (*CTS; Par Vision Systems Corp., New Hartford, NY*)	Elevation-based systems that projects a grid onto the corneal surface after instillation of fluorescein. Distortions in grid patterns are analysed to determine corneal elevation based on camera and grid projection angles (rasterstereography)

Table 6.1 *Commonly used corneal topography systems and aberrometry systems—cont'd*

System	Working principle
V. *Very high frequency (VHF) ultrasound-based system*	
1. Artemis 3 (*ArcScan, Colorado*)	Arc scanning with VHF ultrasound
VI. *Optical coherence tomography-based systems*	
1. Visante Omni (*Carl Zeiss Meditec, Germany*)	Rotating optical coherence tomography and Placido disc imaging
2. SS-1000 Casia (*Tomey Corp., Japan*)	Rotating optical coherence tomography
3. RTVue-100 (*Optovue, Inc. Fremont, CA*)	Spectral domain optical coherence tomography-guided corneal power measurement (both anterior and posterior curvatures)
4. IOLMaster 700 (*Carl Zeiss Meditec, Germany*)	Swept source OCT technology with 32-marker Placido pattern
5. 3D OCT-2000 (5) (*Topcon Medical Systems*)	Spectral domain OCT
6. Cirrus HD-OCT 5000 (2) (*Carl Zeiss Meditec, Germany*)	Spectral domain OCT, Confocal scanning laser ophthalmoscope (CSLO)
B. CORNEAL TOPOGRAPHERS WITH ABERROMETERS	
1. KR-1W Wavefront Analyzer (*Topcon Medical Systems*)	• Hartmann–Shack Aberrometry • Near-infrared corneal topography
2. iTrace (*Tracey Technologies, Houston*)	• Ray-tracing aberrometry • Placido disc corneal topography (sequentially projects 256 near-infrared laser beams into the eye to measure forward aberrations, processing data point-by-point)
3. ATLAS 9000 Corneal Topography System (*Carl Zeiss Meditec, Germany*)	• Placido disc topography (22 ring) • Patented 'cone of focus' alignment system • Ray-tracing aberrometry
4. OPD-Scan III (*Nidek, Gamagori, Japan*)	• Placido disc topography (33 blue mires) • Dynamic skiascopy for aberrometry
5. WaveLight Allegro Oculyzer II (*Alcon, USA*)	• Rotating 3D Scheimpflug imaging topography • Tscherning principle aberrometry
6. Cassini TCA (*i-Optics, USA*)	• Placido disc corneal topography • Ray-tracing aberrometry systems
7. Discovery (*Innovative visual systems, USA*)	• Placido disc corneal topography and • Hartmann–Shack principle
C. ABERROMETERS	
1. Zywave II Wavefront Aberrometer (*Bausch & Lomb*)	• Hartmann–Shack principle
2. WASCA Analyzer/Aberrometer (*Carl Zeiss Meditec, Germany*)	• Hartmann–Shack principle
3. LADARWave (*Alcon, USA*)	• Hartmann–Shack principle
4. VISX WaveScan Wavefront Aberrometer (*Abbott Medical Optics, Inc. [AMO], USA*)	• Hartmann-Shack principle
5. WaveLight Allegro Analyzer (*Alcon, USA*)	Tscherning principle
6. Optiwave Refractive Analysis (ORA) System (*Wavetec, USA*)	Infrared light and Talbot–Moiré interferometry (intraoperative wavefront aberrometer)
7. HOLOS IntraOp Wavefront Aberrometer (*Clarity Medical Systems, Inc., USA*)	Continuous real time intraoperative wavefront aberrometer

PLACIDO DISC-BASED CORNEAL TOPOGRAPHY SYSTEMS

Placido disc CTS were originally limited to evaluation of the anterior corneal surface. Presently, many of the Placido disc-based systems include the imaging of back surface of cornea and direct evaluation of elevational changes of both anterior and posterior corneal surfaces, enabling point-to-point pachymetry. In other words, the CTS can now be called *corneal tomographs*, as they allow three-dimensional evaluation of corneal tissue. This technique has an excellent accuracy and reproducibility. Most corneal topographers evaluate 8000–10,000 specific points across the entire corneal surface.

PLACIDO DISC PRINCIPLE

Placido disc-based CTS work on the reflection principle. The anterior surface of the cornea acts like a convex mirror and hence the size of the image formed by it is determined by its curvature. A steeply curved cornea will produce a smaller image, while a flatter cornea will produce a larger image of the same object situated at the same distance from the cornea. These devices thus measure the slope and compute the curvature. They have different projection devices that use lighted circular rings of varying sizes and numbers, these rings are reflected by convex cornea and through an opening in the centre of the target, the images are obtained by an acquisition camera.

BASIC UNIT OF CORNEAL TOPOGRAPHY SYSTEMS

The basic unit of a corneal topographic/tomographic system thus primarily consists of the following:

- A projection device,
- Acquisition device (video camera) and
- Analytical device (a digital computer attached with a slit-lamp chin rest).

1. PROJECTION DEVICE

These systems imply Placido disc-based projection device. Historically, the Placido disc-based systems were the first to be developed and thus are the most widely used and understood. Most Placido disc-based systems project around 8–32 concentric rings on the cornea. The rings are numbered from inside out. A specified ring in different instruments may cover different areas. Therefore, it is important to mention the diameter of the projected ring along with the number. The virtual images of these reflected rings are located anterior to the iris.

2. VIDEO CAMERA

The reflected images of the rings projected on to the cornea are captured on charge-coupled device (CCD) camera for videokeratoscope. The image accuracy and precision are dependent on focusing, decentration factors, shadows (artefacts) and proper acquisition of good images. These images of the rings are digitized and algorithms are used to determine the radius of curvature of the innermost ring. Once this is determined, then the distance of the next ring from this is calculated and used to determine curvature of this ring and so on till peripheral ring is achieved. The cornea between the rings is not imaged and no actual data for these points and the apex of the cornea, which is inside the innermost ring, are also not measured.

- Dioptric power is calculated from curvature using the formula:
  Dioptric power = refractive index of cornea – refractive index of air/radius of curvature in metres.
- Measured radius of curvature is of anterior corneal surface, so provides power of anterior surface but cannot measure the true power of posterior corneal surface.

3. COMPUTER

The video camera is hooked up to a computer that generates a 'topographic map' of corneal curvature based on the measured distance between the rings reflected from the cornea. The accuracy of the corneal curvature data processing depends a lot on the software-editing features. After analysis, the graphic picture of the patients' topography is displayed in various forms.

LIMITATIONS OF PLACIDO DISC-BASED TOPOGRAPHY SYSTEMS

Limitations of Placido disc-based topography systems include the following:

- There is *a lack of standardization between instruments*; it depends on reference axis, alignment and focus. The corneal apex is the point of maximum curvature on the cornea, whereas the vertex is the point nearest to the camera of the Placido instrument located on the corneal topographer axis (CT axis). Before acquisition, the topographer aligns this axis normal to the cornea. This is possible only in ideal scenario, but in patients with positive angle kappa, the line of sight does not pass through the apex of the cornea and the reflected image appears displaced and is shown as asymmetric bow-tie in otherwise normal cornea. The effect of decentration is nullified to an extent in elevation-based devices.
- *The elevation maps* are derived in Placido devices by using angle of reflection and by making mathematical assumptions, so cannot be as accurate as true elevation maps of slit scan and Scheimpflug devices.
- *Intraobserver and interobserver* variability errors, alignment errors, focussing errors or errors of calibration.
- *Central regions* require a higher degree of subpixel resolution in order to detect a 0.25 D change than do peripheral region.
- *Difficulties in determination of the power and location* of the steepest meridian when using artificial tears in post-penetrating keratoplasty (post-PK) eyes.

COMMERCIALLY AVAILABLE PLACIDO DISC TOPOGRAPHY SYSTEMS

Commercially available CTS based on Placido disc principle are listed in Table 6.1. Cardinal features of some presently available systems are described briefly.

1. EYESYS DESKTOP

EyeSys Desktop (Fig. 6.18B) from EyeSys Vision, Inc., USA, is a 25-ring videokeratoscopic device with USB 2 connectivity with fast image processing time of 3 s and colour-coded contour map plots in addition to a host of other presentation schemes including customized packages. It analyses 9000 data points. The software with the system takes the Stiles–Crawford effect into consideration and allows display of relative brightness of light entering the pupil. This results in more practically useful information. It utilizes the technology of EyeSys 2000 corneal analysis system.

- ***EyeVista*** is the portable available model with similar functions, with which patients confined to a bed or wheelchair can easily be examined and supine patients can be mapped in the operating room under a surgical microscope

2. TMS-4 TOPOGRAPHIC MODELLING SYSTEM

The TMS-4 Topographic Modelling System from Computed Anatomy, Inc. through Tomey Technology, Inc., Cambridge, utilizes 31 projected rings providing 7000 data points. The corneal coverage is 0.02–11 mm with an accuracy of 0.10 D. It has a patented laser alignment system for accurate alignment and an exclusive refractive surgery planning programme.

3. ASTRAMAX

AstraMax is a Placido disc corneal tomography system manufactured by LaserSight Technologies, Inc., Winter Park, Florida (Fig. 6.18C). AstraMax is a new generation 3D corneal topography with enhanced resolution ideally suited for custom cornea-based treatment. AstraMax is a three-camera imaging system that uses stereo ray tracing for high-precision, patient-specific corneal measurements. Patented polar grid yields critical measurements to measure complex corneal shapes. High-definition graphics provide eye simulations and 3D surface modelling.

4. ATLAS 9000 CORNEAL TOPOGRAPHY SYSTEM

Working principles of Atlas 9000 Corneal Topography System (*Carl Ziess, Germany*) include the following:

- *Ray-tracing technology* to display higher-order corneal aberrations.

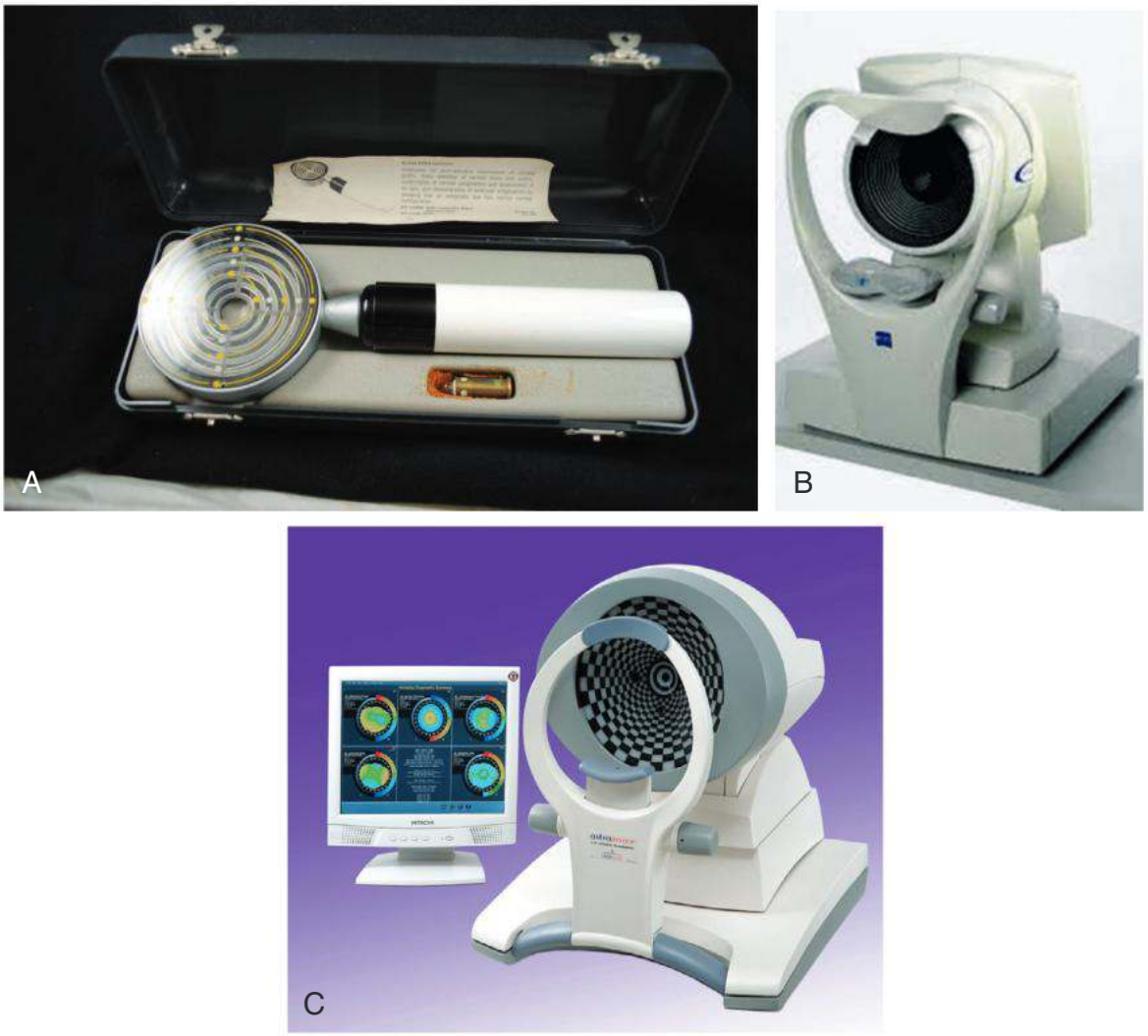


Fig. 6.18 *A, Placido disc keratoscope (Keeler's). B, Corneal topography system: EyeSys Desktop (EyeSys Vision, Inc.). C, Corneal tomography system (AstraMax).*

- *Placido disc technology* with *Cone-of-Focus* alignment system. It has *non-visible Placido ring illumination,* which is comfortable for even the most light-sensitive patients. The 22-ring Placido disc is optimized to avoid ring crossover, which allows reliable results for a wide range of patients.

Applications. This system based on Corneal Wavefront Analysis is a diagnostic instrument that measures the curvature of the cornea and produces topographical images. It supports many important optometric applications, including contact lens fitting, pathology detection and management and selection of aspheric IOLs.

5. OPD SCAN III

The OPD III (*Nidek, Japan*) is five-in-one refractive workstation, which combines the following:

- *Wavefront aberrometry* gives assessment of visual acuity and quality of vision in addition to traditional refraction and keratometry. Simulation of retinal contrast sensitivity and visual acuity charts enable objective quantification of visual clarity.
- *Corneal topography* provides intuitive maps and numerical data for the corneal surface and provides neural network assisted detection of corneal pathology such as keratoconus suspect, keratoconus and pellucid marginal degeneration.

- *Autorefractometer* provides exceptionally accurate refractions for various pupil diameters including refractions under photopic and mesopic conditions, critical for proper assessment of both refractive surgery patients and common refractive problems.
- *Autokeratometer* provides conventional keratometry and novel corneal surface descriptors such as average pupil power (APP) and effective central corneal power (ECCP) which aid in the calculation of the correct IOL power for post-operative corneas.
- *Pupillometry* measures photopic and mesopic pupil diameters. Pupil images reveal the shape of photopic and mesopic pupils, which can alter refraction and important surgical data. Identification of the first Purkinje image (corneal light reflex) and pupil centre is provided. The distance between these two landmarks is calculated to assist in centration during refractive surgery and to assess IOL centration.

6. CASSINI TCA

Cassini total corneal astigmatism (TCA) (*I-optics, USA*) uses multicoloured LED point-to-point ray tracing to provide a GPS-like analysis of the cornea along with high-resolution images utilized for surgical guidance. There is a total of 679 LEDs; 224 red, 224 green, 224 yellow and 7 white. The unique measuring principle enables highly accurate and repeatable measurements of the TCA. Cassini TCA measures the posterior cornea using second Purkinje reflections and provides a TCA measurement. The multicoloured LED coverage is equal across the entire cornea, leaving no space for central scotoma. The accurate axis and magnitude of astigmatism play a vital part in the correct selection and positioning of a toric IOL.

DISPLAY OF PLACIDO DISC-BASED CORNEAL TOPOGRAPHIC SYSTEM DATA

The corneal topographic data analysed by the computers can be displayed in the following formats:

A. Numerical power plots,
B. Keratometry view,
C. Photokeratoscopic view,
D. Profile view and
E. Colour-coded topographic maps.

The most useful form of data presentation is a colour-coded corneal contour map, which will be discussed in detail.

A. NUMERICAL POWER PLOTS

In numerical power plots, the corneal curvature of specific areas is shown in dioptre values (Fig. 6.19). The data are displayed in 10 concentric circular zones with 1 mm interval between each. The numerical values are displayed in colour, which are in agreement with the colour scale being used. The display also shows the average dioptric value of each of the 10 concentric circular zones individually along with the average overall corneal curvature.

B. KERATOMETRIC VIEW

Keratometric view (Fig. 6.20) depicts the keratometric reading in two principal meridians (K_1 and K_2) in three different zones simultaneously. The three zones measured are *central* 3 mm zone (as in a conventional keratometry), *intermediate* 3–5 mm zone and *peripheral* 5–7 mm zone.

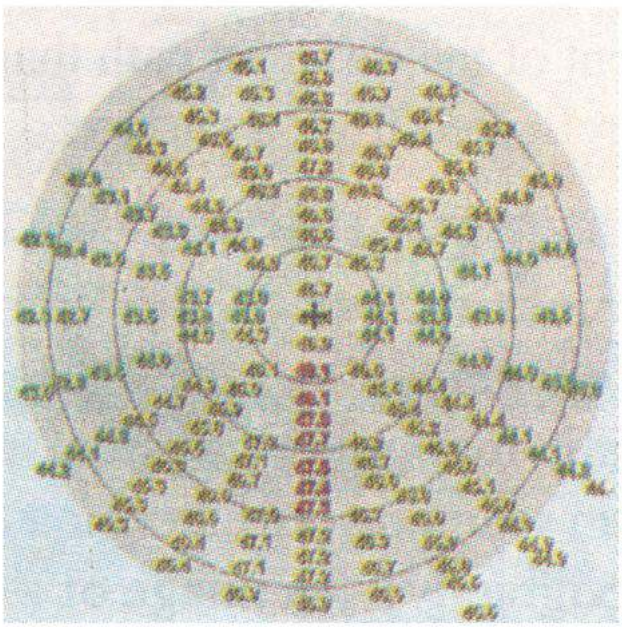


Fig. 6.19 *Numerical power plot. (Courtesy: Dr Rajib Mukherjee.)*

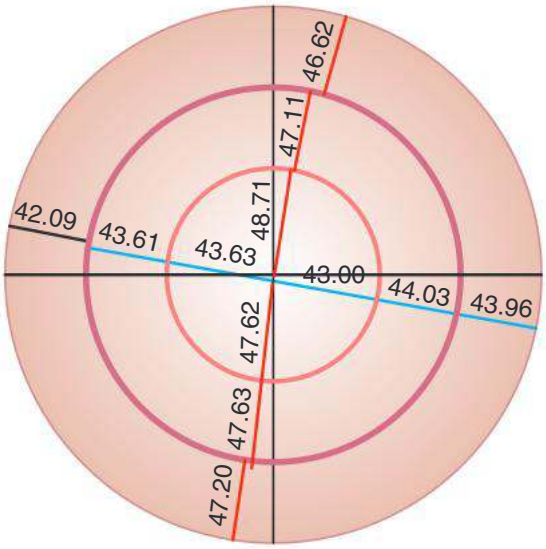


Fig. 6.20 *Keratometric view of the data. (Courtesy: Dr Rajib Mukherjee.)*

It is an important map for assessing the skewing of semimeridians. The more the keratometric readings in principal meridians deviate from being perpendicular to each other, the more irregular or non-orthogonal corneal astigmatism exists.

C. PHOTOKERATOSCOPIC VIEW

Photokeratoscopic view (Fig. 6.21) depicts the actual black and white photograph of the Placido rings captured by the video camera. This view helps in confirming the proper patient fixation and in identifying the eye captured. The reflected rings on the cornea are situated more towards the limbus on one side than the other, and on the nasal side, the distance between the rings is comparatively narrower.

D. PAR CTS PROFILE VIEW

The profile view (Fig. 6.22) shows the graphical plotting along the XY axis of the steepest and the flattest meridians of the cornea and the difference between the two in dioptres. The display button shows the astigmatic difference (Difference plot, Delta Map) between the flat and steep meridians. A grey zone in this difference plot denotes the pupillary area. In a symmetrical eye, the tracing across this grey band is a straight line. In the presence of astigmatism, an apparent slag is seen. The more this slag increases, the more asymmetrical cornea is.

E. COLOUR-CODED TOPOGRAPHIC MAP

Colour-coded contour maps of the cornea are the most useful and most commonly used display formation. Colour coding is adapted from the Louisiana State University Color-Coded Map.

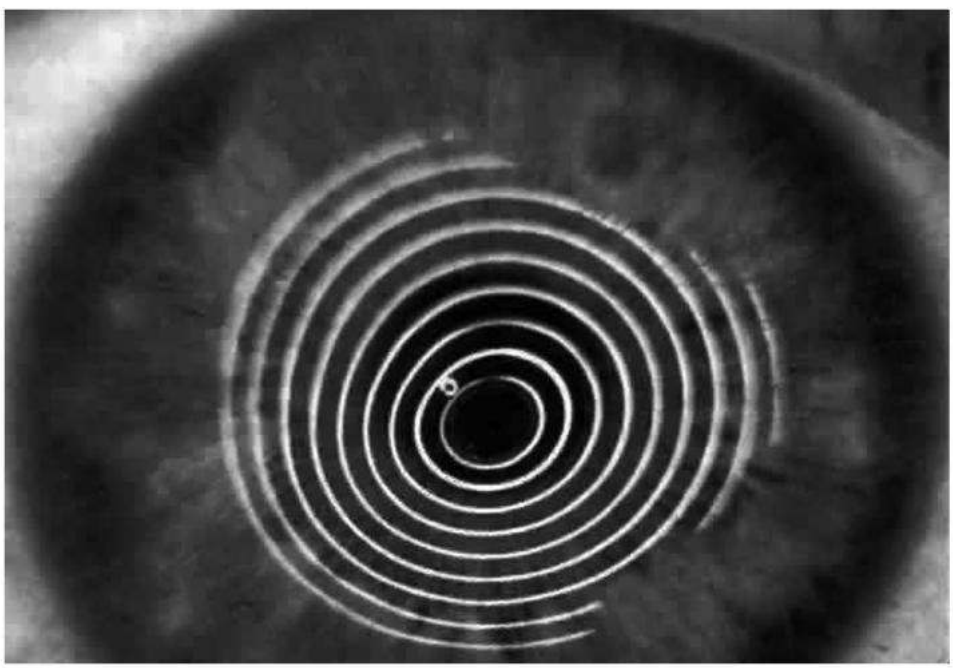


Fig. 6.21 *Photokeratoscopic view showing egging of mires in a patient with keratoconus. (Courtesy: Dr Rajib Mukherjee.)*

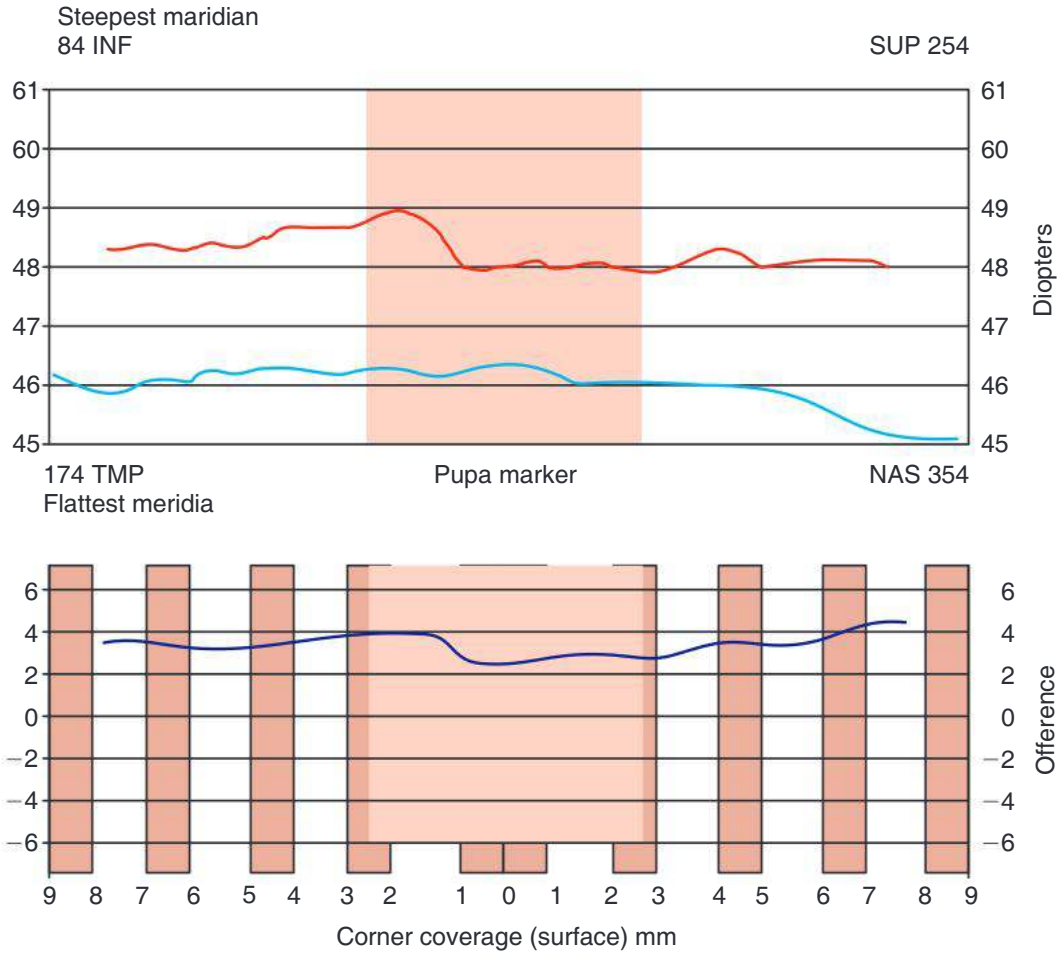


Fig. 6.22 *Profile view. (Courtesy: Dr Rajib Mukherjee.)*

Interpretation of a Colour Map

While interpreting colour-coded contour maps of the cornea, following parameters should be considered:

1. ***Colour codes.*** These are used as follows:
   - *Hot colours*, i.e. red and its various hues represent the steep portions of cornea.
   - *Cool colours*, i.e. blue and its various hues represent the flat portions of cornea.
   - So, the colours red–orange–yellow–green–purple–blue denote progressively lessening refractive power.
     The colour intensity is relative, meaning that an area of 45 D is less red as compared to an area of 46 D.
2. ***The scale used.*** It is very important to know the scale used before interpreting a colour map. The two apparently similar maps may in fact show markedly different cornea depending upon the scale used. The commonly used scales are absolute and normalized scales.

Absolute scale. In it, each colour represents a 1.5 D interval between 35 and 50 D, whereas above and below this range, colours represent 5 D intervals. This scale is useful in routine practice (e.g. preoperative screening).

- *Disadvantage* of absolute scale is that it does not show subtle changes of curvature and thus can miss subtle local changes (e.g. early keratoconus).

Normalized scale. In it, the cornea is divided into 11 equal colours spanning that eye's total dioptric power. In this scale, more minute topographic details within an individual cornea are appreciated.

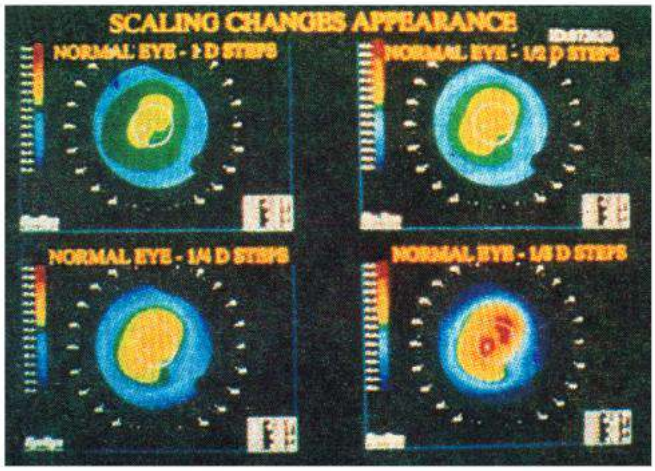


Fig. 6.23 *Scaling change showing apparently different maps of the same cornea. (Courtesy: Dr Rajib Mukherjee.)*

- *Advantage* of normalized scale is that it shows more detailed description of the surface than the absolute scale.
- *Disadvantage* of normalized scale is that the colours of two different maps cannot be compared directly and have to be interpreted based on the keratometric values from their different colour scales.

Note. Figure 6.23 shows a corneal topography map with different scales. Many workers feel that the absolute scale is easier to read and the normalized scale magnifies clinically insignificant information.

3. ***Quantitative indices***. As part of the display, quantitative indices are also generated to give extra information. These include the following:

- Predicted visual acuity based on corneal shape,
- Simulated keratometric readings (Sim K),
- Mean keratometry reading,
- Surface regularity index (corneal irregularity measurement [CIM]),
- Surface asymmetry index (shape factor [SF]) and
- Point spread function (PSF).

i. *Simulated keratometric readings.* These characterize corneal curvatures in the central 3 mm area. The steep simulated K reading is the steepest meridian of the cornea in central 3 mm area. The flattest Sim K reading is the flattest meridian of the cornea and is, by definition, 90 degrees apart.

ii. *Surface asymmetry index*. The index of asphericity indicates how much the curvature changes upon movement from the centre to the periphery of the cornea. A normal cornea is prolate (i.e. becomes flatter towards the periphery) and has the asphericity Q of –0.26. A prolate surface has negative Q value and an oblate surface has positive Q value. Most myopic laser vision corrections change the anterior corneal surface from prolate to oblate. A negative SF usually indicates a post-refractive surgery eye with the centre flatter than the periphery. The SFs (e_2) for the general population are as follows:

- Normal 0.13–0.35,
- Borderline 0.02–0.12 and 0.36–0.46 and
- Abnormal 1.0–0.01 and 0.47–1.0.

iii. *Surface regularity index/CIM*. It is a number or index that represents the irregularity of the corneal surface. The higher the irregularity index, the more difficult it is to fit the corneal surface with a contact lens. It often can predict irregular astigmatism or visual distortions. Higher CIM values indicate that ocular pathology such as keratoconus or other pathological cases is more probable. The general population exhibits the following distribution ranges:

- Normal 0.03–0.68 µm
- Borderline 0.69–1.0 µm
- Abnormal 1.1–5.0 µm

iv. *Mean toric keratometry.* The mean toric keratometry (TKM) indices use elevation data to compare the toric reference to the actual cornea. The mean apical curvature value helps select the best toric fit using a spherocylinder design. This provides the most accurate toric representation of a patient's cornea. Human TKM ranges are as follows:

- Normal – 43.10–45.90 D
- Borderline – 41.80–43.00 D and 46.00–47.20 D
- Abnormal – 36.00–41.70 D and 47.3–60.0 D

PathFinder corneal analysis. The Atlas Corneal Topographer (Carl Zeiss Meditec, Inc.) uses special software that combines the above indices (CIM, SF and TKM) to determine the probability of irregular corneas. This helps practitioners qualitatively and quantitatively measure the probability of keratoconus. The PathFinder corneal analysis also helps determine whether a rigid gas permeable (RGP) or soft toric lens fits poorly on the cornea or should be replaced with a different base curve. It also helps when fitting RGP lenses. New keratoconus fitting philosophies use a lens-to-cornea relationship with less central bearing. Trend with Time or Stars technology can monitor corneal disease and determine how corneal shape responds with new contact lens designs.

CORNEAL TOPOGRAPHIC PATTERNS IN NORMAL CORNEAS

The normal cornea flattens progressively from the centre to the periphery by 2–4 D, with the nasal area flattening more than the temporal area. The topographic pattern of the two corneas of an individual often shows mirror-image symmetry, and small variations in patterns are unique for the individual.

Depending upon the corneal curvature, Rabinowitz *et al.* in 1996 described 10 different corneal topographic patterns in normal eyes as seen on colour-coded absolute scale maps (Fig. 6.24). These can be grouped as follows (figures in the parentheses indicate approximate distribution of keratographic patterns):

Regular pattern (Fig. 6.24):

- Round (23%)
- Oval (21%)
- Steepening
  Superior steepening
  Inferior steepening

Astigmatic patterns (Fig. 6.24):

- *Symmetrical and orthogonal*, i.e. bow-tie effect (18%)
  Symmetrical bow tie with non-skewed axis
  Symmetrical bow tie with skewed axis
- *Asymmetrical and orthogonal* (31%)
  Asymmetric bow tie with superior steepening
  Asymmetric bow tie with inferior steepening
  Asymmetric bow tie with skewed radial axis
- *Irregular*, i.e. no pattern and non-orthogonal (7%)
- *Special shapes* include butterfly pattern, crab-claw appearance in pellucid marginal degeneration.
- *Enantiomorphism* is the phenomenon wherein the individual topographies are non-superimposable but almost mirror images of each other.

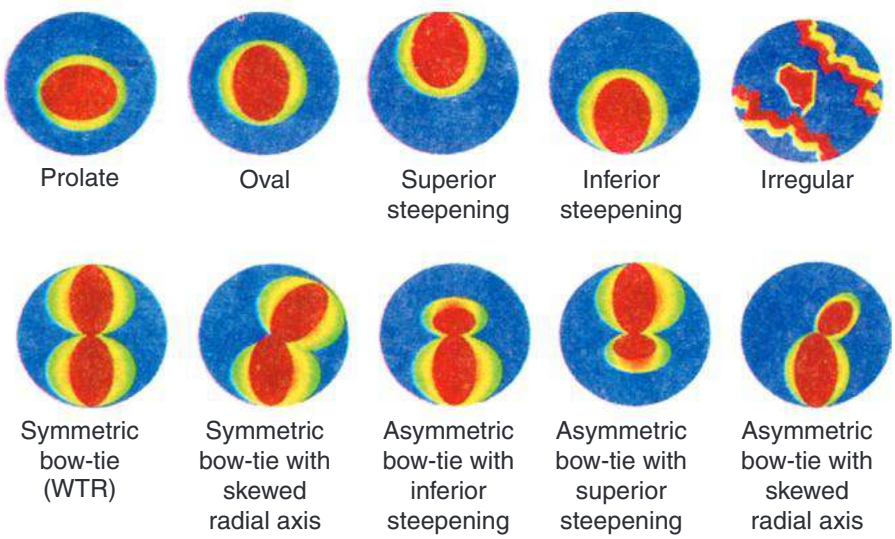


Fig. 6.24 *Corneal topographic pattern seen on colour-coded maps in absolute scale. (From Rabinowitz et al. 1996; Courtesy: Dr Rajib Mukherjee.)*

FORMATS FOR DISPLAY OF DATA ON COLOUR MAPS

Various formats used for display of data on colour-coded maps are as follows.

1. Corneal Power Map (Sagittal or Axial)

The corneal power map (Fig. 6.25) is a 24-colour representation of dioptric power at various points on the cornea. The radius of curvature is measured 360 times for each Placido ring image from centre to vertex. The sagittal algorithm averages the data points from first to the next ring and so on. Due to common reference axis, small irregularities may not be visible or smoothened out. They are spherically based and assume that centre of rotation of best-fit sphere (BFS) lies on optical axis. The axial map is more commonly used to produce a good estimate of overall corneal shape, which appears smooth with little noise as it provides average of adjacent curvature values.

2. Tangential Map

The tangential map (Fig. 6.26) gives better geographical representation of the cornea as compared to the axial/sagittal corneal map. In it, tangents are projected outwards from the centre vertex 360 degrees. Ring curvature is measured along the tangent (ring intersection). This is also known as *instantaneous curvature map.* This is the best indicator of corneal shape but is a poor indicator of corneal power. Therefore, tangential reading must never be used for calculating K values. This map is a very useful tool for accurate diagnosis of corneal ectatic conditions like keratoconus and also accentuates focal abnormalities as more sensitive.

3. Elevation Map

Elevation is not measured directly by Placido-based topographers, but certain assumptions allow the construction of elevation maps. Elevation of a point on the corneal surface displays the height of the point on the corneal surface relative to a spherical reference surface. The reference surface in most instruments was chosen to be a sphere. Best mathematical approximation of the actual corneal surface, called BFS, is calculated by instrument software for every elevation map separately. The same surface

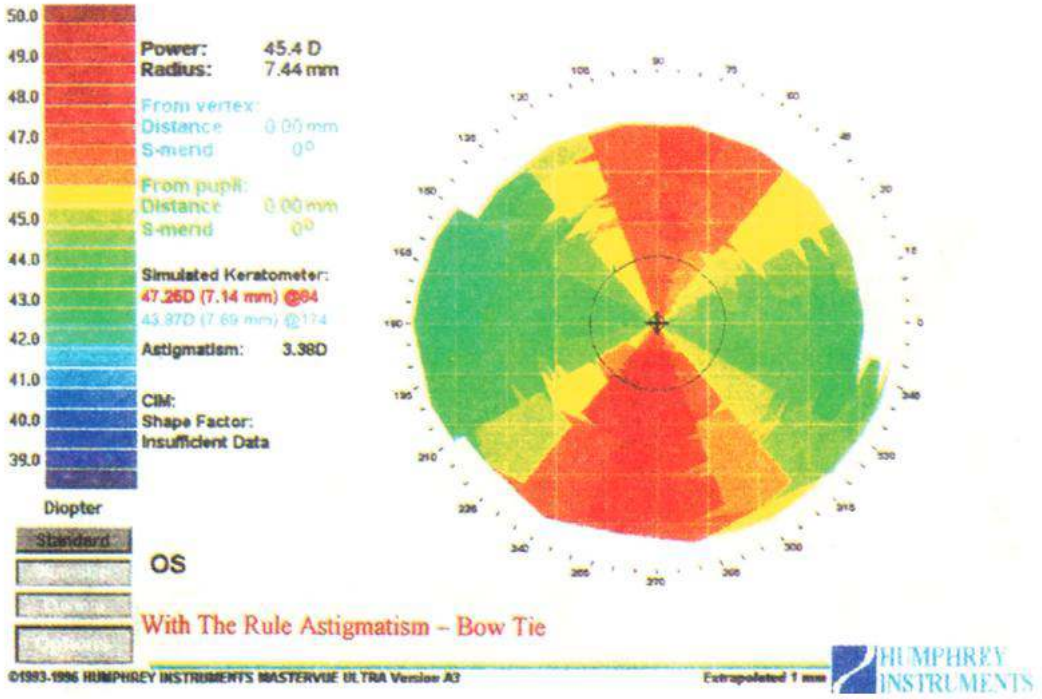


Fig. 6.25 *Corneal power map showing symmetrical 'bow-tie pattern' in a patient having with-the-rule astigmatism. (Courtesy: Dr Rajib Mukherjee.)*

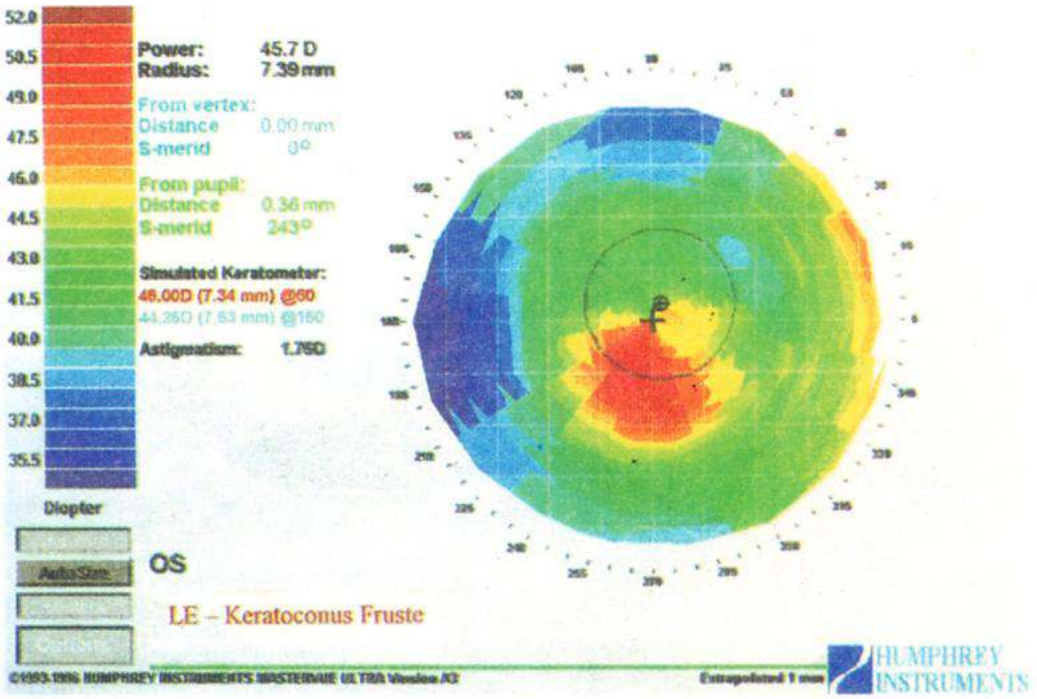


Fig. 6.26 *Tangential map showing inferior steepening in a patient with keratoconus left eye. (Courtesy: Dr Rajib Mukherjee.)*

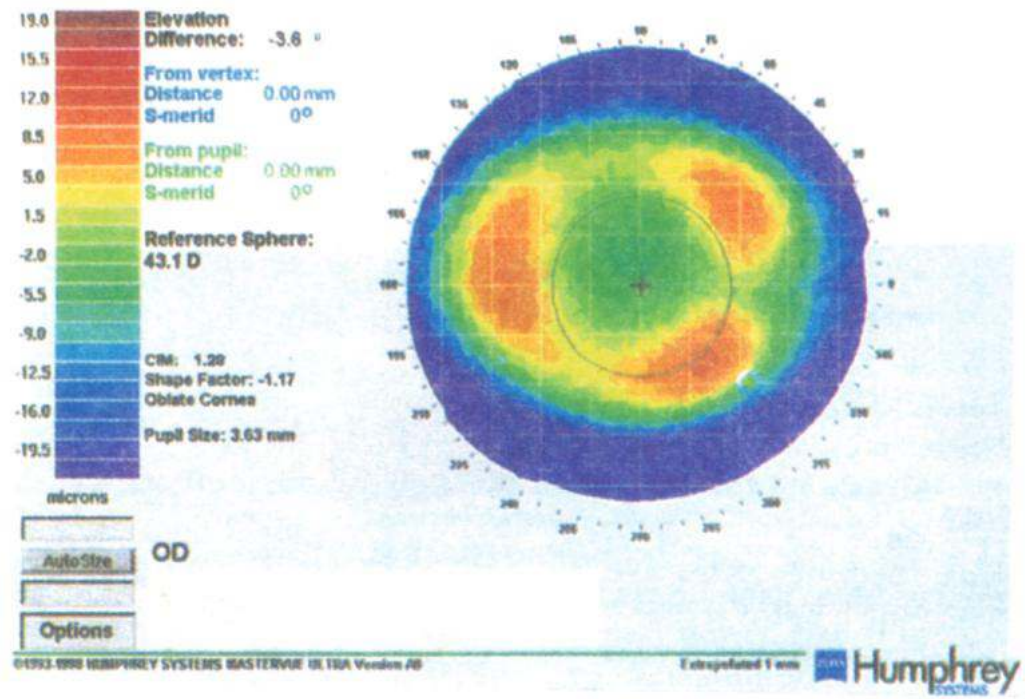


Fig. 6.27 *Elevation map of a post-radial keratotomy (post-RK) patient. (Courtesy: Dr Rajib Mukherjee.)*

may appear different when mapped against different reference surfaces. Consequently, it is difficult to compare directly two elevation maps that likely have slightly different BFSs as reference values, and comparison only can be intuitive. The elevation map (Fig. 6.27) helps in distinguishing localized elevations (steep because of projection) from otherwise steep corneal area. The interpretation can be confusing, but it is important to remember that 'Red is

Raised (steep)' and 'Blue is Below (flat)'. The hotter colours show areas that are elevated above the reference sphere and cooler colours represent the areas that are depressed under the reference sphere. The elevation measurements are simply difference measurements.

In laser refractive surgery, the refractive power is changed by removing tissue from the corneal surface, and elevation data appear more relevant for calculation of ablation depth and optical zones.

4. Refractive Power Map

The refractive power map (Fig. 6.28) modified the standard map, taking into account the effects of spherical aberrations. It illustrates how the corneal curvature refracts light in true dioptres of power and not curvature. It uses ray tracings and Snellen's law of optics to perform the calculations.

In it, the spherical cornea has cooler colours in the centre with increasing hotter colours extending out to the periphery (Fig. 6.28). Thus, in true sense, the refractive map should be called the *asphericity map* of the cornea. This map is very useful for determining the optical zone for rigid gas-permeable lenses and also in performing refractive corneal surgery.

5. Irregularity Map

The irregularity map (Fig. 6.29) shows areas on cornea that are hot in colour. It displays the distortion of cornea using previous elevation map results with toric reference instead of a reference sphere. The hotter colours represent the higher value of distortion measured in units of wavefront error. The wavefront number can be translated to dioptre of distorted power, known as *spectacle blur.* This map allows the surgeon to quickly assert, if the cornea is causing poor visual acuity. If there is a significant hot colour within the pupil zone, the acuity will be compromised.

6. Trend and Time Display

In this, changes occurring in topography with time (post-operatively) can be displayed in chronological order (Fig. 6.30).

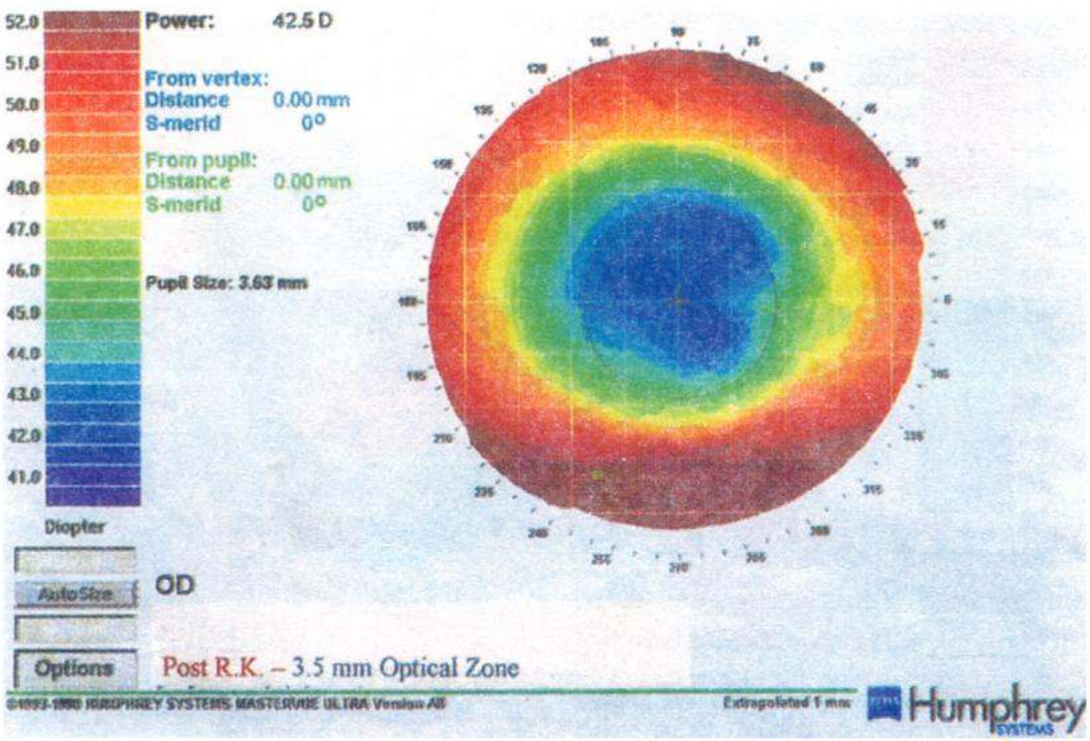


Fig. 6.28 *Refractive power map of a post-RK patient. (Courtesy: Dr Rajib Mukherjee.)*

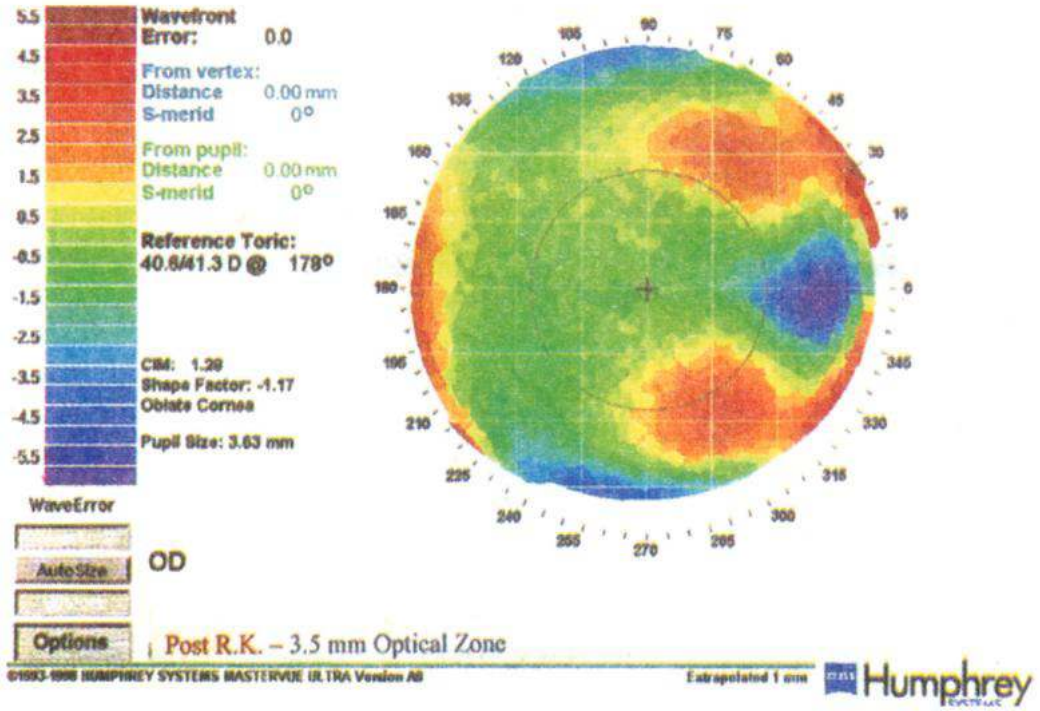


Fig. 6.29 *Irregularity map of a post-RK patient. (Courtesy: Dr Rajib Mukherjee.)*

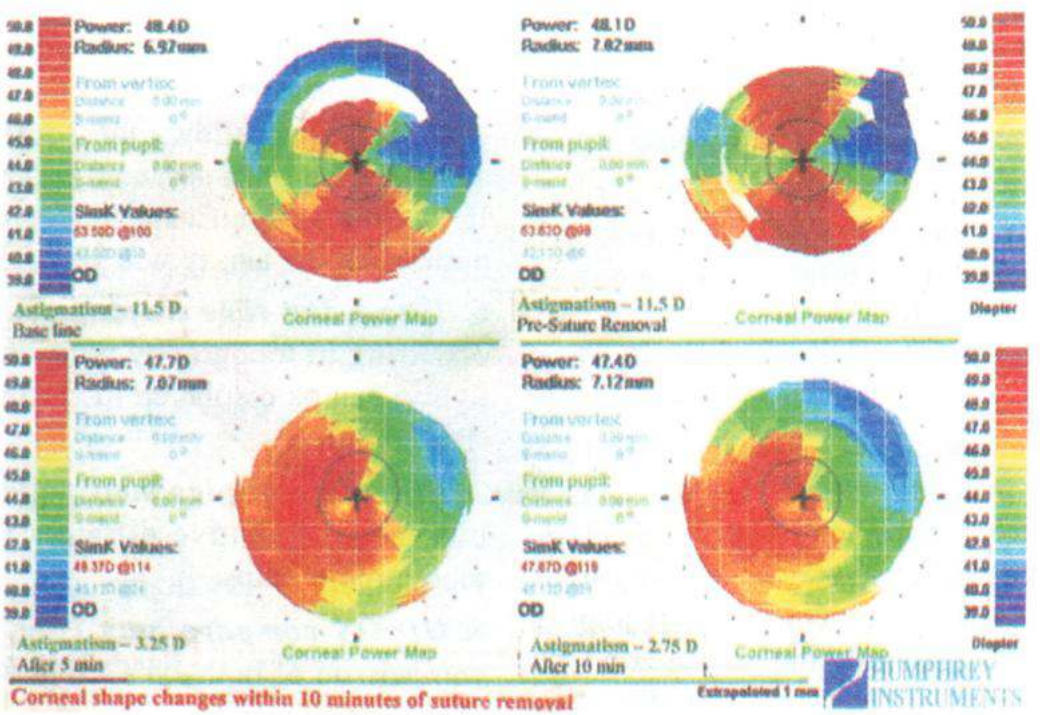


Fig. 6.30 *Trend with time display. (Courtesy: Dr Rajib Mukherjee.)*

7. Difference Display Map

Difference display map (Fig. 6.31) exhibits the comparative difference in two given topographic maps.

8. Right Eye/Left Eye (OD/OS) Compare Map (Fig. 6.32)

Allows the comparison of both eyes simultaneously.

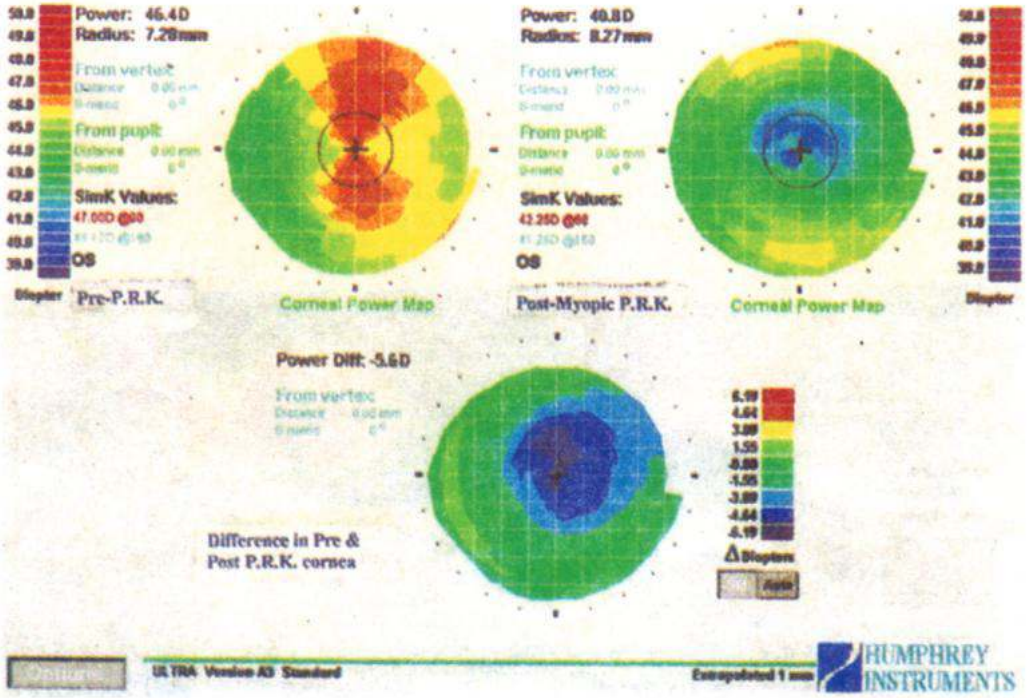


Fig. 6.31 *Difference display map. (Courtesy: Dr Rajib Mukherjee.)*

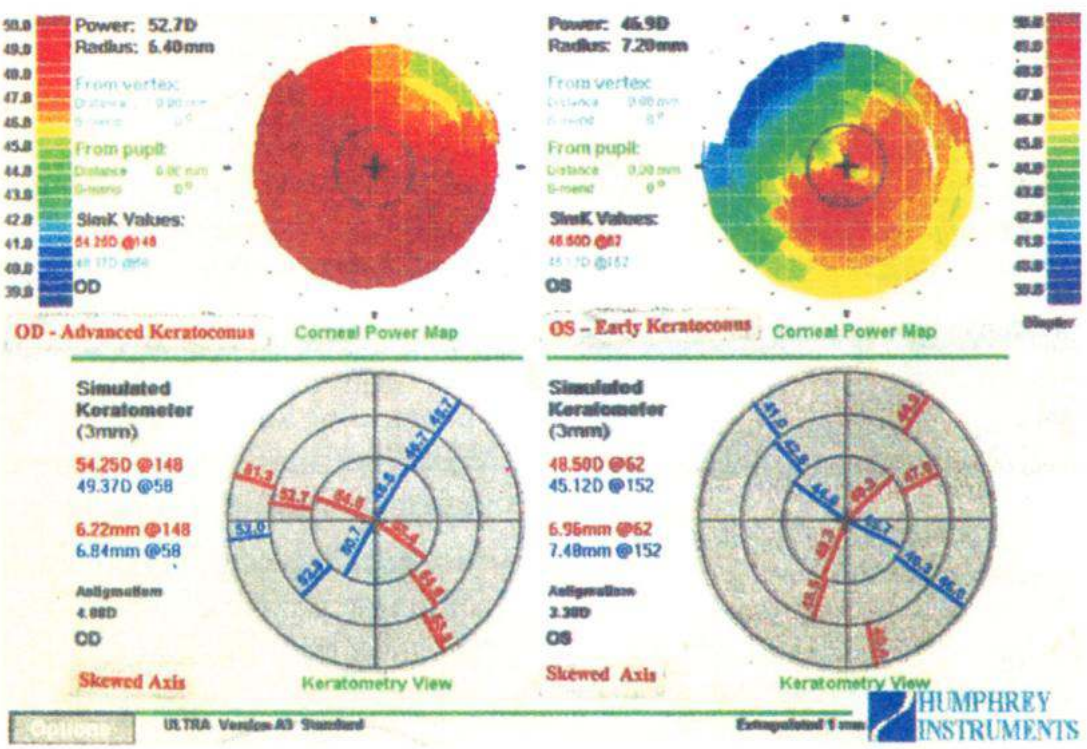


Fig. 6.32 *Right eye/left eye (OD/OS) compare map. (Courtesy: Dr Rajib Mukherjee.)*

SLIT-SCANNING CORNEAL TOMOGRAPHY SYSTEM

Working principle. *Slit-imaging tomography system* uses scanning slits that step over the corneal surface to acquire topographic information. This is similar to a slit lamp in principle. In this principle, an edge point on the corneal surface is triangulated by mathematically intersecting the diffuse reflected camera edge ray with the calibrated slit beam surface. Two slits are used, positioned at 45-degree angles to the right and left of the instrument axis. Twenty slit images are captured from each direction with overlap in a 7 mm diameter central area. Total corneal coverage is up to 10 mm, depending on the individual corneal shape. All images are captured within approximately 1.5 s.

In addition to the digital capture of the anterior surface of the cornea, this system is also capable of directly measuring the posterior surface. Thus, corneal thickness (defined by the distance between anterior and posterior surfaces) can be instantly measured at any point on the cornea.

Commercially available system, based on this principle, the Orbscan listed in Table 6.1 is described here.

ORBSCAN III

Orbscan, introduced in 1995, which was later improved in 1999 to Orbscan II and now in 2014 to Orbscan III (Fig. 6.33). It combines the advantages of slit-scanning technology with an advanced Placido disc system, i.e. it is actually a hybrid system consisting of a projective (slit scanning) and reflective (Placido disc) technique.

Fig. 6.33 *Orbscan III.*

The Orbscan III system uses the principle of projection. Forty scanning slit beams (20 from the left and 20 from the right with up to 240 data points per slit) are used to scan the cornea from limbus to limbus and to measure independently the x, y and z locations of several thousand points on each surface. Orbscan III acquires over 23,000 data points as compared to 9000 data points. Orbscan II in 1.5 s to meticulously map the entire corneal surface (11 mm). The images captured are then used to construct the anterior corneal surface, posterior corneal surface and anterior iris (white-to-white diameter) and anterior lens surfaces. Data regarding the corneal pachymetry and anterior chamber depth are also displayed. It also provides pre- and post-operative difference maps. The advantage of this system is that slit-scan imaging is not dependent on spherical assumption. Eye tracking is used to reduce data error resulting from eye movement.

TOPOGRAPHY MAPS WITH ORBSCAN

The computer calculates a hypothetical sphere that matches as close as possible to the actual corneal shape being measured. This is called the BFS. It then compares the real surface to the hypothetical sphere, showing areas 'above' the surface of the sphere in warm colours and areas 'below' the surface in cool colours (Fig. 6.34).

Green is 'sea level' (match with a sphere that best matches the cornea). Warmer colours are above 'sea level'. Cooler colours are below 'sea level'. The normal cornea is prolate, meaning that meridional curvature decreases from centre to periphery. The result is a *central hill of warm colour.* Immediately surrounding the central hill is an annular sea of *cool colours* where the cornea dips below the reference surface. In the far periphery, the prolate cornea again rises above the reference surface, producing *peripheral highlands.*

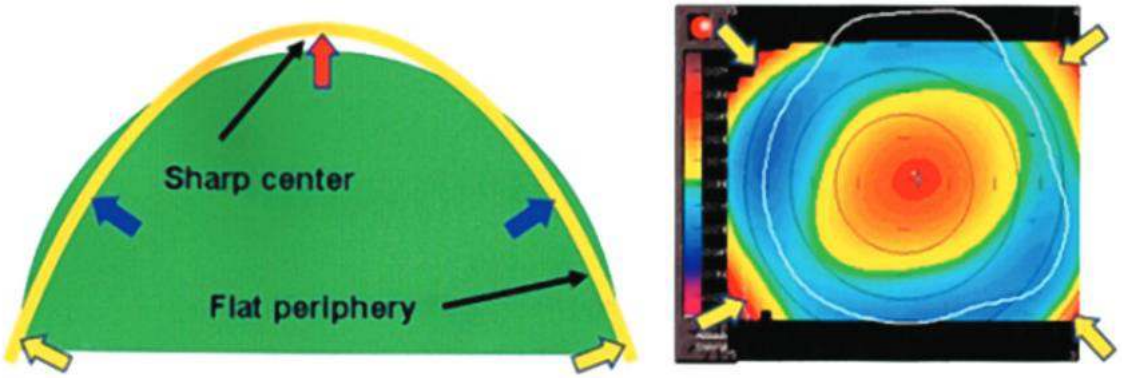


Fig. 6.34 *Orbscan elevation maps: A, in prolate cornea; B, in a cylindrical cornea.*

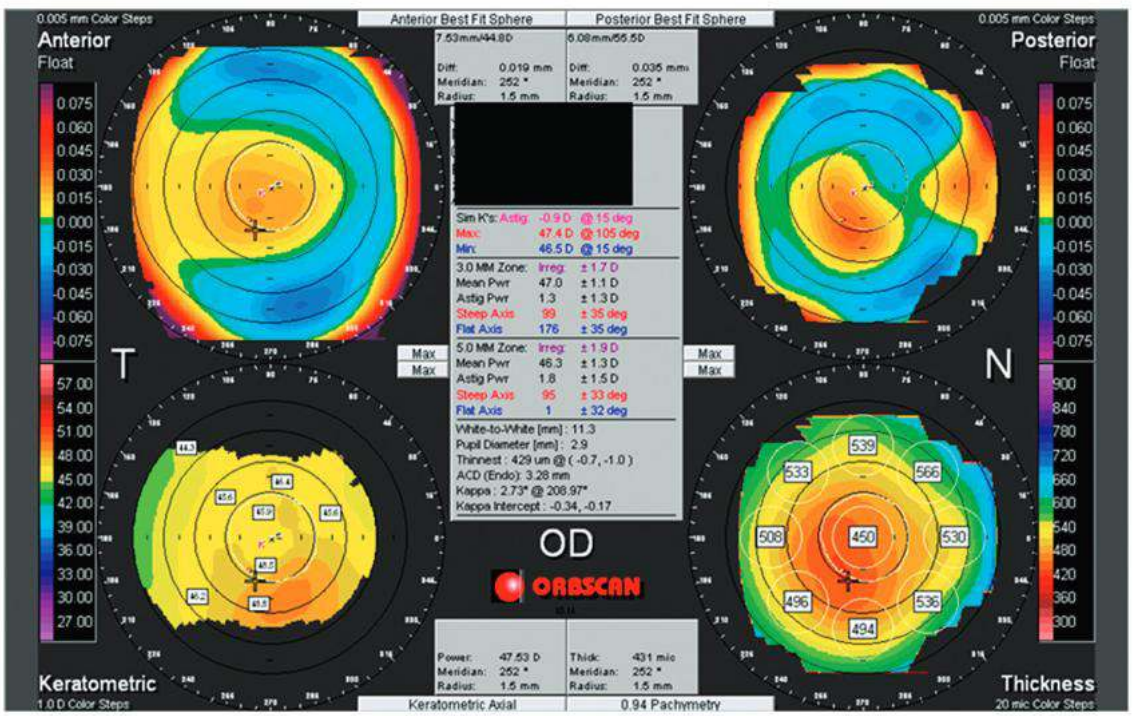


Fig. 6.35 *Orbscan: Quad map.*

Functions: The Orbscan III provides the following:

- Anterior and posterior corneal elevation and curvature,
- Full corneal pachymetry,
- White-to-white diameter and
- Pre- and post-operative difference maps.

QUAD MAP

Quad map refers to the typical Orbscan map which comprises following four different maps, each portraying different information about cornea (Fig. 6.35):

- Anterior elevation map (anterior float),
- Posterior elevation map (posterior float),
- Curvature map (axial keratometry map) and
- Pachymetry map.

Anterior Elevation Map and Posterior Elevation Map

Anterior elevation map, also known as anterior float, and posterior elevation map, also known

as posterior float, are shown in the top left-hand map and top right-hand map, respectively, in Figure 6.35.

As mentioned earlier, slit scanning provides elevation data and this can also create a 3D interpretation of the cornea. A 3D interpretation of both the elevation maps can be seen in Figure 6.35. The meshwork effect indicates how the cornea would appear, if it were entirely spherical and is referred to as the reference sphere. This elevation data can be interpreted usefully in a number of ways.

Curvature Map (Axial Keratometry Map)

The axial keratometry map is based on Placido technology. This is similar to maps produced from the majority of commercially available topography systems and provides detailed keratometric information across the diameter of the cornea.

For laser-assisted in situ keratomileusis (LASIK) surgery, this information is important for a number of reasons. The 'K' readings are important, because limits of 'K' readings are between certain values; the cornea must be neither too steep nor too flat. It is difficult for the microkeratome (blade designed for flap cutting) to create a good quality corneal flap in LASIK if either of these extremes is the case, as this can lead to surgical flap complications.

In addition, 'K' readings of more than *48 D* are an indication of potential keratoconus, particularly where there is decentred inferonasally. Details of the 'K' readings can be found in the statistics and data information in the centre of the quad map.

Pachymetry Map

This is map four of our quad map in Figure 6.35. Traditionally, pachymetry has been measured using ultrasound, which provides a reading of corneal thickness from Bowman's membrane to Descemet's membrane. Through slit-scanning technology, Orbscan provides us with a pachymetry reading from the *precorneal tear film to the endothelium*; therefore, slightly thicker readings can be expected. The Orbscan can, however, be calibrated to take this into consideration when comparing readings. The true advantage of the pachymetry map is that it *provides us with thickness information across the cornea from limbus to limbus, not just* in single points as with ultrasound. This once again gives the opportunity to detect areas of weakness, thinning or scarring. Auffarth *et al.* state that the relationship between the highest point on anterior and posterior elevation maps and the thinnest point (shown by a yellow dot) is an indicator of keratoconus.

SCHEIMPFLUG IMAGING-BASED CORNEAL TOPOGRAPHY SYSTEMS

WORKING PRINCIPLE

Scheimpflug imaging is based on a geometric rule that describes the orientation of the plane of focus of an optical system when the lens plane is not parallel to image plane. In this scenario, an oblique tangent can be drawn from the image, object and lens planes and the point of intersection is Scheimpflug point, where image is in best focus.

COMMERCIALLY AVAILABLE SYSTEMS

Commercially available systems based on the principle are depicted in Table 6.1. Commonly used Scheimpflug imaging-based systems include:

- Pentacam,
- Galilei and
- Sirius.

PENTACAM

Pentacam, a popular system based on this principle can obtain 50 images in less than 2 s. Each image has 500 true elevation points for a total of 25,000 true elevation points for surface of cornea. The Pentacam has two cameras. One is for detection and measurement of pupil and helps in fixation and orientation. The second camera is used for visualization of anterior segment. Pentacam is able to image both anterior and posterior surfaces of the cornea.

Latest version, Pentacam AXL (OCULUS Optikgeräte, Wetzlar, Germany) is the upgraded Pentacam HR, with axial length measurement

which allows surgeons, in addition to other features, to make IOL calculations.

Note. Details of working of Pentacam are described in Chapter 12 at page 478. Clinical applications of Pentacam as corneal tomography system are described here.

CLINICAL APPLICATIONS OF PENTACAM CORNEAL TOMOGRAPHY

- Measurement of corneal shape
- Measurement of corneal thickness (pachymetry), including relative pachymetry maps,
- Measurement of corneal power,
- Corneal elevation maps,
- Corneal curvature maps,
- Keratoconus screening,
- Preoperative screening before refractive surgery and
- Corneal wavefront analysis.

In other words, Pentacam displays include:

- 4 quad map displays
- Belin Ambrósio enhanced ectasia display
- Topometric/KC-staging display
- Colour-coded maps.

4 QUAD MAP DISPLAYS

Measurement of Corneal Shape

Anterior Sagittal Map

It displays the dioptric power of the anterior surface of the cornea.

- *Steep areas* are displayed as hot colours – red/orange
- *Flat areas* are displayed as cold colours – green/blue.

Topography includes making a map that describes the elevations and depressions on the surfaces of the cornea similar to the way that a topographic map illustrates the mountains and valleys on a geographic terrain (Fig. 6.36). With the Pentacam, topographic analysis of the corneal front and back surfaces is based on the true elevation measurement from one side of the cornea to the other (limbus to limbus). In addition to the larger area, the Pentacam provides significantly more accurate elevation measurements than other machines. In addition, other Placido disc-based topographic devices must infer elevation from curvature data. Such inferences can lead to improper medical conclusions.

There appears 3 circles at 3 mm, 5 mm and 7 mm on the anterior sagittal map and parameters are read on 5 mm circle:

- *Normal pattern* is symmetric bow tie.
- *Normal I_S difference* is <1.5 D
- *Abnormal pattern* includes skewed radial axis (SRAX) of >22 degrees.

Anterior and Posterior Elevation Maps

The patient's cornea is compared to normative age-related database, which shows elevations and depressions in the anterior and posterior corneal surfaces.

Reference shapes used are:

- *Best-fit sphere* – quantifies the shape measured.
- *Best-fit toric ellipsoid* – quantifies the parameters of that surface.

Display points above the reference surface are expressed in plus values (hot colours) and those below the reference surface in the minus values (cool colours) depicting the elevations and depressions, respectively.

Interpretation of Maps

Patient particulars, to compare patient's data with the normative age-matched controls.

Numerical data of quality specification of the scan include from the corneal front, corneal back, true net power, pachymetric data and anterior chamber details.

Normal values are as follows:

- Q value (asphericity of the cornea) – 0 to –1
- K1 (flat): >34 D
- K2 (steep): <49 D
- Kmean: <40 D = Free flap complications
  >46 D = Buttonhole complications
  - Kmax: <49 D with <2 D difference between two eyes
- Topographic astigmatism compared with manifest astigmatism: <1 D difference and <15 degrees difference in axis
- Thinnest local point: >500 um difference between two eyes

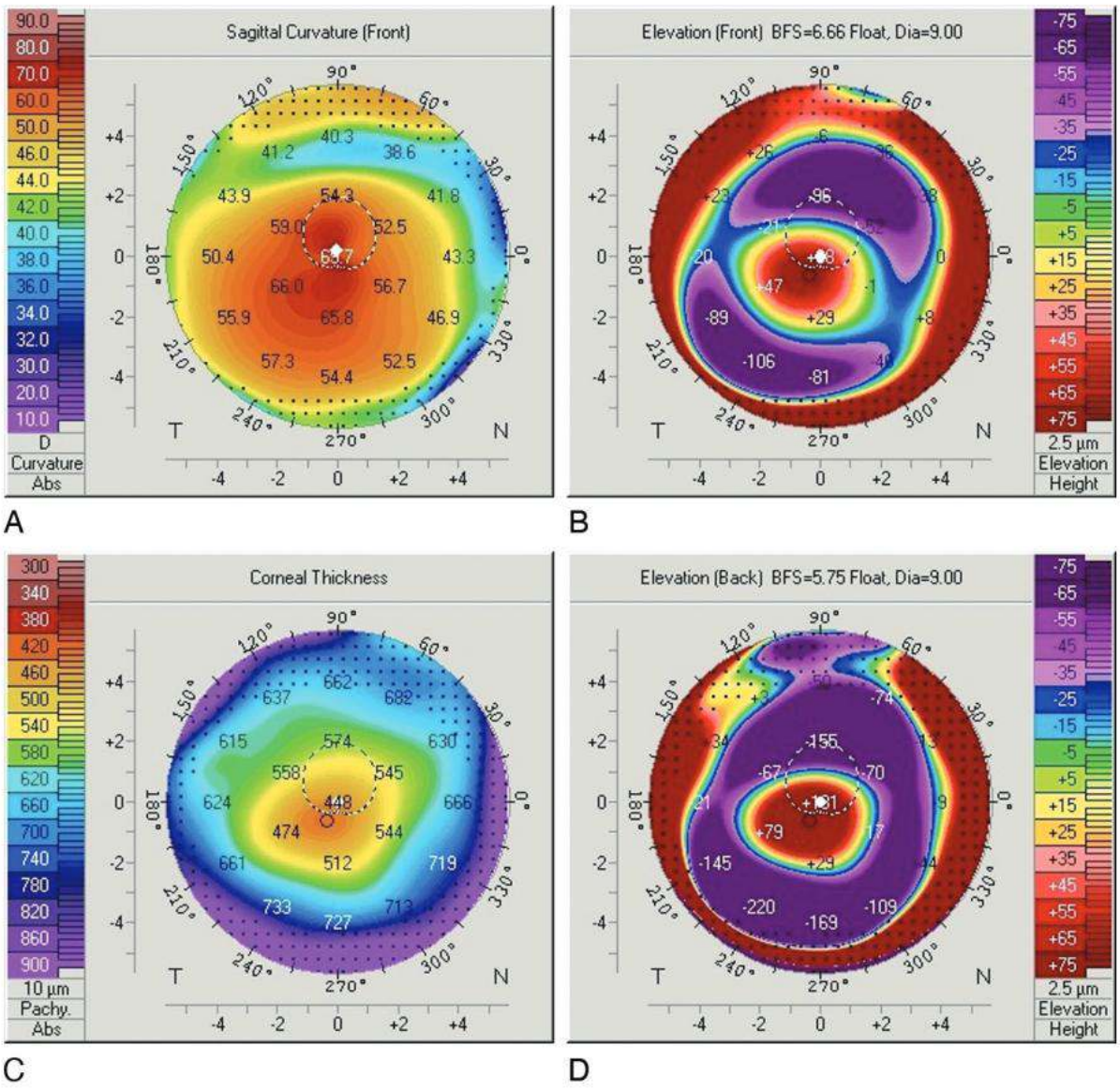


Fig. 6.36 *Pentacam: corneal topography.*

- Y co-ordinate (vertical displacement of thinnest local point): <0.5 mm.

Measurement of Corneal Thickness (Pachymetry)

One of the most important measurements about the cornea besides its shape is the true thickness. Since the Pentacam provides highly accurate information about both the front and back surfaces of the cornea, it is possible to generate 25,000 data points that describe the true thickness of the cornea across its entire breadth and width (Fig. 6.37). This is the ideal as even manual ultrasound pachymetry can only image one

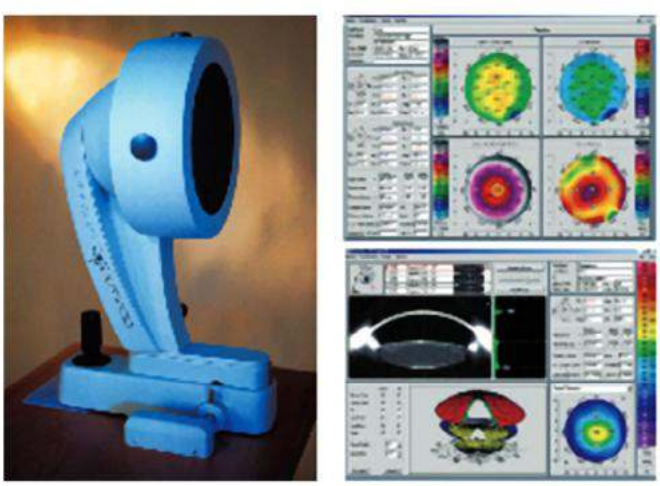


Fig. 6.37 *Pentacam analysis including pachymetry.*

single data point making it nearly impossible to provide the amount of thickness detail that can be obtained with the Pentacam.

- *Corneal thickness* is calculated from the top of the epithelium to the anterior surface of the endothelium, excluding the tear film. It is displayed as a colour image over its entire area from limbus to limbus.
- The software allows for IOP modification taking into consideration the corneal thickness. This feature is of immense importance for obtaining IOP in post-refractive surgery patients as well as ocular hypertension and glaucoma screening.
- Important parameters like thickness in the centre of the pupil, apical corneal thickness and the thinnest location are provided. The distance and position of the thinnest point relative to the apex of the cornea are also available, which are useful for early detection of keratoconus.
  - *Corneal apex* is shown by a '+' sign
  - *Thinnest location* is shown by a '0' sign
  - *Normal difference between the superior and inferior points* is less than 30 μm.

Abnormal patterns include:

- Horizontal displacement of T_L
- Dome shaped
- Bell shaped – pellucid marginal degeneration
  - Generalized thinning – keratoglobus
- *Anterior chamber analysis* includes a calculation of the chamber angle, chamber volume and chamber height and a manual measuring function at any location in the anterior chamber of the eye.
- *It has availability of two-map and four-map comparisons and numerical analysis of anterior segment progression,* which is useful to compare pre- and post-operative results in refractive surgeries and also see the long-term progression follow-up in patients undergoing collagen cross-linking.
- The *corneal thickness spatial profile and percentage thickness increase graphs* describe the annular pachymetric increase from the thinnest point. These graphs are available on the Pentacam and have been successfully used.

Abnormal shapes include:

- Quick slope/S shape – seen in keratoconus
- Flat curve is seen in oedematous cornea, Fuchs' endothelial dystrophy
- Inverted curve is seen in pellucid marginal degeneration.

Belin Ambrósio enhanced ectasia display (BAD – D)

It consists of multivariate index and integrates anterior elevation, posterior elevation and pachymetry data. It gives a complete overview of the corneal shape and a quick screening tool.

- *Belin/Ambrósio display (BAD)* considers the deviations of normality values for different parameters, so that a value of zero represents the average of the normal population and one represents the value is one SD towards the disease (ectasia) value. A final 'D' is calculated based on a regression analysis that weights differently the parameters.
- BAD II software package features an enhanced reference surface that excludes the 3.5–4-mm area centred on the thinnest part of the cornea in order to eliminate the ectatic regions or 'mountains'. The goal of the BAD was to combine elevation-based and pachymetric corneal evaluation in one comprehensive display to give the clinician a global view of the tomographic structure of the cornea.

BAD-D comprises three sections:

- Enhanced/exclusion map
- Pachymetric indices like CTSP, PII, PPI, ART-Max
- D value.

Enhanced/exclusion map: Anterior and posterior elevation data relative to BFS located outside 4 mm circle around the thinnest local point is calculated with exclusion of central 4 mm zone. Difference map between standard and exclusion map is seen as a colour-coded map.

Pachymetric indices include:

- PPI – pachymetric progressive index. Average should be <1.2
- ART – Ambrósio relational thickness. It is the ratio between the thinnest point and the PPI
- ART-Max value <412 is seen in keratoconus.

- *ART is calculated as the ratio between the thinnest point and the PPI.* The 'ART' concept combines thinnest with the pachymetric distribution, which facilitates the identification of an abnormal cornea despite its thinnest value. The ART is calculated for the average and maximal progression indices (ART-Ave and ART-Max). The best cut-offs for the diagnosis of keratoconus are 339 for ART-Max and 427 μm for ART-Ave. For detecting ectasia susceptibility, we use 391 μm for ART-Max and 512 μm for ART-Ave. Practically, it is best not to perform LASIK if ART-Max is lower than 400 μm.

D-value. It is the derivative value which is calculated from five parameters:

- Df (front elevation),
- Db (back elevation),
- Dp (pachymetric progression),
- Dt (corneal thickness at the thinnest location) and
- Da (corneal thinnest point displacement).

D value:

- Normal <1.6 (white) and
- Suspicious 1.6–2.6 (yellow)
  - Keratoconus >2.6 SD (red).
- *Pachymetric progression indices (PPIs)* are calculated for all hemimeridia over the entire 360 degrees of the cornea, so that the average of all meridians (PPI-Ave) and the *meridian with maximal (PPI-Max) pachymetric increase are noted.*

Measurement of Corneal Power

Scheimpflug imaging can also be used to measure corneal power, which is of interest to surgeons performing cataract surgery. This application is especially useful in patients following excimer keratorefractive surgery, in which the relationship between the anterior and posterior surfaces is altered yielding inaccurate keratometry readings required for IOL calculation. For example, following myopic LASIK, an overestimation of keratometry readings causes an underestimation of IOL power resulting in hyperopic outcomes. Conversely, following hyperopic photorefractive keratectomy (PRK), an underestimation of the keratometry readings causes an overestimation of the IOL power resulting in myopic outcomes.

Keratoconus Screening

Pentacam is the only technology which gives the direct measurement of elevation data and hence detection of keratoconus. There is an inbuilt keratoconus screening software, which also helps in grading of keratoconus (KK1–4).

Various indices shown are as follows:

- Index of surface variance (ISV)
- Index of vertical asymmetry (IVA)
- Keratoconus index (KI)
- Central keratoconus index (CKI)
- Index of height asymmetry (IHA)
- Index of height decentration (IHD)
- Rmin – denotes maximum steepness of concentration
- Topographic keratoconus index (TKI)
- ABCD KC staging
- KISA percentage (Rabinowitz criteria).

Preoperative Screening Before Refractive Surgery

Pentacam has facility for preoperative screening before refractive surgery to exclude ectasia and forme fruste. Diagnostic criteria for detecting forme fruste based on magnitude of elevation maps put forth by Michael W. Belin is as follows:

- Normal values for anterior elevation are differences less than +12 μm.
- Between +12 and +15 μm are suspicious.
- Greater than +15 μm indicate keratoconus.
- Normal values for posterior elevation are approximately 5 μm higher than those for anterior elevation.

Corneal Wavefront Analysis

The anterior and posterior corneal surfaces are described separately by Zernike polynomials based on the measured elevation data. Together, the corneal wavefront analysis and keratoconus detection improve the preoperative screening for patients who are interested in refractive surgery as well as the post-operative progression control.

ADVANTAGES OF PENTACAM

Advantages of Pentacam as corneal topographer include:

- Higher resolution of central cornea,
- Measure surface irregularities – keratoconus,
- Calculate pachymetry from limbus to limbus and
- Wavefront analysis to detect higher order aberrations (HOAs).

OCULAR COHERENCE TOMOGRAPHY-BASED CORNEAL TOMOGRAPHY

Ocular coherence tomography (OCT) of the cornea is an optical method of cross-sectional scanning based on reflection and scattering of light from the structures within the cornea. *Optical interferometry* is *used to generate a log reflectivity profile*. Each peak of the profile corresponds to specific layers of the cornea. Low coherence interferometry achieves axial resolutions from 3 to 20 µm using a non-contact technique. A large area can be imaged in a single scan, and the images have been used to identify the thickness of the corneal epithelium, LASIK flap, intracorneal ring segment depth and three-dimensional structure of the cornea under normal or pathological conditions with precision. A sample image is shown in Figure 6.38A.

COMMERCIALLY AVAILABLE OCT SYSTEMS

Commercially available OCT systems for corneal tomography include the following (Table 6.1):

- *Visante Omni* (Carl Zeiss Meditec, Germany). It is based on rotating optical coherence tomography and Placido disc imaging.
- *SS-1000 CASIA* (Tomey Corp, Japan). It is based on rotating optical coherence tomography.
- *RTVue-100* (Optovue, Fremont, USA). It is based on spectral domain optical coherence tomography-guided corneal power measurement (both anterior and posterior curvatures).
- *IOLMaster 700* (Carl Zeiss Meditec, Germany). It is based on swept source OCT technology with 32-marker Placido pattern.

VERY HIGH FREQUENCY ULTRASOUND CORNEAL TOMOGRAPHY SYSTEM

Artemis 3 imaging machine (ArcScan, Morrison, Colorado) is a VHF ultrasound biomicroscope, which allows corneal tomographic study. VHF ultrasound scans a series of meridians in an arc motion matched to the curvature of the cornea. This allows measurement of the thickness of individual corneal layers over an 8–10 µm zone in three dimensions, as seen in Figure 6.38B. This technology can produce topographic maps of

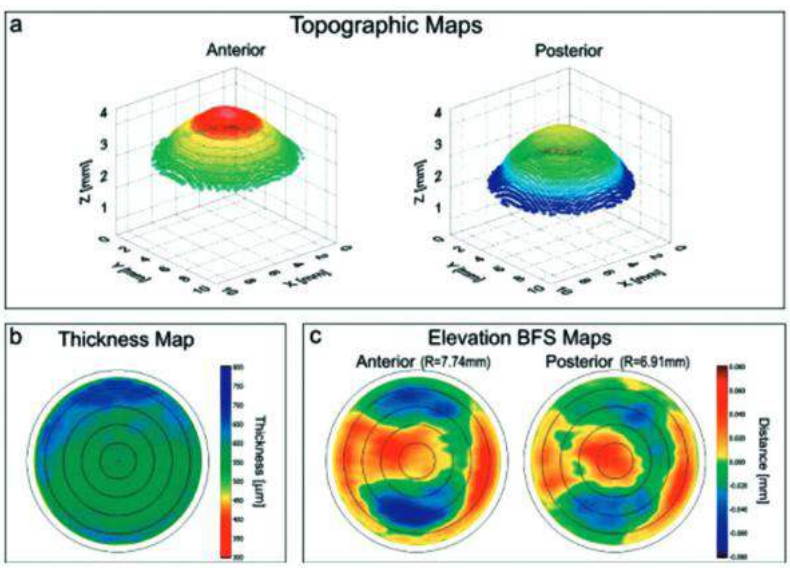


Fig. 6.38 *Corneal topography with anterior segment OCT.*

the individual corneal layers, such as the epithelium, the flaps and the stroma. It has been reported that the topographic information can guide free cap replacement based on epithelial irregularities in the flap. This system has been shown to measure flap thickness with high reproducibility.

DIGITAL RASTERSTEREOGRAPHY-BASED TOPOGRAPHY SYSTEMS

Rasterstereography-based CTS uses a calibrated grid which is projected on to the corneal surface and the diffuse reflection is recorded at two separate known angles. Commercially available *PAR CTS* is based on this technology.

PAR CTS

The PAR CTS from PAR Microsystems Inc., PAR Vision Systems Corp, New Hartford, New York, uses close range photogrammetry (rasterphotogrammetry) to measure and produce a corneal topographic map. A grid pattern of horizontal and vertical lines spaced 0.2 mm apart is used.

Corneal rasterphotogrammetry involves imaging of a projected grid on to the cornea. A modified operating room microscope or slit lamp, as described by Warnick *et al.*, can be utilized. PAR Technology (New Hartford, New York) records video images of the projected grid to give a corneal topography map. Sodium fluorescein is added to the tear film and is excited by blue light, which causes a grid pattern to become visible on the cornea. This is then imaged by the camera and analysed by a digital image processor using algorithms to give information about corneal topography. The accuracy of the system is 0.3 D for a diameter of 7 mm. The contour plots of the cornea appear like keratographs, but actually, each line is an isopter, representing areas of equal height on the corneal surface. The advantage of this system over the keratoscopic one is that it includes information across the whole of the cornea and even includes part of the sclera. Furthermore, the projected nature of the test does not allow interference due to corneal surface or stromal defects.

Note. This system is not much in use presently.

LASER HALOGRAPHIC INTERFEROMETRY-BASED TOPOGRAPHY SYSTEMS

Working principle. *Laser halographic interferometry*-based CTS relies on sophisticated optical techniques of *'light wave interference' fringes as projection device*. The commercially available CTS, the Corneal Lens Analysis System (CLAS II) unit, is based on this technique.

CLAS II UNIT

It is a non-Placido disc-based CTS machine, which is based on the technology of laser holographic interferometry. The CLAS II applies three-dimensional imaging to the analysis of corneal surface changes. The object and reference beams are not split. Instead, they oscillate at the same frequency and remain in phase with each other, thus minimizing the effects of vibration. The CLAS II analyses optical aberrations from reflecting surface by measuring the optical path difference (OPD). This is a measurement of the different path that light takes when it is reflected from a surface.

Note. This system is not much in use presently.

CLINICAL APPLICATIONS AND LIMITATIONS OF CORNEAL TOPOGRAPHY SYSTEMS

CLINICAL APPLICATIONS

1. Role in Early Diagnosis of Corneal Diseases

Computer-assisted videokeratography is helpful in diagnosing following conditions in early stages, i.e. before they could have been diagnosed otherwise:

- Keratoconus,
- Epithelial dystrophies and other epitheliopathies,
- Terrien's marginal degeneration and
- Pellucid marginal degeneration.

2. Topography and Contact Lenses

- Corneal topographic analysis helps in giving a comfortable fit in routine contact lens practice, particularly in rigid contact lens fitting, thus providing maximum possible visual correction.
- It is of unquestioned help in contact lens fitting of difficult cases such as:
  Post-keratoplasty,
  Keratoconus and
  Post-radial keratotomy.
  Other conditions with irregular astigmatism:
- It also helps in early diagnosis of contact-lens–induced changes in cornea like central irregular astigmatism, corneal warpage and loss of radial symmetry. These changes are usually reversible.
- The practitioner and contact lens manufacturer can use corneal topography to verify contact lens specifications, however complex they may be.

3. Topography in Keratoconus

- One of the most useful applications of corneal topography is the *detection of keratoconus* before the appearance of slit-lamp findings.
- Topography has helped a lot in *understanding the features of keratoconus.* Before the introduction of this technique, keratoconus was described as having two basic shapes: oval and nipple type. Videokeratography has demonstrated that corneal shape is more complex than was previously described.
- Classically, keratoconus is depicted as a localized area of increased surface power, surrounded by concentric zones of decreased surface power (Fig. 6.39). The area of steepening may occur anywhere on the cornea. Most frequently, initial involvement is seen in inferotemporal quadrant with superior half of the cornea remaining normal at this stage. Thereafter, the steepening spreads nasally, and then eventually to the superotemporal cornea. The superonasal cornea is the last part to be affected.
- *Contact lens fitting in keratoconus*, which otherwise is very difficult, is facilitated by topography studies.
- Videographic analysis of family members of patients with keratoconus has demonstrated a mild form of disease without any overt clinical signs. This was called *forme fruste* by Amsler.

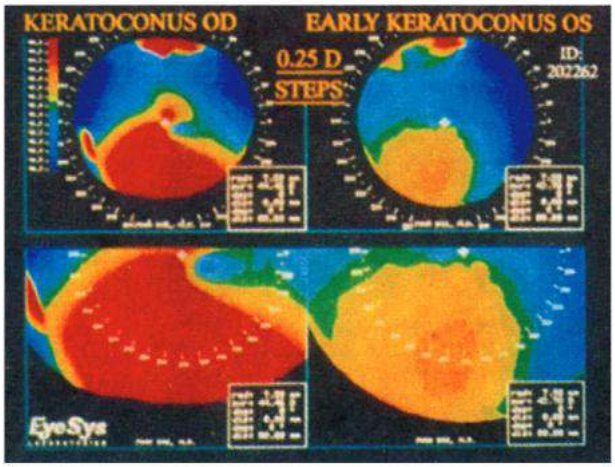


Fig. 6.39 *Corneal topography colour map in a patient with bilateral keratoconus.*

4. Topography in RK

- The role of corneal topography in RK is in evaluating the cornea pre- and post-operatively, i.e. to understand better the mechanics of surgery and, therefore, to further improve the predictability of the procedure in future.
  - *Preoperative topography* reveals that corneas with same central curvature given by keratometer may have markedly different shapes, i.e. prolate, oblate and spherical.
  - *Post-operative topography* reveals flattening of the entire cornea with only relative peripheral steepening.
- ***Repeat RK surgery***, when required, can be better planned with the help of colour-coded maps.
- ***Contact lens fitting post-RK*** can be a problem wherein the keratometric methods would lead to a very flat fit based on central corneal curvature measurements. Corneal topographic methods of contact lens fitting allow peripheral corneal topography evaluation and thus the prescription of a steeper lens based on these curvatures.

5. Role of Topography in Post-Keratoplasty Astigmatism

- *Removal of tight sutures* for control of post-PK astigmatism has been facilitated by the advent of corneal topography (Fig. 6.40).

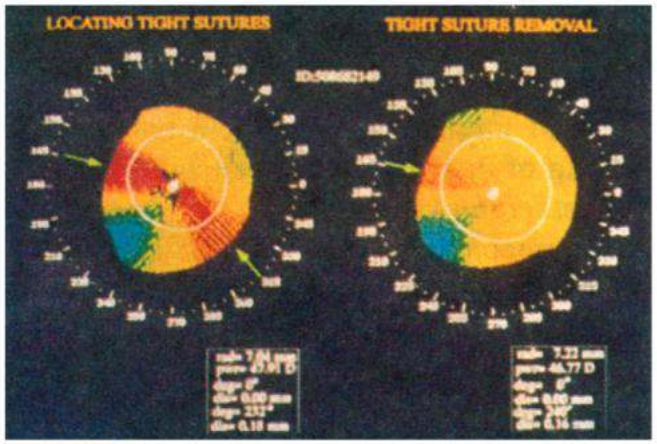


Fig. 6.40 *Corneal topography colour map in a patient with post-penetrating keratoplasty (tight suture at 165 degrees).*

- *Corneal relaxing incisions* when required to manage post-PK astigmatism are better planned with topographic evaluation. After the advent of topography, the relaxing incision is placed at the steepest corneal meridian at the steepest point and not at the graft–host interface as was advocated earlier.
- If topography reveals excessive corneal flattening due to wound gap (diagnosed by the typical teardrop formation on videokeratographic image), then wound revision and wedge resection may be indicated instead of relaxing incision 90 degrees away.
- *Post-PK contact lens fitting* by corneal topographic analysis has shown better results as compared to lens selection based on keratometric finding.

6. Role of Topography in PRK and LASIK

Corneal topography is virtually indispensable for performing PRK and LASIK. Keratorefractive surgery, in general, has been made more predictable with the use of corneal topography.

- Videokeratography is not only essential for screening candidates for these procedures, but it also provides important information about the quality of ablation zone, the diameter of the ablated zone, centration of the ablation and the stability of topographic alterations.
- Differential topographic maps are used to give the desired dioptric change in the corneal power.
- *Decentration of the ablation* zone detected on post-operative topography might explain post-operative halo or glare effect.
- *Irregular ablation zones* (as is seen in central islands) often explain decreased visual acuity and decreased quality of vision after these procedures. Recognition of these abnormal zones has resulted in modification of the procedures to prevent their occurrence.

7. Other Applications of Topography

- *IOL power calculation* can be done more accurately by employing the corneal topography to measure the necessary K value, instead of using the conventional keratometer.
- *Laser pachymetry* for corneal thickness is possible with *corneal modelling systems*, using a dual beam scanning laser slit lamp.
- *Corneal topographic analysis* can be stored to show the pre- and post-operative conditions for self-study and patient satisfaction purposes.

■ LIMITATIONS

Though quite useful and advanced, computerized corneal topography does have some limitations.

1. *Algorithms for power calculation* are based on spherical optical systems, which may lead to qualitative and quantitative erroneous interpretations, as the normal cornea is aspheric.

2. The *correlation between corneal curvature and power* (as shown by colour-coded maps) is valid for spheres and elliptical surfaces as long as there are no areas of abrupt transition in corneal curvature. If abrupt transition exists, software directly showing the surface elevation is more accurate than one that back calculates it from dioptric files. In fact, manufacturers have been advised to display colour curvature maps instead of colour dioptric maps.

3. *Data are averaged across meridians*, thus tending to magnify the 'blend' zones rather than show

the sharp boundaries, if present, for example in pre- and post-operative PRK patients.

4. *The formulae employed* for power calculation are centred on the corneal apex and not on the more relevant line of sight.

5. *Central corneal power is interpolated* from central rings and it may give overestimations in cases of oblate corneas.

6. The *keratometric index of refraction* (1.3375) usually employed underestimates the changes in corneal power after procedures like PRK, as the actual index of refraction of the cornea is 1.376.

7. Videokeratography maps after an unsuccessful PRK may not show a change in corneal topography based on corneal surface, although a change in corneal thickness has taken place.

8. Placido disc-based computerized videokeratographic instruments have *problems of critical focus* and inability to measure highly irregular corneas.

ABERROMETRY AND WAVEFRONT TECHNOLOGY

ABERRATIONS

Although the human eye is an optical marvel, yet it suffers many deviations from being an ideal optical system. All forms of deviations (refractive errors) are basically aberrations. Aberrations can be grouped as follows:

I. ***Lower order aberrations*** (LOAs) include myopia, hypermetropia and regular astigmatism. These aberrations can be understood without sophisticated analytical methods and surgically can be treated by conventional LASIK. LOA constitute 85% of aberrations. There are three types of LOA:

- Tilt of prism,
- Defocus and
- Astigmatic aberration.

II. ***HOAs*** are subtle deviations from the ideal optical system. These constitute 5% of aberrations of the eye and include spherical aberrations, chromatic aberrations, coma, decentring, oblique aberration and centring. These have been described in detail on page 37.

HOAs do not lend themselves to easy solutions. Thus, HOAs limit the potential visual acuity of the eye. It is a well-known fact that the retina has a much higher resolving power and a much better potential visual acuity of about 6/2–6/1.5, but this is greatly reduced by diffraction of light and the aberrations of the eye.

RAY ABERRATIONS VERSUS WAVE ABERRATIONS

There are two ways to analyse aberrations: ray aberrations and wave aberrations.

RAY ABERRATIONS

Ray aberrometry is based on Snell's law. Ideally, all rays from a single object point converge to a single image point. This ideal is never achieved in practice due to aberrations. In ray aberrometry, an imaginary plane is located near the desired image point and the intersection of each ray with the plane is plotted as a spot diagram (Fig. 6.41). Usually, spot diagrams are generated for several planes in front of, at and behind the image, yielding a set of through-focus spot diagrams. The advantage of the spot diagram is that it gives an immediate visual representation of the total amount of aberration present and the image quality. However, spot diagrams are more difficult to interpret when several aberrations are present, as is usually the case in most optical systems, including the eye. Therefore, in practice, ray aberrometry is not much popular.

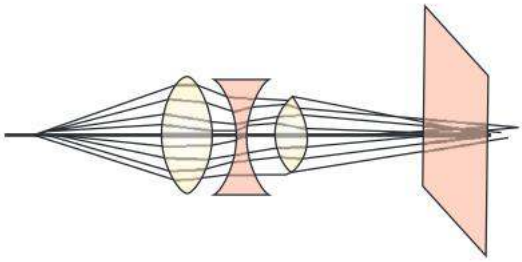


Fig. 6.41 *Ray aberrations and formation of spot diagram in relation to an imaginary plane located near the desired image point.*

WAVE ABERRATIONS

Wavefront refers to any isochronic surface associated with a specific object point. The term isochronic means equal time. Thus, the amount of time required for light to travel from a specified object point to the wavefront is equal for all rays (Fig. 6.42). Note that wavefront is associated with only one object point. Wavefront and rays are two different but closely related ways of representing how light propagates through an optical system. In fact, the rays are perpendicular to the wavefront. Thus, given the shape of the wavefront, the direction of any light ray can be calculated. Conversely, from the direction of light rays, the shape of wavefront can be calculated.

Wave aberrations. In a perfect optical system, there are no distortions induced by the lens system. The ideal wavefront of the perfect optical system thus has spherical shape. The wavefront aberration refers to the OPD between the actual image wavefront and the ideal spherical wavefront. Since the wavefront aberration is the difference between the two surfaces, its surface is usually shaped somewhat like a potato chip.

ZERNIKE POLYNOMIALS AND ZERNIKE TERMS

The monochromatic aberrations are defined and quantified in terms of what are known as Zernike polynomials (ZPs), consisting of Zernike terms (ZTs) and associated spot diagrams.

Using the wavefront sensor method, the aberrations up to 10th order of ZP have been determined. However, for 3 mm pupils, aberrations up to fourth order of ZP are important and the aberrations beyond fourth order are small and have minimal effect on image quality. For 7.3-mm-large pupils, the fifth- to eighth-order aberrations have substantial contribution to the deterioration of image quality. Zernike coefficient (ZC) is an expression of the amount of each individual aberration. Equations are used to calculate ZC for each polynomials.

The most important and commonly encountered first to fourth orders of ZP consist of 14 ZT.

Zero- to fifth-order ZPs are as follows (Fig. 6.43):

- *Zero-order ZP* is also called *piston error*. It consists of the term ZT 0. It has no clinical equivalent and is not significant.
- *First-order ZP* is also called *tilt*. The clinical equivalent is prism and it consists of terms ZT 1 and 2.
- *Second-order ZP*. It corresponds to classical *spherocylindrical correction of refractive errors* and consists of ZT 3, 4 and 5. ZT 4 equals *spherical correction* that corrects the optical aberration of *defocus*. ZT 3–5 equals *astigmatism*.
- *Third-order ZP* consists of ZT 6–9. The ZT 6 and 9 correspond to *trefoil* and ZT 7 and 8 correspond to *coma* aberration.
- *Fourth-order ZP* consists of ZT 10–14. ZT 10 and 14 correspond to *quadrupole* and ZT 11, 12 and 13 correspond to *spherical aberrations*.
- *Fifth-order ZP* consists of ZT 15–20 and corresponds to *secondary coma*.

Note. In normal human eyes of young patients, the contribution to HOA is as follows:

- Third-order ZP – 40%,
- Fourth-order ZP – 25% and
- Fifth- and sixth-order ZP – 30%.

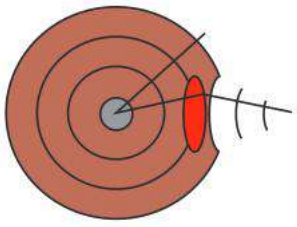


Fig. 6.42 *Diagrammatic depiction of wavefront associated with only one object point. Note that all light from a single object point reaches the wavefront simultaneously. Also, note that rays are perpendicular to the wavefront.*

OCULAR WAVEFRONT

A wavefront is the locus of points characterized by propagation of position of the same phase: a propagation of a line in 1 D, a curve in 2 D or a surface for a wave in 3 D. The understanding of the optical quality of the eye is becoming more accurate with the ability to

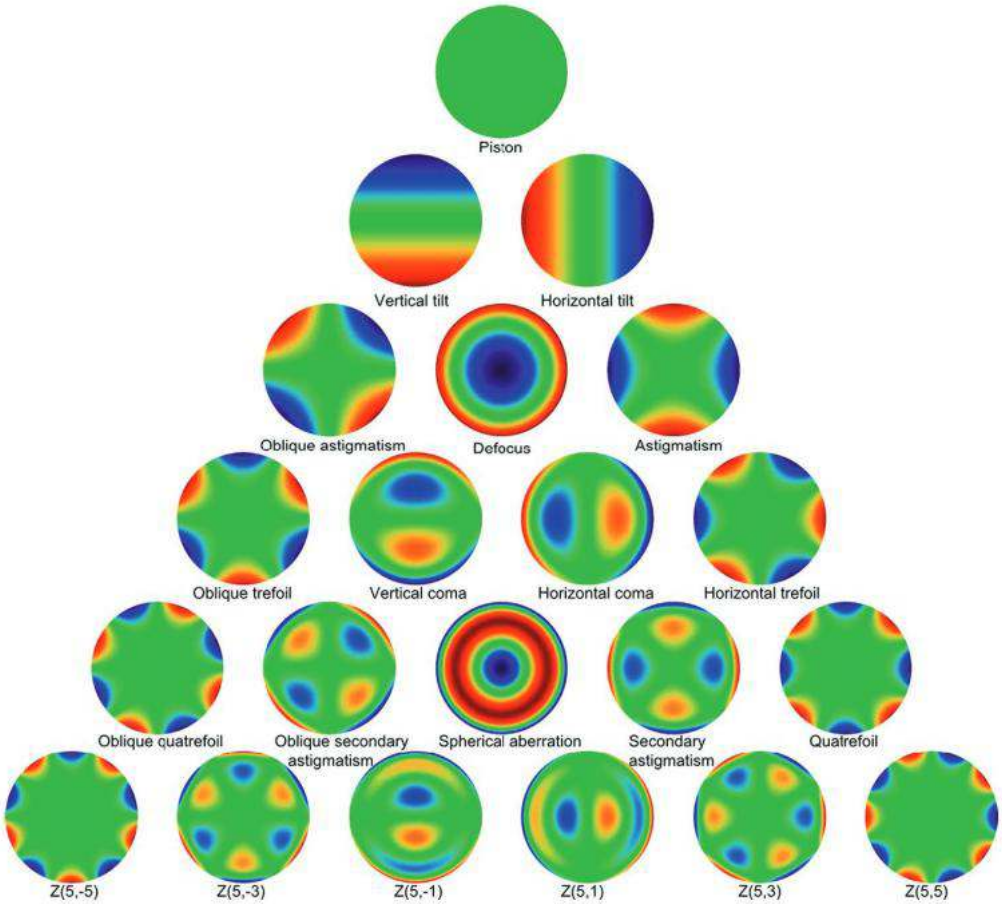


Fig. 6.43 *Zernike polynomials.*

precisely measure the lower and higher order wave aberrations using ocular wavefront sensing techniques. Reliable measurements of the ocular wave aberration also make it possible to correct these aberrations to improve visual performance.

TOTAL OCULAR WAVEFRONT VERSUS CORNEAL WAVEFRONT

The total ocular wavefront is equal to corneal wavefront plus internal wavefront. Thus, the corneal wavefront is one of the components of the *total ocular wavefront*, which can be calculated from the corneal topographic height data, using an algorithm. An algorithm is the calculous procedure used to reconstruct corneal geometry from the calculation of the position of points on the corneal surface relative to axis or a reference sphere.

OPTICAL PATH DIFFERENCE

OPD refers to the difference between the corneal wavefront and an ideal wavefront. It is similar to the spherical offset, which is the height difference between the cornea and a sphere. The OPD forms the basis of corneal wavefront theories.

In ray tracing, the Snell's law is applied to the corneal surface to calculate OPD. Rays are traced from the fovea out of the eye. In the time, a ray travels 3 µm in the cornea, it travels for 4 µm in air. Thus, the *rule of 3*, i.e. every 3 µm of distortion from the ideal shape of the cornea will produce a +1 µm difference in the OPD map and a –1 µm difference in the wavefront error map.

CORNEAL WAVEFRONT MAP

Corneal wavefront map created from the corneal topography can be fitted with a ZP

decomposition in the same way that total ocular wavefront is measured by aberrometry and fitted with the same polynomial decomposition. Furthermore, the corneal wavefront map can be broken down into and viewed as:

- ZC,
- PSF,
- Simulated vision chart,
- Modulation transfer function (MTF; like contrast sensitivity) and
- A street where the patient can see a street scene simulated pre- and post-operatively. This is particularly important for the patients undergoing treatment on highly aberrated corneas to realize the meaning of wavefront and how it adds sharpness to the vision.

FACTORS AFFECTING TOTAL OCULAR WAVEFRONT

Total aberrations of the eye as measures by wavefront analyses are affected by following factors:

1. ***Age***. Total ocular wavefront varies with age, as the aberrations increase with age due to change in both crystalline lens and the cornea. Note that the aberrations of cornea and crystalline lens neutralize each other in the young people. With the increase in age, this balance is lost and thus aberrations of the eye are increased.
2. ***Size of pupil***. The total ocular wavefront map obtained with Hartmann–Shack sensor depends upon the size of the pupil. The pupil becomes small in size with age, which may somewhat offset the increase in aberration occurring with increase in age.

Therefore, the increase in total ocular wavefront aberration with dilatation of the pupil is more significant in the elderly. Aberrations, particularly coma, depend greatly on pupil centration. The change in pupil size with change in illumination due to effect of mydriatics/miotics shifts the pupil centration and thus changes the aberrations.

3. ***Accommodation***. Due to changes in the shape, position and alignment of the lens with respect to pupil and cornea during accommodation, there occurs change in the wavefront aberrations.
4. ***Chromatic aberration***. Presently used aberrometers are laser based, which can measure aberrations at only one wavelength. Thus, the chromatic aberration, one of the eye's major optical defects, is not measured by the clinically used aberrometers.
5. ***Tear film***. Any local change in the tear film affects the ocular aberrations. Such an effect is more prominent in individuals with tear film anomalies, especially the dry eye.
6. ***Misalignment of the eyes*** during wavefront aberrometry affects the accuracy of measurement. Alignment of the eyes is especially critical for HOA.
7. ***Refractive errors***, especially when large, affect the measurement of HOA. This is because the LOA affect the image quality much more than the HOA.

Note. It is important to note that corneal wavefront in contrast to total ocular wavefront is:

- Relatively stable over time and allows serial measurement,
- Not affected by pupil diameter and
- Not affected by accommodation.

MEASUREMENT UNIT OF ABERRATIONS

Measurement unit of aberrations is microns, which is a point-wise measure of the amount of light that is advanced or retarded with reference to a plane. The integrated or total amount of distortion from a reference surface is measured with root mean square (RMS), commonly used mathematical method for reporting distortions.

- RMSg (gross): has to be correlated with manifest refraction.
- RMSh (higher): >0.2 µm needs to be evaluated.
- RMSg: LOA + HOA.

WAVEFRONT ABERROMETRY

Aberrometry refers to analysis of optical aberrations. The analysis of HOA including irregular astigmatism requires advanced technology.

Until recently, there was no need to analyse these defects in detail. However, recently aberrometry has become clinically important, since the progress in imaging and refractive surgery may allow the correction of certain aberrations.

Wavefront aberrometry or the so-called wavefront technology is more popular in clinical practice and is in many ways easier than the ray aberrometry. Wavefront aberrometry refers to measurement of aberrations in the optical system of the eye by wavefront analysis. All methods of measuring the aberrations of the human eye evaluate how the light that enters the eye is modified. With each of these approaches, light is imaged on to the retina and either the image position on the retina or the wavefront as it emerges from the eye is measured.

Commercially available aberrometers, listed in Table 6.1, can be classified into following types and according to operating principle:

I. Backward/outgoing projection type
   - Hartmann–Shack aberrometry

II. Forward/ingoing projection type
   - Tscherning aberroscope
   - Ray-tracing aberrometry

1. HARTMANN–SHACK ABERROMETRY

Hartmann–Shack style aberrometers are currently the most commonly used. In such devices, a single laser beam is projected as a spot on the retina (Fig. 6.44A) and the reflected bundle of rays passes through the optical system of the eye. It is then picked up by an array of small lenslets, which focus these rays into spots on an array of a CCD camera, very much like the compound eye of an insect (Fig. 6.44B). Then the mosaic of spots is used to define the wavefront and analyse its deformation (Fig. 6.44C). The position, the pattern and the PSF of each spot are then analysed and a colour-coded picture of the wavefront is generated by the aberrometer. The shape of the wavefront is represented as a sum of ZPs, each describing a certain deformation (Fig. 6.44D). As an example, the wavefront pattern for astigmatism is shown in Figure 6.44E.

Commercially available aberrometers based on Hartmann–Shack principle include the following:

- LASAR wave (Alcon)
- Zywave, as part of ZyoptixDiofnest Workstation, i.e. ZDW (Bausch and Lomb)
- WaveScan WaveFront system (VISX)
- Corneal Wavefront Analyser (SCHWIND eye-tech-solution)
  - WaveScan WaveFront system (AMO)
  - WaveLight Oculyzer II (ALCON)
  - Alleye Oculyzer.

2. TSCHERNING ABERROSCOPE

Tscherning aberroscope is basically an ingoing retinal imaging aberrometer. In it, a bundle of equidistant light rays is shone on cornea, which is imaged on the retina. A low-light CCD camera linked to a computer is used to analyse the pattern of spots observed on the retina by a method similar to indirect ophthalmoscopy.

Retinal pattern observed is as follows:

- *In a theoretically aberration-free eye*, the retinal pattern consists of equidistant spots corresponding to the incident pattern.
- *In a normal eye*, in clinical practice, the retinal pattern observed is distorted due to the presence of aberrations. The CCD measures the deviation of each spot from the ideal equidistant position.

Commercially available aberrometer based on Tscherning principle includes Allegretto (from WaveLight).

3. RAY-TRACING ABERROMETRY

In this system, pattern of one ray, rather than all rays at the same time, is analysed. In fact, a point incident on the retina and the location of its conjugate focus is analysed with reference to the ideal conjugate focus point. This decreases the chance of crossing the rays in highly aberrated eyes. The wavefront map is calculated from the many such points measured separately. The total time of scanning is 10–40 ms.

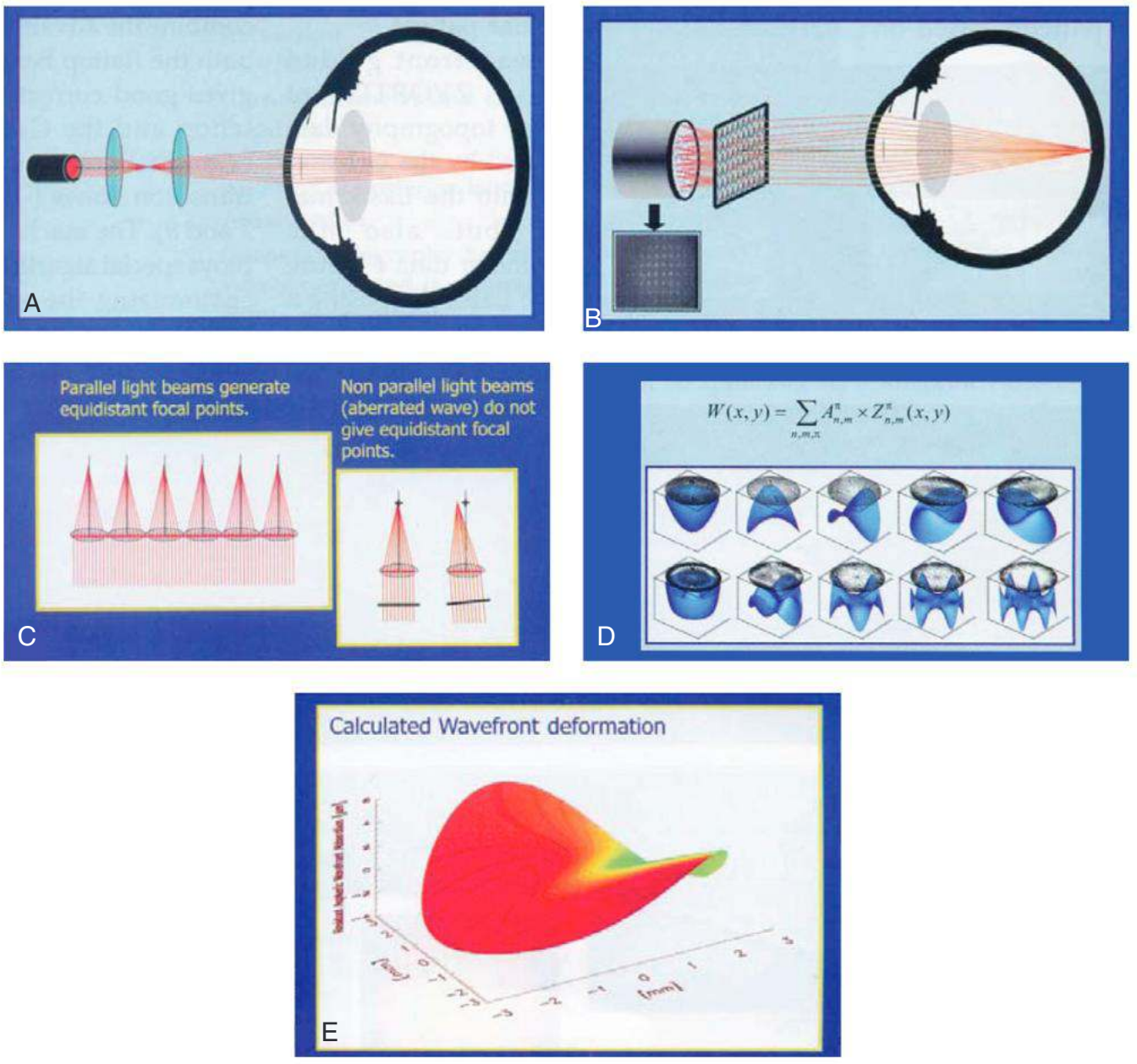


Fig. 6.44 *Optics of wavefront aberrometer: A, a narrow laser beam is focused to the retina to generate a point source; B, array of small lenses focusing the outcoming light ray from the retina on the charge-coupled device camera; C, determination of the wavefront deformation by analysing the direction of the light ray; D, various shapes of wavefronts represented as a sum of Zernike polynomials; E, wavefront pattern of astigmatism polynomials.*

Commercially available devices based on ray-tracing principle are as follows:

- NIDEK OPD Scan III (from Nidek) and
- iTrace (Tracey Technologies, USA).

iTRACE SYSTEM

The iTrace System (Tracey Technologies, Houston, TX) is a combination of ray-tracing aberrometry and Placido disc corneal topography to measure the total aberrations of the eye. It is a serial, double-pass and forward projection type retinal image aberrometer. A topographer is added in the same unit as the aberrometer to measure the corneal aberrations.

Principle of iTrace

- Ray-tracing aberrometry measures forward aberrations of the light going through the eye.

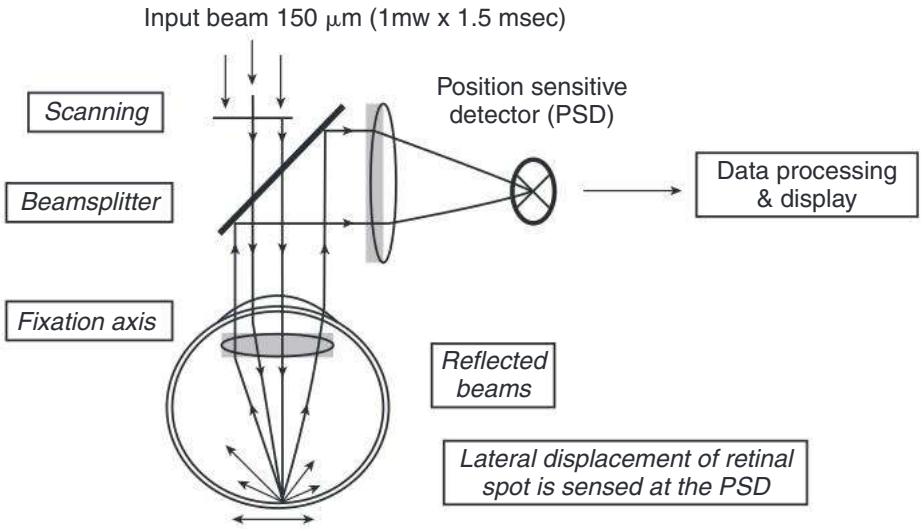


Fig. 6.45 *Diagram of the ray-tracing technique.*

So, it is more physiological as the natural trajectory of the light is being analysed.

- The iTrace uses this principle of ray tracing where a sequential series of infrared beams on the order of 100 μm and a 785 nm wavelength, each is projected into the entrance pupil parallel to the eye's line of sight. Figure 6.45 depicts principle of the ray-tracing technique. It measures the exact location where the laser beam reaches the retina by means of the retro-reflected light captured by reference lineal sensors X, Y. Local aberrations in the path of the laser beam through the cornea and the internal structures cause a shift in the location on the retina.
- This process continues until 64 laser beams have been projected through the entrance pupil four times each (256 points) at high speed (approximately 250 ms). Each of these points represents the entrance of parallel light rays into the eye, which become refracted by the eye's optical power and eventually focus on the retina. All 256 points would be concentrated at a single point in the centre of the macula in an emmetropic eye and reconstruction of the real wavefront error is done.

Data Analysis

1. Wavefront analysis
2. Corneal topographic analysis.

I. Wavefront Analysis (WF)

This depends upon the concept of retinal spot diagram (RSD), which consists of a set of points projected through the pupil onto the retina. RSD is used to obtain MTF and PSF.

PSF shows the image obtained in the retina when the patient sees a point source of light. A sharper and smaller PSF is considered to be better. The MTF is a measure of the transfer of modulation (or contrast) from the subject to the image by an optical system at different spatial frequencies. It measures how accurately it reproduces (or transfers) detail from the object to the image produced by the lens.

Basic Data Graphs

Basic data graphs include the following:

1. *Wavefront verification display* shows the RSD with the horizontal and vertical point profile.
2. *Wavefront map* (total aberrations and HOA) is a colour-coded map, with warm colours showing that the wavefront is in front of the reference plane and cool colours showing retardation.
3. *The RMS* measures the magnitude of aberrations.
4. Total refractive and HOA refractive maps.
5. PSF total and HOA PSF.

6. Snellen letter total and HOA.
7. *Zernike polynomials bar graph*, showing the total, corneal and internal aberrations.

Uses of Aberration Analysis

1. *In case of high total aberrations*, it helps to decide whether the refractive procedure would be better in cornea or lens.
2. *Before and after cataract surgery*, the analysis helps to study the induced or compensated aberrations by the IOL.
3. It also helps to identify which type of IOL will be suitable and to analyse different types of IOL.
4. The contribution of an opacified lens in total ocular aberrations can be measured.
5. *Measurement of angle alpha and angle kappa* to plan for premium IOLs.
6. *To evaluate the corneal and total astigmatism.*

II. Corneal Topographic Analysis

This is based on a Placido disc format named as Vista, which covers up to 10 mm of peripheral cornea. This provides the following:

1. Standard keratometric readings
2. Refractive power of cornea in central 3 mm
3. Corneal index: inferior–superior index (I–S)
4. Topographic maps, such as:
   - Standard axial map
   - Tangential curvature map
   - Refractive map
   - Elevation map
   - Corneal wavefront map

Advantages of Ray-Tracing Aberrometry

1. It allows sequential capture of data and there is no confusion since each point is processed separately and sequentially.
2. The pattern of laser beams projected adapts to the pupil size.
3. High accuracy and resolution since each point is measured separately using linear detectors.
4. The XY-scanner can be programmed to analyse any other rectilinear or polar pattern.
5. iTrace is less susceptible to eye motion and tear film artefacts.

INTRAOPERATIVE, REAL-TIME WAVEFRONT-GUIDED ABERROMETRY

These aberrometers have been evolved recently to refine the outcome of laser vision correction and cataract surgery by providing greater diagnostic refractive precision. This core technology, referred to as HOLOS (Clarity Medical Systems, Inc., Pleasanton, CA) is a novel technique for dynamically achieving accurate wavefront images or refractive profiles for real time, refinement during surgery.

OPERATING PRINCIPLE

- The aberrometer use Talbot Moiré's interferometry based on two transmission grids spaced a specific distance apart and rotated relative to each other. The spectacle correction in a aberrated ocular wavefront is determined by using Fourier transform calculation and is represented in the resulting interferogram.
- *Light source (collimated) used is the 830 nm superluminescent diode*, which is launched into the eye and focused on the retina to create the returned wavefront. The collected data on the magnitude and location of the offset error by the quad detector is correlated with the refractive error of the eye. The sequential wavefront aberrometer achieves real-time, high-resolution sampling mainly by the speed at which the mirror rotates and the number and position of samples synchronized to pulses of the light source per revolution (Fig. 6.46).
- *The refractive outcome of the real-time sampling* is seen in an image overlaying a live eye image as viewed through the microscope and is presented as both qualitatively and quantitatively.
- *The qualitative data are seen* as a circle for spherical error, a thin ellipse for astigmatism and a dot for emmetropia.
- *The quantitative data are displayed* as sphere, cylinder and axis at the bottom of the screen.

CLINICAL APPLICATIONS AND ADVANTAGES

- Identification of the astigmatic axis during surgery instead of the preoperative markings, which can save time.

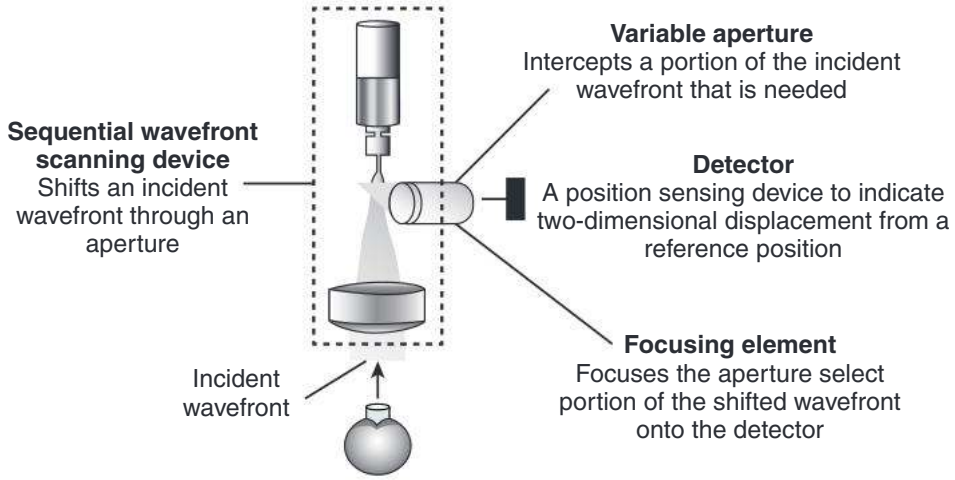


Fig. 6.46 *Working principle of intraoperative wavefront aberrometry.*

- The potential to manage the Limbal Relaxing Incisions (LRIs) by guiding their placement location and using real-time feedback to titrate their length until neutralization.
- The real-time refraction can also guide the toric IOL rotation until neutralization.
- The added size and dimensions do not change the surgeon's working distance.
- Provides high-quality data regardless of the microscope or room illumination.
- Does not lengthen the surgical time.
- The real-time refractive data is integrated with the surgical video obtained.

CLINICAL APPLICATIONS OF ABERROMETRY

1. ***Wavefront-guided refractive surgery***. See page 419.
2. ***Role in early diagnosis of keratoconus***. Wavefront technology is an excellent adjunct to topography in the diagnosis of an early keratoconus. A topographic map showing slight inferior steepening accompanied by significant coma on wavefront analysis could be a cause for great concern. Preliminary research indicates that using a combination of inferior/superior value (derived from topography) and vertical coma (derived from wavefront) best separates early keratoconus from normal.

Increase of ocular HOA in keratoconic eyes results from an increase in corneal HOA. Coma like aberrations are dominant compared with spherical like aberrations in keratoconic eyes. Wavefront analysis will enable us not only to evaluate the quality of vision but also to differentiate keratoconic eyes from normal eyes by analysing characteristics of HOA. Typically, it may show increased values of ZC – C_7 and C_8.

3. ***Wavefront-guided LASIK enhancement.*** Corneal wavefront-guided enhancements in patients with night vision symptoms and high positive spherical aberrations after myopic laser refractive surgery is effective in improving night vision symptoms, reducing corneal spherical aberrations and decreasing asphericity of cornea.
4. ***Intraoperative real-time wavefront-guided aberrometry.*** For details, see page 217.

7 Spectacles

Chapter Outline

INTRODUCTION

Spectacles are defined under British standards as the optical appliance comprising lenses and a frame, with sides extending towards the ears. They should be differentiated from eyeglasses, which are optical appliances comprising a lens or lenses and a frame having no sides. Eyeglasses were used in the past and have been largely replaced by spectacles. Spectacles are a common, cheap and easy method of prescribing corrective lenses in patients with refractive errors and presbyopia.

Practice of refraction is an integral part of any ophthalmologist's job. It does not stop with giving the prescription. An ophthalmologist should have a working knowledge about spectacle lenses and frames and the process of dispensing, because this will help him or her to give exact instructions to the optician. Some important

aspects of the spectacles are, therefore, discussed in this chapter.

SPECTACLE FRAMES

The frame is the portion of spectacles that holds the lenses in position and maintains in front of the eyes for visuals. These are available in different styles, designs and are made of different materials.

PARTS OF A SPECTACLE FRAME

Each frame has two main parts: front and side. The front consists of rims, bridge, joints, lugs and end piece (Fig. 7.1.I).

Frame Front

It includes the following:

Frame rim is also known as *eyewire*. Rims may be complete or incomplete. In spectacles like nylon supra, which have incomplete rims, the lenses are supported by nylon or steel wires. There are rimless frames as well where side pieces are directly screwed to the lenses.

Bridge is that part of front which forms the connection between two rims. Bridges may be of three basic types (Fig. 7.1.II):

- *Regular bridge*. It rests on the nose with full surface in contact.
- *Inset bridge*. It projects behind the frame plane so that the area of contact lies behind the lens plane.
- *Saddle bridge*. It is a combination of regular and inset bridges.

Metal frames have got metal bridges, but they do not lie in contact. Instead, the weight of the frame is borne by two plastic or rubber *nose pads*. Most plastic frames have built-in nose pads.

Lugs are projections on the sides to which the side pieces are attached.

End piece (guard arm). The end is the small part of the front frame that extends outward from the lenses to connect the front frame to the hinges. In other words, the left side and right side of the front frame where temples attach are known as end piece. Some plastic frames may have a metal shield on the front of end piece.

Side Pieces or Temple

Side pieces are the principal parts that fix spectacles to ears. In plastic frames, they are made from plastics reinforced with metal wires. In metal frames, they are made from metals covered with thin plastic end covers.

Each side piece is subdivided into four parts (Fig. 7.1.III):

- *Butt or butt end* is the portion of the temple (side piece), which is attached to the frame front.
- *Shaft (shank)* is the portion of the temple, which lies between the butt end and the bend.
- *Bend* is that portion of the temple where the temple first bends down to go over the ears.
- *Ear piece (temple tip)* is the part of the temple beyond the bend and behind the ear. It is a plastic piece that covers the temple end. It provides extra comfort to the wearer, especially with metal frames.

Frame Measurements

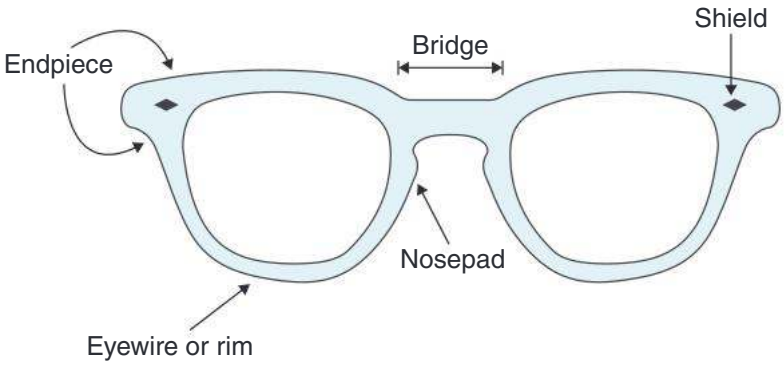
These include the following:

- *Total length of side*: The distance from the assumed spectacle plane to a point just behind the lower ear lobe.
- *Length to bend*: The distance from the assumed spectacle plane to the ear point.
- *Length of drop*: Length of drop is the distance from the crown of the ear to a point approximately two-thirds down the back of the ear.
- *Downwards angle of drop*: The downward inclination of the side from the assumed line of the side measured at the ear point.
- *Head width*: The horizontal distance between the ear points.

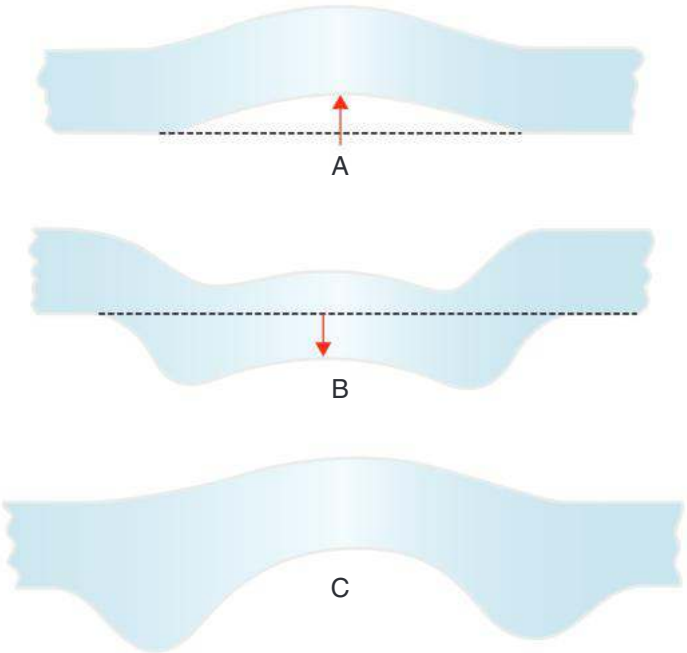
SPECTACLE FRAME MATERIALS

Qualities of an ideal spectacle frame material. Spectacle frames are made up of various synthetic materials and metals. An ideal material should have the following qualities:

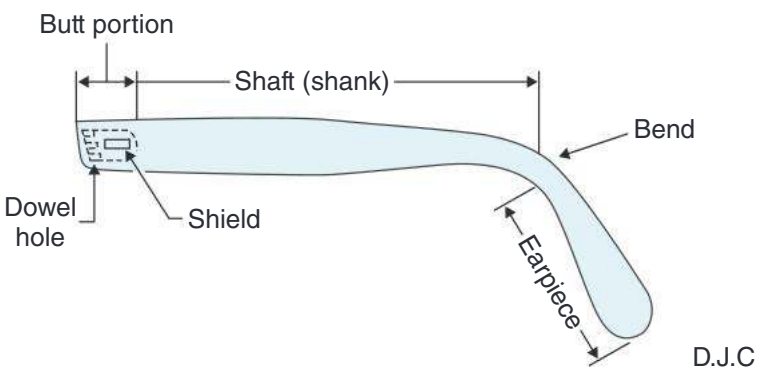
- Non-allergic,
- Resistant to corrosion,



I. The frame front



II. Plastic spectacle bridges



III. Parts of a temple

Fig. 7.1 *I: Parts of frame front; II. Types of plastic spectacle bridges (diagrammatic view from above): A, regular bridge; B, inset bridge; C, saddle bridge; III. Part of frame side piece.*

- Non-flammable,
- Inexpensive,
- Durable and
- Adjustable.

Spectacle frame materials could be any of the following:

- Natural material (tortoiseshell frames),
- Plastic frames,
- Nylon supra frames,
- Metal frames and
- Combination frames and rimless mounts.

1. Tortoise-shell Frames

In the past, natural materials like tortoise-shell and horn have been extensively used.

These were basically made from the shell of hawksbill turtle, which is found in West Indies and Seychelles. Its quality depended on the colour of the shell, which ranges from amber to dark red. Frames were made from spliced blanks, 4 mm thick, which are made up after pressing together two pieces of steamed turtleshell. These frames were durable, had attractive colours and mottling and were easy to maintain. So, these frames were quite popular in yesteryears. But with the advent of new materials and mass production of spectacles, their use is very rare nowadays.

2. Plastic Frames

Plastics were introduced when the need for an inexpensive material that could be mass-produced and could be easily worked upon arose. The material was initially derived from cotton or petroleum extract, but later on newer materials polymerized in the laboratory were used. Plastics are divided into two groups:

- Thermosetting (thermohardening) and
- Thermoplastic (thermosoftening).

Thermoplastic materials can be heated and cooled without losing their plasticity. That is why these materials are preferred for spectacle frames.

i. ***Cellulose nitrate.*** It is derived from cotton lint after subjecting it to various chemical processes. Frames are made from sheets made of this material. Cellulose nitrate is hard, retains its shape even in hot climates and is easy to work upon. The only disadvantage is that it is inflammable. With the introduction of newer and better materials, its use has declined.

ii. ***Cellulose acetate.*** It is also obtained from cotton lint. It is less inflammable than cellulose nitrate, but its stability is also low, making it somewhat inferior to cellulose nitrate frames. Cellulose acetate frames can be made from sheets or injection moulding.

iii. ***Cellulose propionate.*** It lends itself easily to injection moulding and is used in combination frames.

iv. ***Perspex.*** It is a synthetic acrylic resin, also known as polymethyl methacrylate (PMMA). Frames made from it are highly stable, so they retain their original form better than cellulose frames. It is non-allergic, but since it is rigid, it is not easy to work on.

v. ***Epoxy resins.*** Epoxy resins are thermoplastic, and frames made from these are lightweight yet stable and do not lend themselves to warping as in cellulose frames.

3. Nylon Frames

The nylon frames are made up of very tough material which can be used in protective spectacles and sunglasses. Nylon frames are rarely used nowadays; these were used in spectacles for children where chances of breaking were high.

4. Metallic Frames

Metallic frames are very popular. Mass production of metallic frames is much easier. Apart from that, they are stable, quite adjustable and non-allergic (except for nickel). They are non-flammable, inexpensive and pleasing too. Metallic frames have been made from a variety of materials. Previously silver was also used, but since it was soft, its use did not gain much popularity.

i. ***Stainless steel.*** Stainless steel is an alloy of iron and chrome. Most stainless steels contain

10%–30% chromium, which imparts an excellent resistance to corrosion, abrasion and heat. Stainless steel is lightweight, has low toxicity and is very strong and when made very thin, has an element of flexibility that makes it well suited for temples. It is also nickel-free and thus hypoallergenic. It is highly resistant to corrosion, highly stable and easy to manufacture, so it is quite often used for making frames.

ii. ***Monel metal.*** Monel is whitish, pliable for good adjustment, resists corrosion and accepts a high polish. It is made from nickel, copper, iron and traces of other elements. The largest component of the material is nickel at 63%–70%. The second largest component is copper. Iron constitutes only 2.5%, and there are traces of silicon, carbon and sulphur.

This material is a mixture of any of a broad range of metals and is the most widely used material in the manufacture of frames.

iii. ***Titanium.*** Titanium is extremely lightweight and will not rust. Its strength allows it to be made thin, but it is hard to solder or weld. Titanium is a silver-grey metal that is lightweight, durable, strong and very corrosion-resistant. Frames made from 100% titanium may be recommended to customers who are allergic to nickel. The only drawback to this material can be high cost due to its manufacturing process.

iv. ***Flexon (a patented memory metal).*** Flexon is a titanium-based alloy with nickel and some other elements in it. It does not corrode and is lightweight.

v. ***Tickle.*** Ticral, which is relatively new to the market, is an alloy of titanium, copper and chrome. It is nickel-free and thus hypoallergenic. It is also extremely lightweight and offers many of the features of titanium without the high cost. The material is also strong, durable and available in a variety of colours.

vi. ***Beryllium.*** Beryllium, a steel-grey metal, is experiencing increased popularity as a lower-cost alternative to titanium eyeglasses. It resists corrosion and tarnish.

vii. ***Ruthenium.*** This material is a member of the platinum family and is one of the most expensive materials used on the manufacture of frames. Frames made of this material are strong and durable. Ruthenium is mainly used for plating on other metals.

viii. ***Nickel silver.*** It is also known as German silver and is not used nowadays. It was resistant to corrosion, but users developed contact dermatitis.

ix. ***Anodized aluminium.*** It is a popular material. Spectacle frames made from it are lightweight, inexpensive and highly resistant to corrosion. They are easy to work upon and can be dyed into different colours.

x. ***Gold.*** Gold spectacles are made by layering gold on to some base material like German silver and then pressure rolling it together. This bonds a fine layer of gold to the base metal. After the manufacturing process is complete, the frame is gold-plated to cover any irregularities. Gold-rimmed frames are very attractive and resistant to corrosion as well as non-allergic.

5. Combination Frames

Many frames are made by combining one piece of plastic with metals. In this way, the frames become more sturdy and attractive. Combination frames may have plastic fronts and metal sides. Sometimes metal sides are covered by plastics, particularly at the sites where these touch the skin. This helps because metals are cold to touch and may become uncomfortable in winters.

These include the following:

i. ***Keymont frames:*** These are the frames made by the combination of both metal and plastic. The upper part of the frame is made of plastic and the lower part of the frame is made of metal.

ii. ***Supra frames:*** A supra frame is a frame which has the support with either metal or plastic from the top and the lower region of the lens is supported by a nylon wire. These frames are not suitable for high powers. The best lens of option in a supra frame is a plastic lens or CR-39 (Columbia Resins), as they are light and unbreakable.

iii. ***Semirimless frames:*** These are similar to the supra frames, but the only difference is that they do not have the nylon wire supporting the lens in the lower region. Even in these frames, the best lens of choice would be plastic or CR-39.

iv. ***Rimless frames:*** These are also called as three-piece frames. In these frames, the lens is held in place with the help of the screws, which clamp the lens to the temples and the nose bridge. They are very delicate and have to be handled carefully.

DIMENSIONS OF SPECTACLE FRAME

Systems of Spectacle Measurement

To ensure reproducibility and better manufacturing practice, various systems of spectacle measurement have been devised. These include the following:

- *Datum system.* It was developed in 1930 and is applied uniformly to spectacle frames as well as lenses. In datum system, datum line, datum centre and datum centre distance are some keywords with which an ophthalmologist must be conversant. These landmarks are of particular importance in decentred lenses and so have been discussed in the section on optical centration and decentration (see page 248).
- *Other systems* like boxing system and GOMAC system have also been developed.

Front to Bend Length

Another dimension is front to bend length, which is the distance between the back surface of the front to the ear point. Too large a front to bend length will cause the frame to sag down on the nose, thereby causing much discomfort as well as forcing the patient to look through the periphery of lens.

Pantoscopic Tilt

Most of the spectacles are so fitted that the lower end of the frame is tilted backwards towards the face (pantoscopic tilt). In this way, the optical centre of spectacle lens coincides with the fixation axis. This is done because most of the time the eyes are looking in somewhat downward direction. Pantoscopic tilt also reduces the chromatic aberrations of a high-power lens and is cosmetically more attractive.

SPECTACLE LENSES

LENS MATERIAL

Like frames, lenses are also made up of a variety of materials. In the past, almost all of the lenses used to be made up of glass, but with the advent of newer materials, its use has come down.

An ideal lens material should have the following properties:

- High degree of transparency,
- Good impact resistance,
- Free from defects, like bubbles and inclusions,
- A high index of refraction and low dispersion are desired,
- Durable,
- Low weight,
- Easy to manufacture and process,
- Good scratch resistance and
- Inexpensive

Commonly used lens materials typically belong to either of the two broad classes of lens materials: **organic materials** (plastics) and **mineral materials** (glass).

1. GLASS LENSES

The idea of using glass for optical purposes is centuries old. Mostly, *crown glass* with a refractive index of 1.5223 is used. Sometimes, *flint glass* with higher refractive index of 1.62 is combined with crown glass lenses as in fused bifocals. Flint glass has got lead salts in it, which reduce its impact resistance. Leaded flint glass spectacles are nowadays used only for X-ray protection.

Problems with glass lenses:

- Owing to lower refractive index, high-powered lenses tend to be thicker and heavy.

- Glass lenses shatter on impact, which is a quality highly undesirable.

Impact and scratch resistance of a glass lens is increased by the process of heat tempering. In this process, lens material is first heated till its softening and then rapidly cooled. This creates a thick compression layer on the lens surface, thus making it more sturdy. Alternatively, chemical tempering can be carried out. Here the lens is dipped into potassium-containing solutions. Potassium enters the lens and compresses its molecules. Chemical tempering is better than heat tempering, but is more time taking.

High-power lenses tend to be thicker, thereby inducing various aberrations at the lens periphery. Since thickness of a lens is inversely proportional to its refractive index, it was thought that high-index lenses were made by incorporating titanium salts to the glass mixture. Though the lenses were of a significantly lower thickness, they were heavier and the problem of chromatic aberration still remained. Therefore, these lenses never gained much popularity.

2. PLASTIC LENSES

Organic materials (plastics) can be further classified by whether they are **thermosetting** or **thermoplastic** materials.

Thermosetting Plastic Lenses

i. ***CR-39 lenses.*** The majority of spectacle lenses are made from *allyl diglycol carbonate*, a thermosetting plastic lens material referred to as **CR-39**. The manufacturing of spectacle lenses was revolutionized by the introduction of CR-39. These allyl resin lenses have refractive index of 1.49. It is a thermosetting material, so can be ground and polished after manufacture without the risk of deformity. It is presently considered to be the 'standard' by which other materials are compared. It is lightweight, impact-resistant and can be tinted to various shades with chemicals. These lenses are slightly thicker than glass lenses because of lower refractive index, but are comparatively lightweight.

Disadvantage is that these lenses are relatively less scratch-resistant and need protective coatings.

ii. ***Zeiss duralet lenses*** are CR-39 lenses coated with a fine layer of silicone. This makes them scratch-resistant. Impact resistance of CR-39 lenses is higher than heat-tempered glass lenses but is equal to chemical-tempered glass lenses.

Thermoplastic Lenses

Thermoplastic materials are not cross-linked like thermosets and can be melted and cooled back and forth from liquid to solid states. A common manufacturing process for producing lenses made from thermoplastic materials is called *injection moulding*. This process involves first heating and melting down thermoplastic pellets and then injecting the melted resin between the two metal moulds under controlled pressure. The melted plastic is then allowed to cool and hardens into a completed lens blank. The most common thermoplastic lens material is polycarbonate.

i. ***Igard lenses*** were made using PMMA, which is an acrylic resin with refractive index 1.49. Lenses were cast in preformed steel dies. PMMA lens had got high degree of transparency and half the weight of the glass. *Disadvantages* were that being of thermoplastic material, they became soft and deformed in hot climates and were more liable to abrasions.

ii. ***Polycarbonate*** is another synthetic material that has been used for spectacle making. Polycarbonate lenses have got high refractive index (1.58), so they are thinner and owing to low density, they are lightweight too. Because of their unique molecular structure, they can flex easily without getting deformed. Therefore, they have got high impact resistance, which is much higher than glasses. This property has made them universally accepted for protective eyeglasses used in industries and sports. Polycarbonate lenses are soft and so get abraded easily. To prevent this, they usually have got two layers of protective coating.

Other Plastic Lenses

Various other plastics that have been tried are polyurethane (Hyperindex), copolymer (RLX-light) or allyl base (True light). These have got refractive index as high as 1.66 and, therefore, have been tried in high-power lenses.

LENS FORMS

■ FLAT VERSUS CURVED LENSES

The total power of a lens can be achieved by combining different types of curved surfaces (i.e. concave or convex) and this is called the form of lens. Depending upon the form, lenses could be of two types: flat and curved (bent).

A. Flat Lenses

These are early lens forms, seldom employed today. A lens is said to be flat when:

1. Both its surfaces have got same type of curvature, e.g. biconcave (Fig. 7.2A) or biconvex (Fig. 7.2B).
2. One surface is flat and the power is ground on the other surface, e.g. *planoconcave* (Fig. 7.2C) and *planoconvex* (Fig. 7.2D).

Note. Flat lenses are used in spectacles only in exceptional cases as in high minus powers. They have got higher degree of aberrations.

B. Curved (Bent) Lenses

A lens is said to be curved (bent) when there is a convex curve on one surface and a concave curve on the other surface. Curved lenses are of two types: meniscus and toric.

1. ***Meniscus lens.*** The modern lenses are curved where both the surfaces are spherical – anterior surface is convex and posterior surface is concave. Introduction of these lenses has made mass production of lenses easier. Meniscus lenses can be plus (Fig. 7.2E) and minus (Fig. 7.2F).
2. ***Toric lens.*** These are curved lenses where one surface is spherical and the other surface is toroidal in shape. To understand the concept of a toroidal surface, it is necessary to visualize a cylinder. Its one axis is curved while the other axis is straight, which is the axis of cylinder. Now if this axis is also curved, then the surface will become a toroidal. Toric lenses are used where a cylinder is also present in the prescription. Spherical power is ground on the anterior surface and the posterior surface is made toroidal.

■ BASE CURVE

With the advent of mass production of lenses, it was not easy to stockpile a large number of lenses of different powers, so the concept of base curve was devised. Lenses are supplied by the

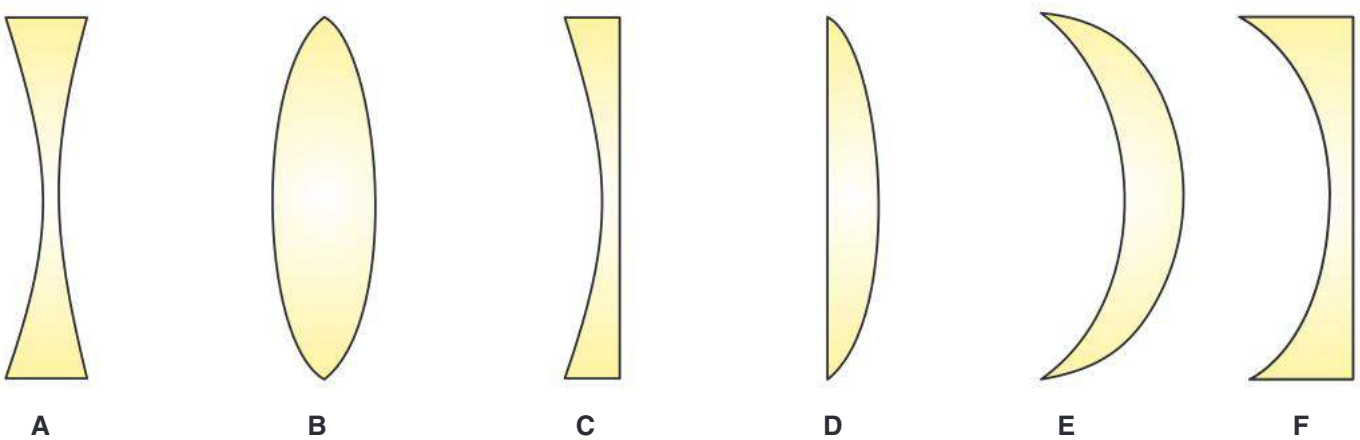


Fig. 7.2 *Types of lenses: flat lenses (A, biconcave; B, biconvex; C, planoconcave; D, planoconvex) and bent lenses (E, meniscus lens; F, minus meniscus lenses).*

manufacturers as *semifinished blanks,* which have one surface ground to have one basic curve, the base curve. The optician grinds its other surface to get the required power. Mostly the base curve is added on the anterior surface. To get plus power lenses, negative base curves are used and vice versa; e.g. to get a +2.0 DS, a lens blank with base curve –6.0 D is taken and then a curve of +8.0 D is ground on the other surface.

A meniscus lens of base curve 6 D is called a *deep meniscus lens*, whereas a lens with base curve of 1.25 D is called *periscopic lens*. Periscopic lenses are not much used nowadays. Base curve used for toric lenses invariably is 6 D. The difference between the base curve and the curvature of toric surface equals the power of cylinder. The exact base curve required is selected on the basis of nomogram tables provided by the manufacturers.

SINGLE-CUT MENISCUS LENS, LENTICULAR FORM LENSES AND ASPHERIC LENSES

A. Single-Cut Meniscus Lenses

These lenses (Fig. 7.3A) are used for making spectacles in small or moderate degree of refractive errors. The standard curved lenses are ground with a concave posterior surface (–1.25 D in the periscopic type or –6.0 D in the deep meniscus type) and the spherical correction is then added to the anterior surface.

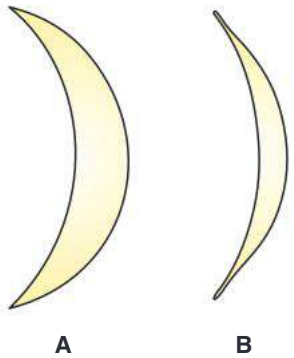


Fig. 7.3 *Single-cut meniscus lens (A) and lenticular lens (B).*

B. Lenticular Lenses

These lenses (Fig. 7.3B) have been created particularly for use in high powers. Here a central portion of the lens is ground to have the power and this is called the aperture. Peripheral part of the lens acts as a carrier. The aperture is usually 30–40 mm in diameter. Thickness of the peripheral part poses a difficulty while fixing the lens to the frame. This difficulty is offset by grinding the peripheral part, which reduces the thickness by 1.2–2 mm and improves the cosmetic appearance as well. Lenticular lenses are of various types:

I. ***High-plus-power lenses***

1. *Solid lenticulars* (Fig. 7.4A and B). In these lenses, the carrier has got convex slope.

2. *Plano lenticulars.* In these lenses, the carrier is plane and the aperture is convex.

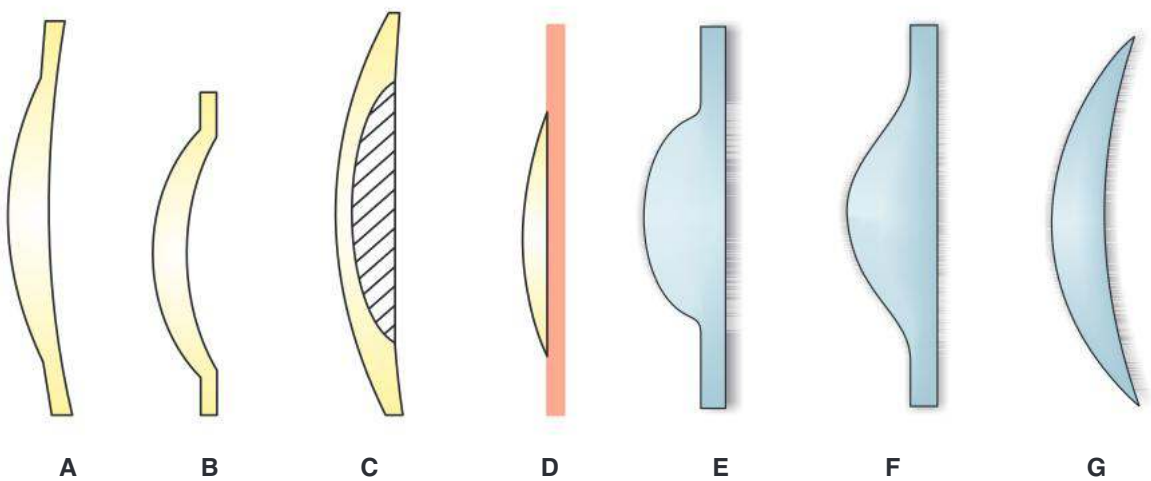


Fig. 7.4 *Types of plus lenticular lenses (A and B, solid convex; C, cemented; D, fused); minus lenticular lenses (E, minus lenticular or myodisc design; F, blended minus lenticular or blended myodisc design); and a type of aspheric lens (G, full field aspheric lens).*

3. *Cemented lenticulars* (Fig. 7.4C). In these lenses, the aperture part carries the sphere and is glued on a carrier on which the cylinder is incorporated.
4. *Profile lenticulars.* In these lenses, the aperture edge follows the same shape as whole lens shape so that the aperture is made as inconspicuous as possible.
5. *Fused lenticulars* (Fig. 7.4D). In these lenses, the aperture is ground on the back surface of a plus lens and is filled with glass of higher refractive index and heated at 600°C. This reduces the composite power by a large amount. The front surface can then be ground to reduce the same amount of power.

II. ***High-minus-power lenses.*** As minus power increases, lens shapes become planoconcave or even biconcave to correct off-axis aberrations. Edge thickness is also greatly increased and is the most important problem when high-minus lenses are prescribed. This problem can be solved by following modifications:

1. *Small round frame-shaped lenses* are a simple solution.
2. *High index lens material lenses* are another solution for this problem.
3. *Minus lenticular or myodisc design lens* are created by grinding away thick outer edge of the lens on its back surface (Fig. 7.4E). This design, like its plus power counterpart, will have a central bowl containing the refractive correction and a peripheral carrier.
4. *Blended minus lenticular or blended myodisc lenses* (Fig. 7.4F) are created by smoothening and polishing the junction of bowl and carrier of minus lenticular design to improve the cosmetic appearance. This process is termed myothinning.

Lenticular lenses reduce the weight of spectacles as well as various aberrations associated with high-power lenses.

C. Aspheric Lenses

An aspheric surface is a surface that departs from being perfectly spherical. Aspheric surfaces are rotationally symmetrical surfaces that gradually vary in surface power from the centre towards the edge, in a radial fashion. This change in surface power produces **surface astigmatism** that can counteract and neutralize the oblique astigmatism. Aspheric surfaces free lens designers from the constraints of *best form* lenses. Lenses can be made flatter, thinner and lighter while maintaining excellent optical performance.

Original aspheric designs utilized **conicoid surfaces**, produced by rotating a conic section about an axis of symmetry to produce a three-dimensional surface. The conic section could be any one of five from the family of conics, including the *circle*, *prolate ellipse*, *oblate ellipse*, *hyperbola* and *parabola*.

Most aspheric lenses are designed to allow use of a flatter, more cosmetically pleasing lens, while minimizing off-axis aberrations. Since flattening a lens introduces astigmatic and power errors, the peripheral curvature of the aspheric surface should change in a manner that neutralizes this effect. For instance, *plus* lenses with asphericity on the *front* surface require a *flattening* of curvature away from the centre of the lens to reduce the effective gain in oblique power and astigmatic error. Asphericity on the *back* surface of a plus lens will require a *steepening* of curvature away from the centre of the lens. The opposite holds true for *minus* lenses. Aspheric lenses are also used to make high plus aphakic lenses by modifying the lens curvature peripherally to reduce aberrations and provide better peripheral vision. For high-power requirement, three types of aspheric lenses, all made from CR-39 plastic (because of weight consideration), are available as below:

1. *Aspheric lenticular lens design.* Decreases lens thickness by decreasing the usable size of lens.
2. *Aspheric blended lenticular design.* It is somewhat similar in design to aspheric lenticular lens, but has a smooth transition between the carrier and the optical part.
3. *Full field lens design.* It has a very aspheric front surface, but no carrier (Fig. 7.4G).

High Plus Lenses (Aphakic Lenses)

As with moderate power aspherics, the base curves of these lenses are relatively flat. For

example, a +13.00 DS lens might have a base curve (power at the centre of the front surface) of +16.00 DS resulting in a back-surface power of about –3.00 DS. The front surface will then flatten to the periphery, resulting in an aspheric shape. The aspheric surface of the Hi-Drop aphakic lens rapidly drops between 3 and 4 D from the centre of the lens to its edge to produce an extremely thin profile. This type of lens is called a *zonal aspheric* because of its zones of changing surface power. The combination of an aspheric design and a flat base curve decreases lens thickness, weight and magnification relative to a spherical design, although aphakic lenses are much thicker and provide considerably more magnification than do other lens types.

LENS SHAPES

Lens shape refers to outline of the lens periphery with the nasal side and the horizontal indicated. The term *shape difference* refers to the difference, in millimetres, between the horizontal and vertical dimensions of a lens. Various lens shapes and families of shapes which can either be clearly defined or have been given generally accepted descriptive names are as follows:

1. ***Geometrical shapes.*** These include the following:
   - i. *Round lens* (Fig. 7.5A). This is one of the most ancient lens shapes. Though not much popular, the round shape is still used for some industrial goggles and other forms of spectacles in which the fashion element does not predominate, because it simplifies glazing.
   - ii. *Oval lens.* This is also one of the ancient lens shapes. It is elliptical (Fig. 7.5B) in shape and not much in use.
   - iii. *Pantoscopic round oval (PRO).* It denotes a family of lens shapes formed by the lower half of a circle and the upper half of an ellipse with the same horizontal diameter (Fig. 7.5C). PRO shapes can be made with any shape difference, depending upon the proportions of the ellipse used. PRO shapes have been quite popular because it was the first step towards the recognition of both functional and aesthetic factors.
2. ***Perimetric shapes.*** These refer to the lens shapes which resemble the monocular field of vision. The name perimetric shape is an allusion to the instrument (perimeter) with which the fields are measured. Two types of perimetric shapes – the rounded contour (Fig. 7.6A) and the squarer contour (Fig. 7.6B) have been in vogue.
3. ***Upswept shapes.*** These refer to a shape with a slope upwards towards the temple (Fig. 7.7).
4. ***Rimless or angular shapes.*** These shapes are specially designed or suitable for rimless spectacles (Fig. 7.8).
5. ***Half-eye shapes.*** Lenses with such a shape (Fig. 7.9) are meant to enable the wearer to use a correction for near vision only and to enjoy a useful field of distance vision over the top.

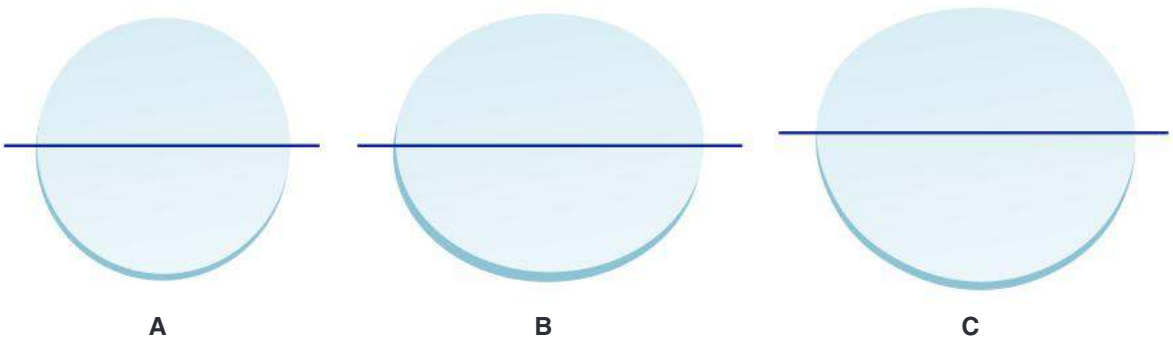


Fig. 7.5 *Geometrical lens shapes: A, round; B, oval; C, PRO.*

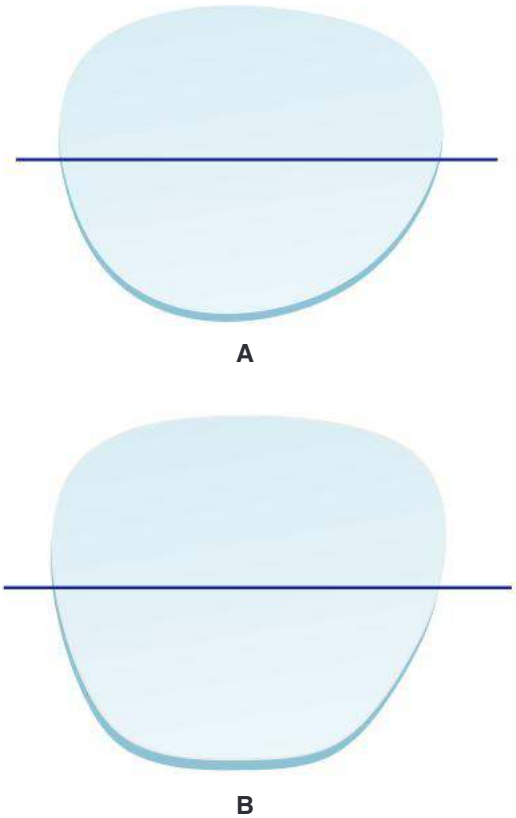


Fig. 7.6 *Perimetric lens shapes: A, rounded contour; B, squarer contour.*

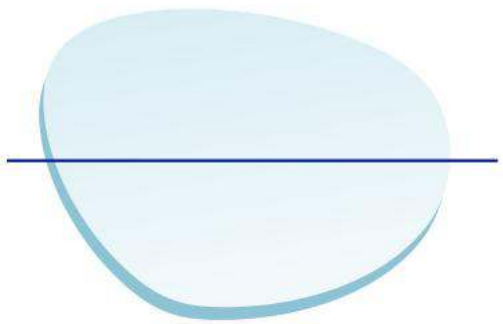


Fig. 7.7 *An upswept shape.*

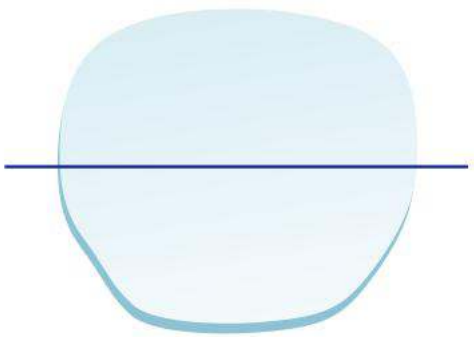


Fig. 7.8 *A rimless (angular) shape.*

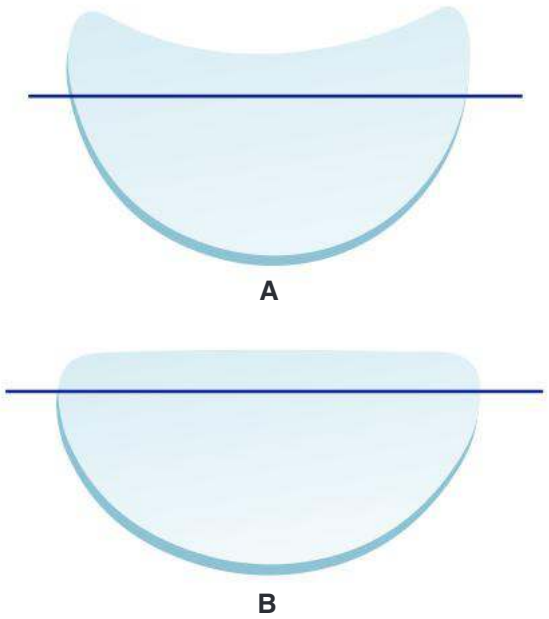


Fig. 7.9 *Half-eye (A) and crescent lens (B).*

LENS POWER

VERTEX POWER AND DISTANCE

Front and Back Vertex

Spectacle lenses have got curved surfaces – front and back. The points where these two surfaces intersect the optical axis are termed *front and back vertex*.

Vertex Focal Length

If the parallel rays of light are made to incident on a lens, they will be made to converge on a point on the optical axis and this is called the *second principal focus*. It lies in front of minus surfaces and at the back of plus surfaces. The distance between the secondary principal focus of a lens and its vertex is called *vertex focal length*. So, in a spectacle lens, there are front and back vertex focal lengths.

Vertex Power

To get a convenient and universally accepted notation of the lens, the concept of vertex power was devised. *Vertex power* is the reciprocal of vertex focal length.

Front vertex power (FVP) is not of much use in spectacles except in bifocals. In these cases,

the near addition is incorporated mostly on front surface of distance correction, so FVP is calculated. In other cases, back vertex power (BVP) is used for spectacle making and dispensing.

BVP is used for specifying the power of spectacle lenses because of its convenience. When a lens of given BVP is placed in front of the eye at a specified vertex distance (lens-to-cornea distance), the lens will correct a refractive error, if its secondary focal point coincides with the patient's far point. The important (and convenient) property of BVP is that any other lens (of any shape) with the same BVP will also correct the refractive error, provided that this lens is placed at the same vertex distance.

Vertex powers can be measured on lensmeters. When the spectacles are kept with front surface down, then the lensmeter reading gives us the FVP and when the back surface is kept downwards, BVP can be calculated.

Vertex Distance

Another term of much importance is *vertex distance,* which should not be confused with vertex focal length. When a lens of a particular power is placed in such a position that it corrects refractive error by bringing secondary principal focus on the retina, then the distance between the back vertex and the retina is the back vertex focal length. It cannot be measured in this condition, but the distance between the back vertex and the cornea can still be measured. This distance is the vertex distance. If a spectacle lens is placed at a distance greater or lower than the vertex distance, then the position of secondary principal focus will change and the same power will not be able to correct the refractive error. So, power of plus lens should be increased and that of minus lens decreased when lens is placed nearer to the eye. Vertex distance is not of much significance till 5.0 D power, but after that significant errors can be introduced, if vertex distance is ignored. Therefore, vertex distance should be specified for prescriptions of more than 5.0 D. Change in effectivity or change in lens power needed, with change in vertex distance, is given by the following formula:

Effectivity change = d × D^2, where d = change in vertex distance in metres and D = lens power in dioptres.

Lens power in dioptres	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Effectivity change in dioptres	0.04	0.08	0.12	0.18	0.25	0.32	0.40	0.50

Effective power changes are significant only for higher power lenses.

Formula for vertex correction is Fc = F/(1 – xF), where Fc is the power corrected for vertex distance, F is the original lens power and x is the change in vertex distance in meters.

SINGLE VERSUS MULTIPLE POWER LENSES

SINGLE VISION LENS

Single vision lens refers to a lens having the same corrective power over the entire surface. These are used to correct myopia, hypermetropia, astigmatism and presbyopia.

MULTIFOCAL LENSES

Multifocal lenses are prescribed in presbyopes where the effort of accommodation is reduced and need of a plus spherical lens arises. The power of these lenses is called near or reading addition. Multifocal lenses have two or more separate portions of different power. They may be bifocals, trifocals or varifocal.

Bifocal lenses have different powers for upper (for distant vision) and lower (for near vision) segments.

Trifocal lenses have three portions: upper (for distant vision), middle (for intermediate range vision) and lower (for near vision).

Varifocal lenses having many portions of different powers are also available.

Segment Architecture

1. ***Centration point (CP).*** The near addition is usually placed on inferonasal part of the

spectacles because the eyes are lowered and converged while reading. So, near addition must have different CP than the distance correction. The near CP lies 2 mm nasal and 8 mm below the distance CP.

2. *Segment shape.* Previously, circular-shaped additions were employed. They created problems because their widest part lay far below reading level, so the reading field was restricted. Moreover, a significant amount of image jump occurred. Image jump is the name given to sudden upward displacement of the image when an object is first viewed through distance and then through the top of reading addition. Both these problems were eliminated by the introduction of flat top segments by Univis, who labelled them Univis D lenses. Their only disadvantage was that the junction line between the distance and the near correction was more conspicuous in these lenses. In Univis C and Sovereign lenses, the top of the segment was made semicircular which was cosmetically more attractive and reduced reflections from dividing line. Executive bifocals are of the most modern design. They are made in such a way that lower half of the spectacle has near addition and upper half has the distance correction. Their dividing line and centres of curvature for distance and near all lie at the same level, thereby reducing the image jump and chromatic aberration and offering widest reading field.

3. *Segment top.* It is the highest point of the segment in cases of curved tops. In cases of flat top segments, it is the midpoint of the upper straight line. Segment top should lie at the level of the lower eyelid.

4. *Segment height.* It is the distance of segment top from the lowermost point of the spectacle lens (and not just from the lowermost point of near segment). Required segment height depends on the patient's vocation. For a patient like accountant and office worker who needs a large reading field, segment height could be increased.

BIFOCAL LENSES

Bifocals were invented by Benjamin Franklin when he took halves of distance and near lenses and placed them together in each rim, thereby creating *Franklin split bifocals*. Their dividing line was quite conspicuous and collected dust, so they quickly went out of vogue. Commonly used bifocals are the following:

1. *Cemented bifocals.* These were first formed in 1888 by Morck. Cemented bifocals were made by grinding distance and near segment separately, then sticking the near segment on the anterior surface of the distance correction by glues like Canada balsam or epoxy resins. They were easy to manufacture, control of CP was easier and the additions could be removed and changed when presbyopia increased. *Disadvantages* were mostly confined to the discolouration and brittleness of glues and the segments got dislocated or fell off.

2. *Fused bifocals.* They were invented and popularized by Borsch in 1908. They work on the principle that difference in the refractive index at any interface produces refraction of light rays at that interface. To achieve the increased refraction needed for near, the addition is made up of flint glass of refractive index higher than the crown glass, which made the distance correction. A concave depression is ground on the lower part of blank for distance correction. Now, flint glass button having one convex surface of equal curvature is mounted on it, clipped and heated till 600°C so that fusion occurs (Fig. 7.10). This composite is then worked upon to get the desired power. The fusion is done on the surface carrying sphere so that the cylinder on posterior toroidal surface acts for

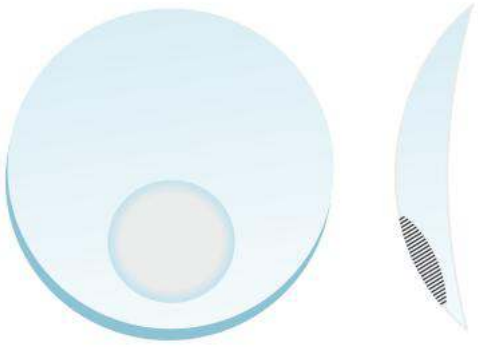


Fig. 7.10 *Construction of fused bifocals: A, front view; B, vertical section.*

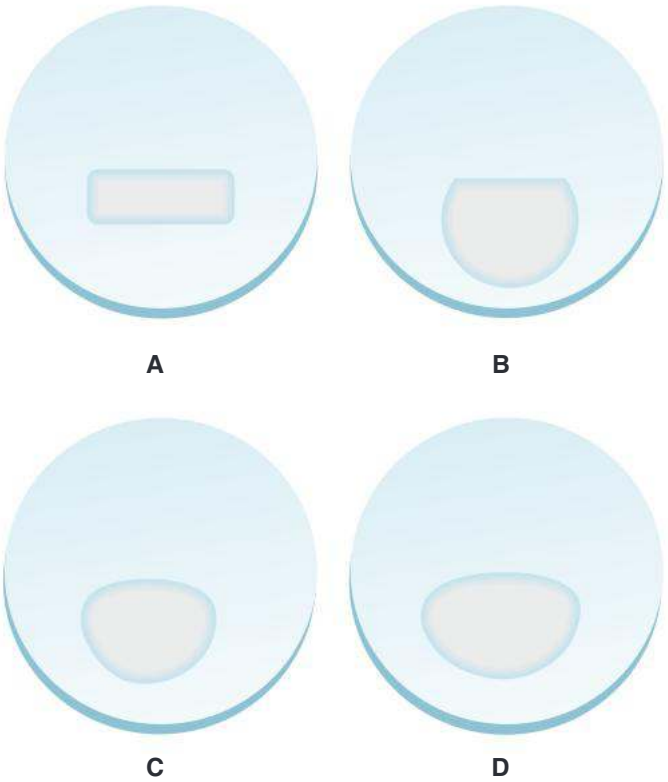


Fig. 7.11 *Various shapes of fused bifocals: A, b-shape; B, d-shape; C, c-shape; D, p (anto) shape.*

near as well. Various shapes of fused bifocals are shown in Figure 7.11. *Advantages* of fused bifocals include inconspicuous dividing line, mechanical stability and low cost. *Disadvantage* is that flint glass has got more dispersive power, so annoying chromatic aberrations are produced while reading.

3. ***Solid bifocals.*** Solid or one-piece bifocals were introduced in 1906 and are the most frequently used bifocal types. They are made up of single piece of lens material – glass or plastic – so the problem of chromatic aberration is solved. They are made by grinding a more strong convex or less strong concave on distance correction. After their construction, cylinder is added by making the other surface toroidal. The dividing line in these bifocals can be made invisible by the better skilled technicians. In young individuals, seamless bifocals in which instead of a dividing line, there is a 2–3 mm wide transition zone of gradually decreasing power should be preferred. It is cosmetically better and image jump is minimized.

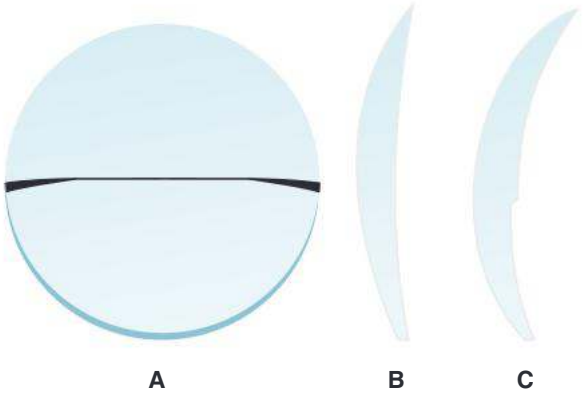


Fig. 7.12 *Executive solid bifocals: A, front view; B and C, vertical sections.*

Most modern type of solid bifocals are Executive or E type (Fig. 7.12). Owing to location of centre of curvatures of distance and near corrections on the optical axis from where rays pass undeviated, image jump is totally negated. Since whole of the lower half functions as near segment, the near field of view is increased.

TRIFOCAL LENSES

Bifocal lenses can focus objects at 6 and 40 cm. A patient near 40 years of age has got sufficient accommodation left to focus intermediate distances at arm's length. However, as the presbyopia increases, intermediate distances become blurred (arm's length blur). For most of the patients, it is insignificant, but for patients who have got more exacting use of intermediate distances like shopkeepers, engineers and computer operators, arm's length blur will create problems. In these cases, another segment is added between the distance and the near segments to focus intermediate zones. Power of this segment is about 50% of the near segment. Trifocals also reduce the image jump because there is less difference between the adjacent segments than there is in bifocals. Trifocals can also be prescribed when reading addition is more than +2.0 DS.

Trifocals are unsuitable when:

1. There is anisometropia and prescription in the two eyes differs by 1.5–2.0 D in vertical meridian.

2. Prism is to be incorporated into reading addition.

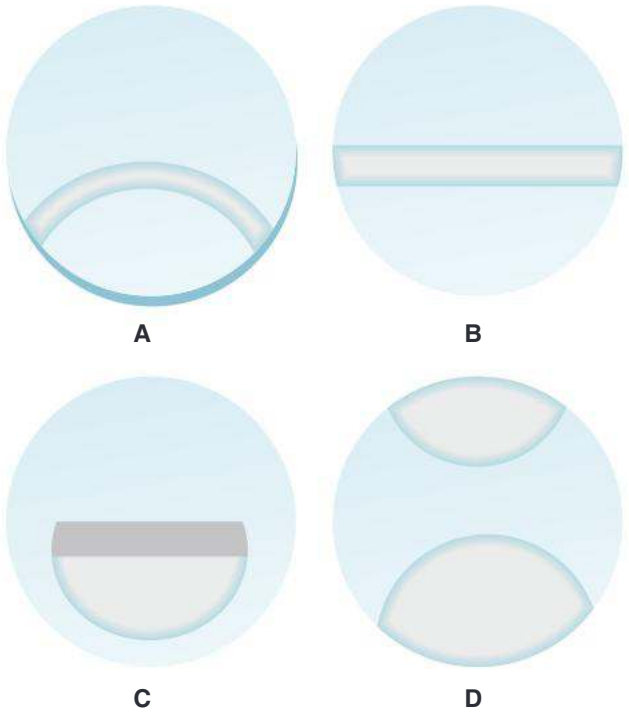


Fig. 7.13 *Principal types of solid trifocals: A, concentric type; B, E-type; C, D-shape; D, combination.*

3. Larger distance segment and smaller near segment are required as in outdoor workers, sports persons, etc.

Trifocals can be fused or solid trifocals and segment shape is just like bifocals, e.g. Univis D, E type, concentric or combination trifocals (Fig. 7.13).

PROGRESSIVE POWER ADD LENSES (PALs)

In a normal human eye, power is gradually increased by the use of accommodation as the object is brought nearer. In presbyopes, bifocals and trifocals provide clear vision at distance, intermediate and near zones, but the power increases in discrete steps and does not resemble the process of accommodation. Progressive power lenses were designed to simulate accommodation as far as possible.

Commercially Available Progressive Add Lenses (PALs)

Various types of lenses were tried – Owen aves lens in 1907, Gowlland lens in 1909, Elephant trunk construction and concentric lenses – but none gained popularity. The progressive power design was revolutionized by the introduction of Essel's Varilux design in 1959 by Bernard Maitenaz. New generation of multidesign progressives introduced in the last decade are as follows:

- Sola's Percepta progressive lenses,
- Kodak progressive lenses (Kodak Precise, Kodak Concise),
- AO compact lenses,
- Essilor's adaptor lenses,
- Carl Zeiss (Precision plus, Precision Superb, Individual 2),
- Nikon (Presio Power, Digilink, Presio W, Presio Go Digital, See Max Power) and
- SWISSCOAT (Genius, MiniPro, SII, ECO, Delux).

Description of Standard PAL

PALs have two areas of prescribed power for near and distance, but the power of intermediate area increases gradually from distance power to near power. The original PALs were designed in such a way that they had progressive area in the form of a central channel, 12 mm wide at the top and 20–22 mm wide at the bottom. Because of its peculiar design, unwanted astigmatism was introduced at the periphery, thereby limiting the field of vision. Improved PALs, which were launched later, had better design, so unwanted astigmatism was greatly reduced. With design modification, it was possible to reduce the magnitude and the rate of change of the unwanted astigmatism.

Structural Features and Major Reference Points of PALs

Standard Structure of a Progressive Add Lens

Traditional general-purpose progressive lenses possess four structural features (Fig. 7.14):

1. *Distance zone*: A stabilized region in the upper portion of the lens which provides the specified distance prescription.
2. *Near zone*: A stabilized region in the lower portion of the lens which provides the specified add power for near.
3. *Intermediate zone or progressive corridor*: A corridor of increasing power connects the above

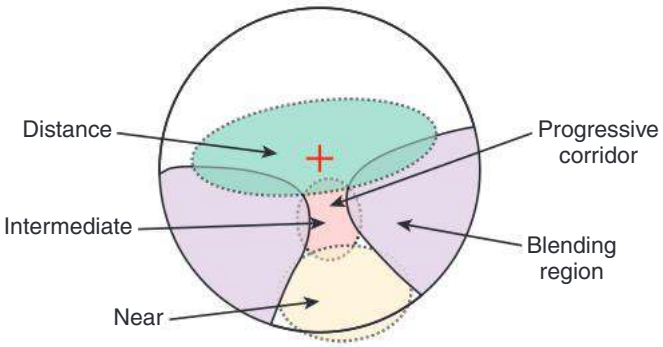


Fig. 7.14 *The structural features of a general-purpose progressive lens.*

two zones and provides intermediate or mid-range vision.

4. *Blending region*: The peripheral regions of the lens contain non-prescribed cylinder power and provide only minimal visual utility.

Major Reference Points of a Progressive Add Lens

Progressive addition lenses are supplied with two types of marking for layout, power verification, dispensing and identification purposes. *Removable markings*, which are ink markings stamped onto the lens, identify the layout, verification and dispensing points of the lens. In addition, *permanent markings*, which are etched upon the lens surface, provide the brand identification and add power of the lens, as well as *alignment reference markings* – which are 34 mm apart and used to reapply the ink markings when necessary. The removable ink markings indicate the locations of the *cardinal reference points* of the progressive lens design that are (Fig. 7.14):

- ***Distance reference point:*** The distance reference point (DRP) represents the location on the surface that provides the exact base curve, which is the optimal location for verifying the distance prescription. It is located at the centre of the *distance checking circle* ink marking.
- ***Fitting point:*** The fitting point (FP) represents the alignment point of the lens design, which is placed directly in front of the visual axis of the eye during *primary gaze*. It is located at the *fitting cross* ink marking.
- ***Prism reference point:*** The prism reference point (PRP) represents the optimal location on the surface for verifying prescribed prism or prism thinning. It is located at the *PRP* ink marking, centred exactly between the permanent alignment reference markings.
- ***Near reference point:*** The near reference point (NRP) represents the location on the surface that provides the full target add power, which is the optimal location for verifying the add power of the prescription. It is located at the centre of the *near checking circle* ink marking.

Optical Description of a Progressive Lens

Lens designers use different methods to graphically represent the optical characteristics of progressive lenses, in particular:

1. ***Power profile***: In Figure 7.15, the curve represents the power progression of the lens along its meridional line from distance to near vision. This power progression is a result of a continuous shortening of the radius of curvature of the front surface.

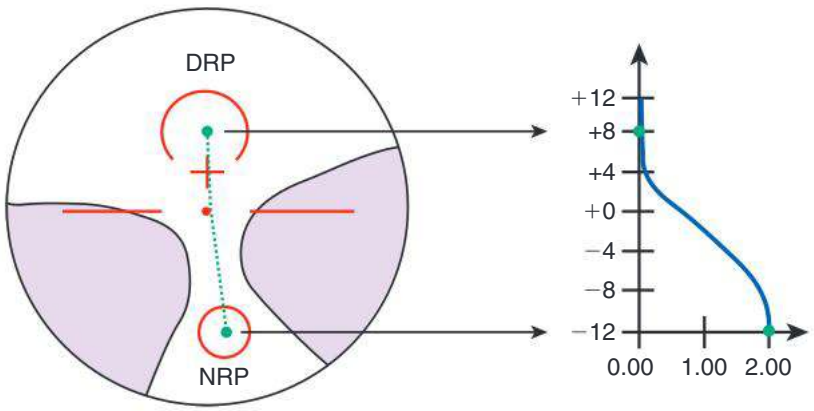


Fig. 7.15 *Power profile of PAL.*

2. ***Contour plot***: This is a two-dimensional map of the lens representing either the distribution of power (Fig. 7.16A) or of astigmatism (Fig. 7.16B). The map shows lines of equal dioptric value (iso-power or iso-astigmatism). Between two consecutive lines, the power or astigmatism varies by a constant value, 0.50 D, in these examples.

3. ***Grid plot***: The grid highlights the distribution of the prismatic effects of the lens by showing how they alter a regular rectangular grid (Fig. 7.17).

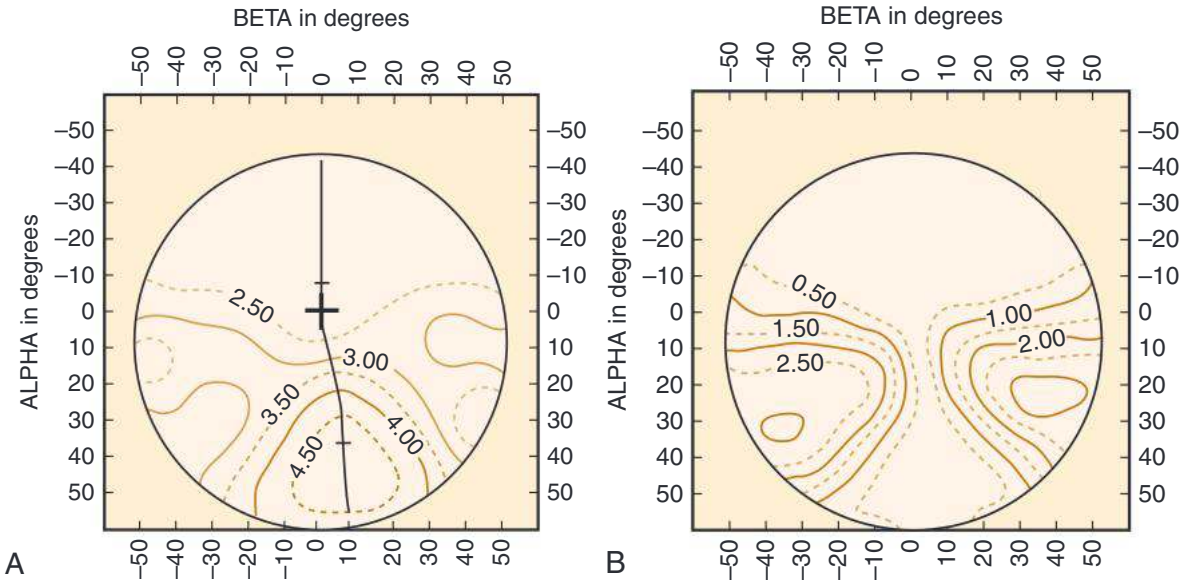


Fig. 7.16 *A. Contour plot of PAL: power; B. Contour plot of PAL: astigmatism.*

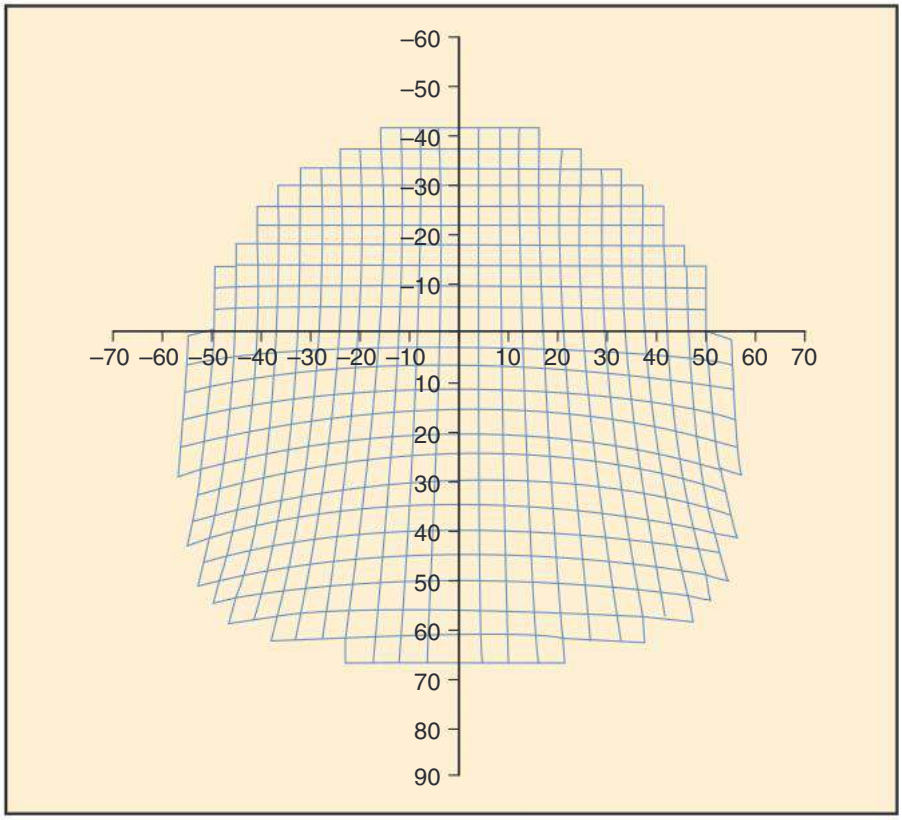


Fig. 7.17 *Grid plot of a PAL (2.50 D).*

4. *Three-dimensional plot:* A three-dimensional representation which plots vertically the value of a given optical characteristic at each point of the lens in relation to a reference plane. It may be used to show the distribution of power, astigmatism, prismatic effects, gradients of power variation, etc. These three-dimensional plots are more demonstrative of lens characteristics than contour plots.

Design of PALs

- Hard-design PALs versus soft-design PALs
- Symmetric design PALs versus asymmetric design PALs
- Mono-design PALs versus multidesign PALs
- Prescription-based design of PALs

Hard- Versus Soft-Design PALs

I. Hard-Design PALs

One of the most fundamental aspects of progressive lens design is the distribution of surface optics, including surface astigmatism and mean add power. The magnitude, distribution and rate of change of unwanted cylinder power and add power define the gross performance of the lens design. *Progressive lenses are often classified as 'hard' or 'soft' design based on the distribution of this astigmatism.*

Features of harder design PAL: A 'harder' progressive lens design concentrates the astigmatism into smaller regions of the lens surface, thereby expanding areas of clear vision at the expense of raising unwanted cylinder power levels in the periphery. Consequently, harder progressive lenses generally offer wider distance and near viewing zones, but higher levels of blur and distortion in the periphery.

Advantages of hard PALs include:

- Large distance and near area free from astigmatism,
- More accessible with downward rotation of eye and
- Wider near zone even at high Rx.

Disadvantages of PALs are as follows:

- High-intensity aberration at periphery,
- Distortion for longer and more difficult period of adaptation and
- Swim effect.

Indications of PALs: Harder designs will generally work better for sustained viewing tasks requiring good visual acuity, so indicated in:

- Previous successful hard lens wearers and
- People who do a lot of reading.

II. Soft-Design PALs

Features of softer designs PALs (Fig. 7.18). A 'softer' design spreads the astigmatism across larger regions of the lens surface, thereby reducing the overall magnitude of unwanted cylinder power at the expense of narrowing the

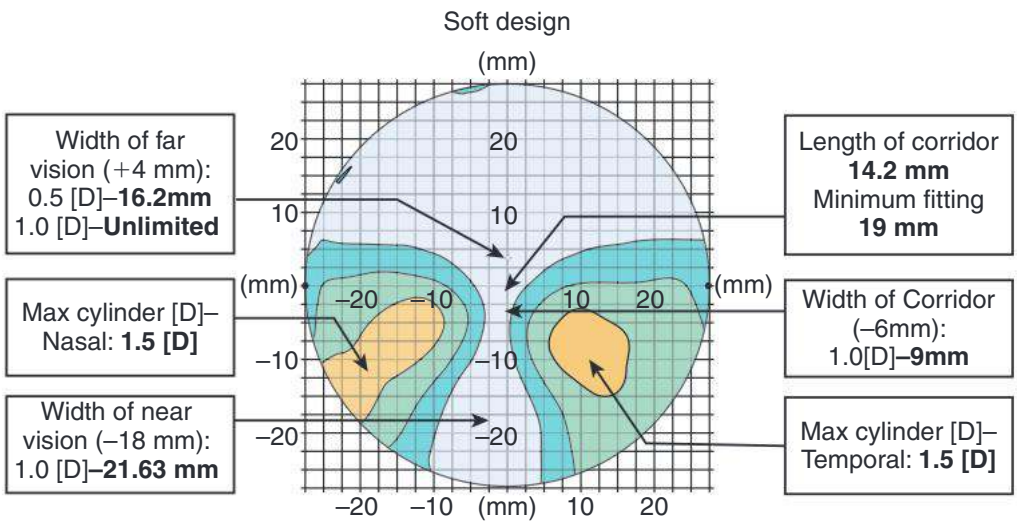


Fig. 7.18 *Features of a soft-design PAL*

clear vision zones. Consequently, softer progressive lenses generally offer less blur and distortion in the periphery, but narrower viewing zones.

Advantages include:

- Decreases intensity aberration at periphery,
- Easier, more rapid adaptation,
- Less distortion of peripheral viewing and
- Reduce swim effect.

Disadvantages are as follows:

- Smaller field at sharp vision and
- Need dropping of eye farther near to read.

Indications. Softer designs are better suited to dynamic vision, so indicated in:

- Young presbyopes,
- Active outdoor profession and
- Professional drivers.

Symmetrical Versus Asymmetrical Design PALs

Symmetrical design PALs. Progressive lens designs were originally *symmetrical, meaning that the right and left lenses were identical*. To achieve the desired near inset, the lens blanks were rotated 9 to 11 degrees. However, this raised the unwanted cylinder power in the nasal region of the lens well into the distance zone, resulting in both a disruption of binocular fusion as the wearer gazed laterally and a reduction in the binocular field of view (Fig. 7.19). This also limited inset control for near vision, since the inset path of the progressive corridor would have to fall along a straight line.

Asymmetrical design PALs. *Most modern lens designs are now asymmetrical,* i.e. using separate designs for the right and left lenses. The amount of cylinder power on either side of the progressive corridor is adjusted independently, which allows the near inset to be achieved without rotating the lens design. Instead, the progressive corridor is initially designed at an angle with the necessary nasalward inclination. This provides better binocular alignment between the right and left viewing zones, affording the wearer larger binocular fields of view (Fig. 7.20).

Mono-Design PALs Versus Multidesign PALs

Mono-design PALs have the following characteristics:

- They describe the range of power for a given design.
- These are classified as hard or soft.
- They describe the characteristics of progressive zone.
- They maintain the same design principles throughout the range of addition.

Multidesign PALs having the following features (Fig. 7.21):

- According to add power, lens design changes.
- They start from soft design for low add power and as the add power increases, they will turn to hard-design lens.

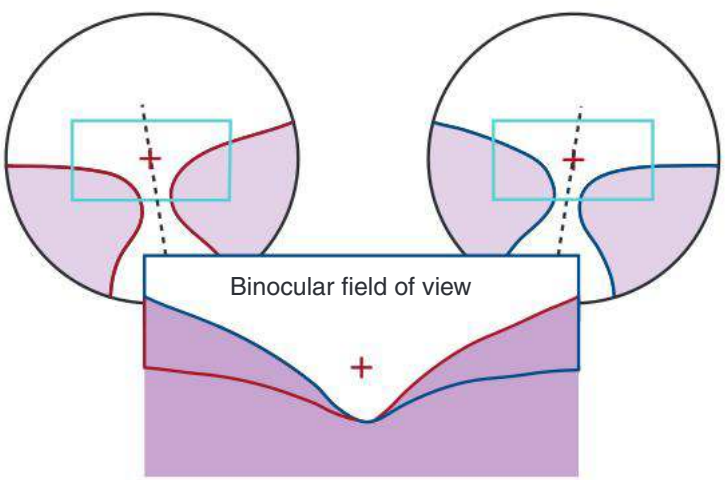


Fig. 7.19 *A symmetrical lens design results in a significant reduction in the binocular field of view and a disruption of binocular fusion as unwanted cylinder in the nasal side of the design is rotated up into the distance zone of each lens.*

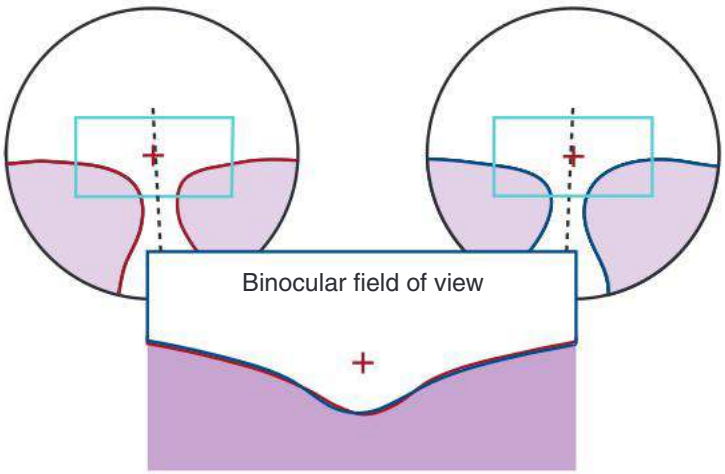


Fig. 7.20 *An asymmetrical lens design maximizes the total binocular field of view by maintaining better alignment between the right and left viewing zones.*

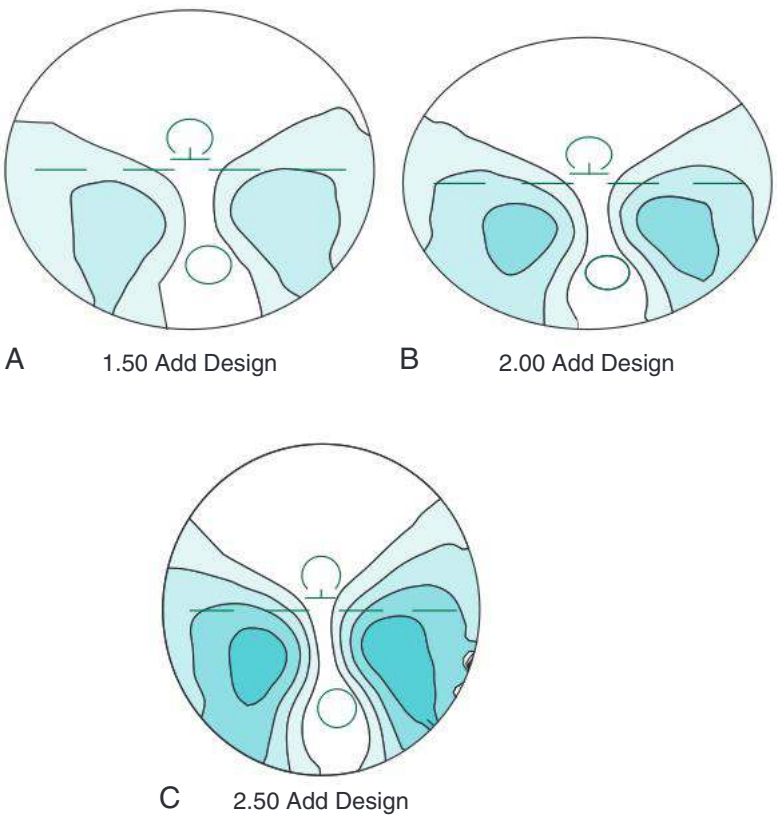


Fig. 7.21 *Features of multidesign PALs change with power add: A, +1.50 add design; B, +2 add design; C, +2.5 add design.*

Prescription-Based Design of PALs

Prescription-based design of PALs is dedicated design for every base and add. It is the result of years of Vision Research.

- *Design by base*: Different designs for hyperopes, emmetropes and myopes.
- *Design by add*: Effective near zone sizes change as the add increases.
- *Near inset position varies* relative to the level of presbyopia/reading distance.
- *Corridor length also varies* relative to both base and add.

Dispensing of Progressive Lens

The placement of a progressive addition lens is determined by the location of its **fitting cross**, which is typically placed directly in front of the centre of the pupil. In progressive power lenses, the change from distance to near power (in other words the near addition) is spread over a 12-mm long channel. In cases of large additions, this change will be rapid, e.g. in case of +3.0 D addition, 1.0 D change will be there for every 4 mm. If the patient's pupil is <4 mm in size, then there will be a difference of 1.0 D between the top and bottom of the pupil, thereby creating a retinal blur. So, progressive power lenses should not be used in patients with larger near additions and large pupil. In addition, they should be avoided where large field of vision is required as in typists and computer operators. Furthermore, patients having cervical spondylitis or vertigo and those who have restricted head and neck movements are not advised for using PALs.

Important tips about dispensing a varifocal (progressive) lens are as follows:

1. *Do not prescribe progressives till the patient is motivated* and his or her profession demands visualization at intermediate distances.
2. *Patient selection is most essential.* These lenses do not give good results in patients with extra-broad nasal bridges and extra-large interpupillary distances (IPDs). Deep-set eyes too are not suitable for these lenses.
3. *The selected patient must be explained about the common problems* during adaptation period such as peripheral distortion, restricted near vision field and difficulty in changing from one viewing distance to another.
4. *Frame selection is the most important* part of fitting of progressive lenses. Following points should be kept in mind:
   - Frame must ideally have fitting height (distance between centre of the pupil and lower rim of the frame) of 24 mm, unless mini-progressive lenses are selected with smaller size of frames.
   - Select a frame with a short vertex distance.
   - Frame should have 7 to 9 degrees of pantoscopic angle (tilt).
   - The frame should be reasonably sturdy to hold its alignment.
5. *The lenses need to be properly centred* in the frame.

Advantages of Progressive Addition Lenses

1. ***Continuous field of clear vision:*** Progressive addition lenses offer a continuous field of clear vision from distance to near. Single vision reading lenses offer a field of clear vision limited to the near area only, while the abrupt change of power in a bifocal creates completely divided fields for distance and near vision.
2. ***Comfortable intermediate vision:*** Progressive addition lenses are the only lenses providing clear and comfortable intermediate vision whatever the addition as the progression of power gives rise to an area specifically designed for intermediate distance correction. Despite their clear intermediate field of vision trifocal lenses are not ideal, since wearers must cope with the image jumps at the two segment lines.
3. ***Continuous support for the eye's accommodation:*** In a single vision reading lens, accommodation is to the eye supported for near vision only. In a bifocal lens, the eye's accommodation experiences abrupt changes when the gaze shifts from distance to near vision across the segment line. Only, for each point of the progressive lens meridian does the power exactly correspond to the eye's focusing distance.
4. ***Continuous perception of space:*** Progressive lenses offer global perception of space: the power changes continuously and gradually in all directions. Single vision reading lenses do not allow real spatial perception, since they provide only a near vision correction. The two portions of bifocal lenses split and alter spatial relationships. Vertical and horizontal lines appear broken and image jump hampers the wearers' vision.
5. ***No visible segments or lines of demarcation*** – provides more cosmetically appealing lenses with continuous vision, free from visually distracting borders.

Disadvantages of PALs

- Straight line appears curved initially and needs more time for adaptation.
- Decreased width at intermediate and near vision leads to limited lateral movement.
- Increase in eye and head movement. Eye must be dropped a longer distance.

USE OF PRISMS WITH SPECTACLE LENSES

SLAB-OFF PRISM

Slab-off prism (also called bicentric grind) may be thought of as prism added to just a part of a lens. In essence, a lens surface is ground to its proper power, then a portion is reground at an angle to the rest of the surface. The finished lens will then have two optical centres (bicentric). This process creates a raised or depressed discontinuity across the lens surface (a 'slab-off line') that is usually positioned along the top edge of a bifocal. Slab-off prism is almost always prescribed as vertical prism for the lower portion of one lens for the anisometropic presbyope. The vertical slab-off prism corrects for the induced differential vertical prismatic effect (vertical imbalance) in the multifocal segment created by the anisometropia.

FRESNEL PRISM AND LENSES

An alternative to plano prism or prism created by lens decentration is the Fresnel prism. This prism is made up of a large number of small prism strips, all of the same prismatic power, oriented base to apex on a flexible plastic membrane.

Uses of Fresnel prisms include:

- Visual field defects such as homonymous hemianopia,
- Prism in bifocal portion only,
- Cosmetic improvement of blind, turning eye,
- Treatment of nystagmus and
- Use as a partial occlude.

Advantages of Fresnel prism include the following:

- The most important advantage of this design over a conventional prism is its greatly decreased thickness.
- Another advantage is the ease of use. Fresnel prisms are attached to a spectacle lens by first cutting the prism to the shape of the spectacle lens using scissors or a razor blade. The smooth surface of the prism is then placed against the lens back surface with both the lens and prism held under water. When the combination dries, a tight seal is formed that can be fairly long lasting. To change prism power, the prism is simply peeled off the lens surface and a new prism attached.

Disadvantages of Fresnel prism include the following:

- *Decrease in the patient's visual acuity*, primarily as a result of reflections from the prism facets.
- *Poor cosmetic appearance* because the prisms appear as a series of lines to an observer.
- *Smudges the lens* on which it is adhered for temporary uses and hence deteriorates the optics.
- *They are difficult to clean and needs extra care* while cleaning with fine brushes.
- *They are not very stable* in high temperatures and decanter from the position.

LENS SURFACING

Spectacle lenses (glass as well as plastics) are supplied by the manufacturer as rough blanks or semifinished blanks which are subsequently ground and polished to a specific curvature and required power by the optician. The whole process involving many steps is called *lens surfacing*. Many a time, the process of lens surfacing is also carried out by the manufacturer and the lenses are supplied as finished uncut lenses where the optician has only to choose the power and then these are cut and fitted according to the spectacle shape.

The process of lens surfacing in glass lenses and plastic lenses involves following steps/stages:

1. ***Marking.*** To correctly locate the lens for different stages of surfacing, certain markings are essential. The markings required on the lens

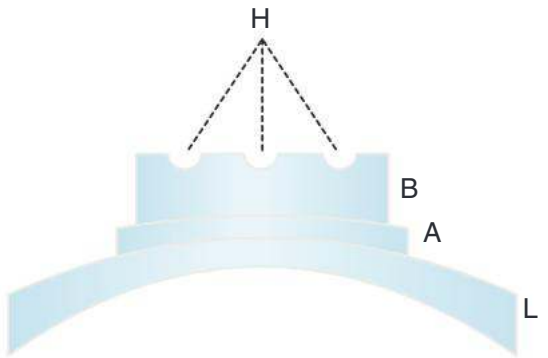


Fig. 7.22 *Lens blocked for surfacing: driving pin location holes (H); button (B); alloy (A); lens (L).*

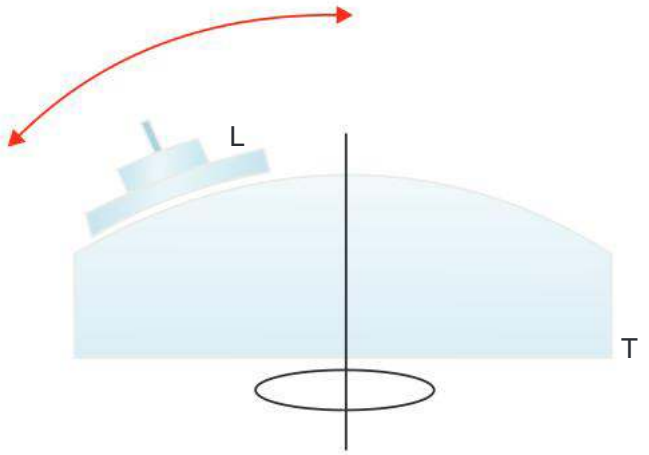


Fig. 7.23 *General arrangement for smoothing and polishing spherical surfaces: lens (L); tool (T).*

vary according to the blocking system employed. In general, they must indicate the optical centre position and, when applicable, the cylinder axis and base apex direction. This can be done either by marking key points on the lens with a suitable ink or by jugging at the blocking stage.

2. ***Blocking.*** It is the process used to hold the lens firmly and accurately for surfacing. A metal button is used to block the lens (Fig. 7.22).

3. ***Grinding.*** Optical surfaces on glass are produced by the process of grinding and polishing. The first stage of grinding – in which the greater part of the unwanted material is removed and the surface is worked to approximately the curve required – is termed *roughing*. This is followed by *trueing and smoothing* – in which the surface is brought to exactly the curve desired and to the state in which it has a satiny sheen. Presently, the process of roughing is performed by machines known as *surface generators* and the process is termed as *generating*. The grinding agent is usually a diamond-bonded disc or wheel, termed a *lap*. The different curves, spherical as well as toric, can be obtained by merely altering the setting of the machine.

4. ***Smoothing.*** The process of smoothing has two different things to accomplish: to *true* the curve and to produce a surface capable of taking a good polish. Essentially, the process is one of the removal of material by abrasion, produced by a separated or continuous relative motion of lens and tool (Fig. 7.23). The mechanism needed for smoothing an astigmatic surface is much more complicated than the process needed to smoothen a spherical surface.

5. ***Polishing***. To obtain a good polished surface, a good smoothing must be accomplished. Presently, the polishing tools are lined with pads cut from polyurethane sheets. These pads are thicker and can be used for many surfaces before replacement.

6. ***De-blocking and cleaning.*** Once the process of polishing is completed, the lens is separated from its holder (*de-blocking)* and cleaned properly. All traces of any lacquer used must now be removed from the lens by a solvent of the type in the lacquer. Ultrasonic baths can be used at various stages of cleaning.

The steps/stages of lens surfacing described above are applicable to both the glass and plastic lenses (CR-39). However, there are certain differences in the process of application of each step for glass and plastics lenses.

TINTED AND PROTECTIVE LENSES

Reflection at lens surfaces. Bright sources of light frequently cast annoying reflexes in the patient's visual field. These arise because of reflection of light waves from anterior and posterior surfaces of the lens. These reflexes can be reduced by the following:

- Antireflective coatings,
- Light tinting of glasses,

- Raising the optical centres of the lenses or
- Changing pantoscopic tilt so that the reflexes move out of the patient's field.

Most of the patients will be satisfied when cause of reflections is explained and when they are instructed to ignore it.

ANTIREFLECTIVE COATINGS

To reduce the reflections from lens surfaces, the phenomenon of destructive interference is utilized. When two waves equal in amplitude but half wavelength out of phase meet each other, they tend to cancel each other. Antireflective coatings produce a wave that is out of phase from that reflected from anterior lens surface.

Lens surface can be coated with antireflective material in vacuum. An antireflective material must have a refractive index square root of that of lens and the thickness of the coating should be one-fourth the wavelength of light. For high-powered lenses, magnesium fluoride is suitable. Refractive index of magnesium fluoride (1.38) is more than what is required for crown glass lenses of lower power. Apart from this, single antireflective coating works for single wavelength only. Light rays from both ends of visible spectrum still get reflected.

Multilayered coating. The limitations of single-layer coatings are overcome by multilayered coatings, which work for a broad range of visible spectrum. Modern antireflective coatings on plastic lenses often employ five or more layers, which alternate between the lower and higher indices of refraction. These multilayer (or *broadband*) coatings are able to cancel reflected light over a wider band of colours.

The application of an antireflection (AR) coating can increase the transmittance of a lens up to nearly 100%, while virtually eliminating visible reflections from the surface of the lens. This can be thought of as a two-step process. The reflections are almost completely cancelled by *destructive* interference, while the light passing through the lens is reinforced to almost 99% or more transmittance by *constructive* interference. These optical interference effects are produced by the interaction of reflections between the various interfaces of the AR-coated lens (i.e. the interfaces between air, the AR layers and the lens substrate). Thus, they reduce the reflection to such a level that only 1% of light is reflected and rest is transmitted across the lens. Since these coatings increase transmittance of light, they are not used for sunglasses. Antireflective coatings have low scratch resistance and so can be damaged easily. Even hot climates will damage them, so these glasses should not be left on automobile dashboards.

ULTRAVIOLET EXPOSURE AND ITS PROTECTION

In normal course of life, one is exposed to high levels of ultraviolet (UV) radiation, particularly in tropical countries. Apart from UV rays in sunlight, other sources are welding arcs, industrial sources, mercury vapour lamps and tube lights. Mostly UV-B rays with wavelength between 290 and 315 nm cause damage to the eye as they are absorbed by the cornea, lens and retina. UV-A rays with wavelength between 315 and 380 nm are absorbed by the lens. In aphakics, more amount of UV rays reach retina. Prolonged exposure to UV rays may result in actinic keratitis, pterygium, pinguecula, cataracts, cystoid macular oedema, skin ageing, etc.

Indications of Ocular Protection Against Exposure to UV Radiation Contained in Sunlight

- *People with retinal disorders, aphakes and pseudophakes,* to prevent retinal damage from the UV rays in sunlight and UV radiation (UVR)-rich light sources.
- *People with cataracts,* to reduce the lenticular scatter from long UVR and short blue light wavelengths found in sunlight.
- *People with pterygia and pinguecula,* because the ocular conditions have been related to exposure to the UV-B in sunlight.
- *People who are prescribed photosensitizing drugs,* such as chlorothiazides, antibiotics and contraceptives; these are limited examples of more than 100 such drugs. Individuals taking

these drugs are more prone to sunburn and skin cancer. Individuals known to be taking these medications should be advised to use UV protective eyewear and use sunscreen for skin protection when appropriate.
- *Workers in vocations rich in UVR,* such as arc welders, electronic chip producers, graphic artists, water workers and researchers.
- *People who participate in activities rich in UVR,* such as snow skiing, sunbathing at the beach and mountain climbing.
- *People who spend excessive hours in sunlight:* UV-B exposures above *8* h a day result in a *3.8-fold* increase in the prevalence of anterior subcapsular cataracts.
- *People who use sunlamps or visit solariums:* Solarium sources are rich in UV-A and contain UV-B, and both have been associated with skin cancer.
- *Children who are exposed to excessive UVR in sunlight*, to delay the photochemical reaction.

Tinting of Lenses for Protection From UV Radiation

When a ray of light is incident on lens surface, part of it is reflected and absorbed and the rest is transmitted across the lens. The percentage of incident light that is transmitted is called transmittance. Tinting of lenses decreases the transmittance, whereas antireflective coatings increase it by reducing reflection. Tinting of lenses is done when the patient is uncomfortable in bright lights or is exposed to UVR.

Methods of tinting. Tinting of lenses can be carried out by following procedures:

- Mixing dye to molten glass material (integral tints),
- Blowing a layer of coloured glass on white glass (flashing),
- Deposition of fine layers of tint on the surface by vacuum process or electron-beam process,
- Deposition of mirror-like coatings and
- Dipping plastic lenses into molten dye.

Integral tints are not used nowadays, because the tint was not uniform over the entire lens area and so transmittance varied. Instead, glass lenses are coated with this layer of tinting material, followed by a coating of thin layer of abrasion-resistant material. The process used may be vacuum chamber or electron-beam-diffusion method. By this method, tint is uniform but abrasion-resistant material may produce its own colour pattern.

Plastic lenses are tinted by dipping them into hot-water-soluble dye so that it penetrates the surface of lens. Mirror-like coatings when deposited on glass plastics reflect most of the incident light, thereby reducing transmittance up to 20%.

Lighter tints with transmittance levels of 75%–80% are mostly prescribed in spectacles meant for indoor use. They reduce annoying reflexes present in the field and are better accepted cosmetically. Light-pink glass tints reduce drastically the transmission of UV-B rays, though UV-A rays can still pass. Strong colour tints should not be given for long-term use because they will result in altered colour perception even after the removal of spectacles.

Dark tints with transmission value as low as 20% are used as sunglasses. They, combined with mirror-like coatings on surface, can reduce transmittance to as low as 1%. Dark tints reduce the transmission of UV rays as well as increase the contrast and so they are recommended for driving during daytime, aphakia, outdoor workers, etc. Glasses with 20%–25% transmittance value work well in these conditions. Transmittance levels can be reduced still further for use in snow, mountain climbing, deserts or flying.

With better recognition of side effects of prolonged UV exposure, use of UV protective lenses is increasing. Glass lenses transmit almost all of UV-A and UV-B rays. Polycarbonate and CR-39 restrict all of UV-B rays and 80% of UV-A rays. Protective coating further decreases UV transmittance. ANSI Z80.3 standards for sunglasses recommend UV-B transmittance of 5% and UV-A transmittance of 15%–20%. While choosing sunglasses, it should be checked that they do not decrease contrast too much, are impact resistant, do not produce distortion of view and have got UV protective value.

SPORTS EYE WEAR

- Virtually all sports demand highly impact-resistant lenses made from such materials as polycarbonate.
- Helmets are required when there is danger of head injury.
- Outdoor sports call for UV protection; when intense sunlight is a factor, sun lenses are appropriate.
- Most sports using round balls call for ASTM (the American Society for Testing and Materials) F803-approved protectors. These include baseball, basketball, soccer and any racquet sports, such as tennis or badminton.
- Underwater sports for those dependent upon their prescription need special in-mask or in-goggle prescription adaptations.
- Billiards and pistol shooting may require prescription changes.
- Golf, flying and shooting may require relocation of multifocal segments and/or optical centres.
- Bicycling and billiards may require changes in the positioning of the frame front.

SELECTING AND PRESCRIBING LASER EYE PROTECTORS

Lasers are classified according to the hazard that their emissions present to the human eye and skin. No eye protection is required when operating either Class I or Class II laser systems, but laser protective eyewear is required for Class III and Class IV lasers and should include side shields.

ANSI Laser Hazard Classification

Class 1: No eye or skin hazard from full-day exposure.
Class 2: No eye hazard from intrabeam exposure within aversion reflex time.
Class 3a: Eye hazard from intrabeam exposure with optical aid.
Class 3b: Eye hazard from intrabeam exposure within aversion reflex time; diffuse reflections may present eye and skin hazards. View only through a diffuse reflector from a distance of >50 mm for <10 s, with a diffuse image diameter of >5.5 mm.
Class 4: Eye and skin hazards from intrabeam viewing or diffuse reflection; fire hazard, if combustible materials are exposed to.

Laser eye protectors are generally made in two designs. Wraparound polycarbonate eye guards are used primarily for Class III protection. Enclosed monogoggles with replaceable filter plates are recommended for use with Class IV lasers. Combinations of glass and polycarbonate filter plates provide both impact and radiation protection. In the event of exposure to a Class IV laser beam, the goggle housing and filter plates are designed to resist the beam long enough for the wearer to become aware of the problem and to move out of the beam's path.

PROTECTING THE EYES AGAINST INFRARED RAYS

Expected ocular tissue damage resulting from acute infrared rays (IR) exposure is as follows:

Ocular structure	Damage
Cornea	Opacification, haze, debris, exfoliation
Aqueous humour	Flare, cells, pigment
Iris	Miosis, hyperaemia, swelling, necrosis
Vitreous humour	Haze or flare
Retina	Depigmentation, oedema, frank bum

An envelope concept should be used to establish safe ocular exposure limits to IR. The IR exposure limits should be set to that portion of the eye that is most sensitive to IR. The cornea, iris and crystalline lens are almost equally sensitive to IR. The retina is the most resistant portion of the eye. Therefore, setting exposure limits for the cornea should provide protection to the retina. One must also be warned that, if extremely high exposures are given in short exposures, severe damage to the eye may occur. An example of this situation is the laser. The absorption of IR raises the temperature of the optical lens. This results in the lens serving as a secondary source of IR, which is now located close to the eye. To eliminate IR from reaching the eye,

metallic coatings that reflect the IR should be applied to the front surface of ophthalmic lenses. Copper and gold coatings reflect approximately 98% of the IR above 750 nm; this makes them the coatings of choice to control IR. Both gold and copper transmit the visible spectrum, and excellent vision is maintained through the coating. Metallic coatings are soft and can be scratched easily when worn in an industrial or sports environment. A protective film of silicon dioxide provides a durable protective coating.

PHOTOCHROMIC LENSES

Photochromic lenses have got silver halide in them, which disintegrates when exposed to UV rays in the region of 300–400 nm, thereby darkening the lens. In dark, these ions once again combine, thereby fading the glass. Photochromic glasses are made up of two types of materials: borosilicate glass and aluminophosphate glass. Each glass has got its own transmittance range, fading rate and reaction time. Transmittance range indicates the maximum (fully faded) and minimum (fully darkened) transmission of UV rays and is written in fraction, e.g. 80/45. Fading rate indicates the time taken to fade back to 70% of original transmittance value. Reaction time is the time taken to darken completely. In first-generation lenses like photogrey, range was narrow (85/45), fading rate slow and reaction time long. The advent of second-generation lenses like photogrey extra has improved the condition. The reaction time and fading rate depend on temperature as well. Photochromic lenses are also available as plastic lenses. As photochromic lenses remain dark indoors also, they should be avoided in patients who need greater vision indoors, like tailors, etc.

CORRECTION OF COLOUR VISION DEFECTS

Maxwell was the first to suggest the use of chromatic lenses by dichromats would assist the colour defective with the discrimination of coloured objects. A practical result from this research was the X-Chrom (red) contact lens that was purported to help dichromats distinguish between objects of red and green colour. However, its deep red colour resulted in an alteration of depth perception (stereopsis), because it was worn in front of only one eye. An unpublished computer graphics program was developed that quantitatively classifies, describes and designs chromatic lenses to aid the dichromat. The concept was experimentally tested using the X-Chrom lens on deuteranopes and protanopes; the protanope gained less luminous information than did the deuteranope. This finding is intuitively correct, because a red lens before a protanopic eye should reduce the remaining spectrum and reduce the luminous intensity information. Deuteranopes also demonstrated an increase in hue discrimination for the blues and the purples.

YELLOW FILTERS

For many years, yellow lenses have been used as 'shooter's glasses' and advertised for night driving. Research demonstrates that any sun lens worn before the eyes while driving at night reduces the same proportion of available light as when worn in sunlight. This results in losses of visual acuity, decreases in reaction time and losses in contrast. The bottom line is that there is no sun lens for night driving. The yellow lens has been reported to improve the visual performance of hunters, target shooters, skiers, mountain climbers, arctic explorers and aviators. Since the yellow filters do not enhance visual performance, how are they supposed to work? For the shooter, skier and outdoorsman, it has been claimed that the short wavelengths in sunlight that are scattered by atmospheric haze and moisture are filtered out. The result is an apparent increase in contrast for long-wavelength objects viewed against the short-wavelength background that has been filtered. It has also been suggested that the absorbance of the short wavelengths of the solar spectrum reduces lenticular scatter and fluorescence and thereby enhances contrast. The rod receptors are the mediators of the enhancement effect, and the stimulation of the chromatic channels does not produce the brightness enhancement. This interpretation is further verified because the brightness enhancement effect was not found when the rods were saturated by bleaching and the cones were fully operative.

Snowscapes and the Yellow Lens

The yellow lens has been recommended for use as ocular protection in snow during whiteout and to improve the perception of depth and contours under poor-visibility conditions. The values of the yellow filter are to enhance apparent contrast between short-wavelength sky and longer spectral objects; to decrease reaction time to low-contrast targets; to provide a brightness enhancement effect within a limited luminance range and to provide better depth perception in the snow.

Shooters' Glasses

Yellow glass lenses called Kalichrome and Ambermatic are available for hunters and competition shooters in plano power.

OPTICAL CENTRATION AND DECENTRATION

Before a spectacle lens is cut to fit in the frame, it must be marked so that its cylindrical axis (if any) and optical centre are in the correct position relative to the lens shape. This process is known as *laying off*. For an accurate centring of the spectacle lens, the two important parameters to be taken into consideration are IPD of the patient and the frame dimensions.

INTERPUPILLARY DISTANCE AND CENTRATION DISTANCE

In British literature, the term *CP* denotes the point at which the optical centre of a lens is intended to be located or at which any prescribed prism is to be effective. The horizontal distance between the right and left CPs is termed the *centration distance* (CD). In American literature, the corresponding terms are *major reference points* and *IPD*, respectively.

INTERPUPILLARY DISTANCE

In an ideal spectacle, optical axis of the lens should lie on the visual axis of the eye. Otherwise, a prismatic effect will be introduced. To avoid this, the measurement of distance between the visual axes of two eyes is taken. Alternatively, distance between the centre points of the two pupils can be taken. There are numerous instruments to measure IPD:

1. *Measuring visual axis distance*
   - Reflex pupillary distance (PD) gauge
   - Essel reflection pupillometer
   - Sasieni reflex PD gauge
   - Bausch and Lomb PD gauge
2. *Measuring centre point of pupil*
   - Pulzone–Hardy rule
   - Fairbanks gauge
   - Topcon sliding PD gauge
   - Bishop Harman rule

The simplest method of measuring IPD is to use a millimetre rule. The examiner closes his or her left eye and the patient is asked to look into the open eye. Now zero mark of the ruler is coincided with temporal border of pupil. Now the examiner opens the other eye and reads the markings corresponding to the nasal border of the other pupil, which gives the IPD.

In children and in patients with squint, measurement of IPD is difficult. In these cases, the distance between the medial canthus of one eye and the lateral canthus of other eye is taken as IPD. In cases of anisocoria, the distance between the temporal border of right pupil and the nasal border of left pupil and similarly between the nasal border of right pupil and the temporal border of left pupil is measured. Average of these two readings is taken as IPD.

Since in most of the patients, the face is not perfectly symmetrical, IPD measurement in conventional way will give erroneous readings. Therefore, half PD measurement is preferred. In this method, one reference point on the centre of nasal bridge is marked and the distance of right and left pupillary centres is measured from it. This gives the half PD of each eye.

OPTICAL CENTRATION, LENS DIMENSIONS AND FRAME DIMENSIONS

The factors other than IPD having a very important bearing on horizontal centring are the lens dimensions and the frame dimensions. In order to align the optical axis of the spectacle

lens with the visual axis of the eye, it may be necessary to decentre the lenses horizontally, depending upon the dimensions of the spectacle frame and the patient's IPD.

Systems for Measuring Frame Dimensions

For measuring frame dimensions, two systems in use are the datum system and the boxing system.

Datum System

Datum system forms the basis of British standard for spectacle measurements. The datum system has been deprecated by the International Organization of Standardization (ISO). It was once the favoured frame measurement system. Still used by some manufacturers in non-ISO countries.

Definition of various lens dimensions and frame dimensions according to datum system are as follows:

- *Datum line* (Fig. 7.24). Datum line (DD) is defined as the line midway between and parallel to the horizontal tangents to the lens shape at its highest (HH) and lowest (JJ) points.
- *Datum length.* It can be defined as that portion of the datum line which is bounded by the lens periphery (AB in Fig. 7.24). It specifies horizontal dimensions of the lens.
- *Datum centre.* It refers to the midpoint of the datum length (M in Fig. 7.24).
- *Mid-datum depth.* It specifies vertical dimension of the lens and is denoted by a vertical line passing through the datum centre (M) and bounded by the periphery of the lens (FG in Fig. 7.24).

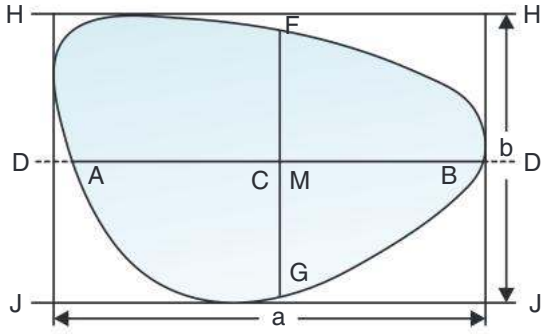


Fig. 7.24 *Datum and boxed lens dimensions.*

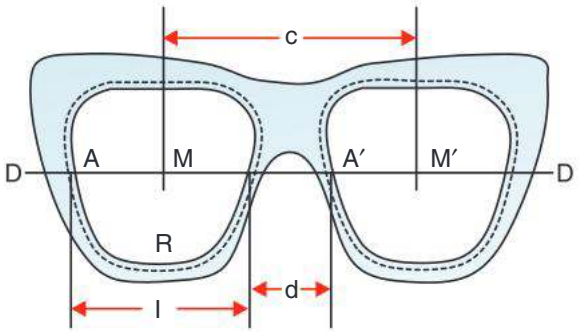


Fig. 7.25 *Frame dimensions affecting horizontal centration: datum line of frame (DD); temporal edge of right lens (A); nasal edge of left lens (A′); datum centre of left lens (M); datum centre of right lens (M′); datum length of lens (l); datum centre distance (c) and distance between lenses (d).*

- *Shape difference.* It refers to the difference, in millimetres, between the horizontal and vertical dimensions of a lens.
- *Datum line of the frame.* It is continuous with the datum line of each lens (DD in Fig. 7.25).
- *Datum centre distance.* Datum centre distance (c) is the distance between the datum centres of right and left lenses when fitted in a frame (MM′ in Fig. 7.25).
- *Distance between lenses.* It is defined as the horizontal distance measured along the datum line, between the nasal edges of the spectacle lenses (d in Fig. 7.25).

Boxing System

Boxing system is alternative to datum system for denoting various lens and frame dimensions in the American standard. The boxing system is endorsed by the ISO and used by manufacturers in countries who are members of the ISO. As the name suggests, system is based on boxing of the lens by adding vertical lines tangent to either side of the lens.

Definitions according to this system are as follows:

- *Boxed lens size* is expressed by the length 'a' and the height 'b' of the rectangle with horizontal and vertical sides tangential to the lens periphery (Fig. 7.24).
- *Geometric centre line* (DD) represents the datum line of British standard.

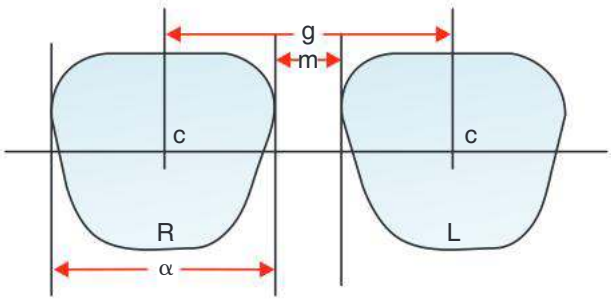


Fig. 7.26 *Boxing system: horizontal dimensions.*

- *Geometrical centre of the box* (c) is the standard optical centre (Fig. 7.26) corresponding to datum centre (M) of the British standard (Fig. 7.25). It is the centre of the box for each lens, i.e. a point on datum line midway between the vertical lines. It has no direct relationship with the optical centre of the lens.
- *Distance between centres* refers to the distance between the geometric centres of the right and left lens boxes (g in Fig. 7.26).
- *Distance between lenses.* It is the distance between the nasal vertical tangents to the lenses at the peak of the bevel, if any (m in Fig. 7.26).
- *Effective diameter* is the distance from the geometric centre of the lens to the apex of the lens bevel farthest from it. Can determine smallest lens blank needed.

LENS DECENTRATION

Apart from the datum landmarks, some other dimensions of lenses are CP and CD. CP of a lens is the point where optical centre of lens is intended to lie and the rays pass undeviated through it. CD is the distance between CPs of the two lenses. Ideally, CP should coincide with the datum centre of spectacle and visual axis should pass through it. CD corresponds to the IPD and datum centre distance of the spectacles. This arrangement is the ideal centration of lenses and ensures that there is no prismatic effect.

A lens is said to be decentred when its CP does not correspond with the datum centre of spectacles. Decentration is done usually for one of the following reasons:

1. When a patient's IPD does not correspond with datum centre distance of the chosen spectacles.
2. To produce a prismatic effect at the CP as in heterophorias.
3. Decentration for near work.

Amount of decentration depends upon the prescription and the required prismatic effect. It can be calculated by a simple formula:

$$\text{Decentration (d) in cm} = \frac{\text{Prismatic effect}}{\text{Prescription}}$$

So for a +4.0 DS prescription and a requirement of 2Δ prism, the lens should be decentred by 0.5 cm. In case of convex (plus) lenses, decentration is done in the direction of the base of the prism. So, if we require a base-in prism (BI), the lens should be decentred nasally. In concave (minus) lenses, decentration of CP is done opposite to the direction of base or towards the apex, i.e. temporally in this example.

If a cylinder is present in the prescription, decentration along the axis will not create any effect. For such cases, amount of decentration is calculated individually for each principal meridian, i.e., horizontal and vertical. For example, +2.0 DS/+4.0 DC × 90 with 1Δ BI and 1Δ base down.

$$\text{d (vertical)} = \tfrac{1}{2} \text{ (as in this axis, only sphere is acting)} = 0.5 \text{ cm (5 mm)}$$

$$\text{d (horizontal)} = \frac{1}{2+4} = 0.16 \text{ cm}$$

So, the lens should be decentred 1.6 mm nasally and 5 mm down from datum centre (in case of minus lens, it would have been 1.6 mm temporally and 5 mm up).

During reading, eyes are lowered by 15 degrees and converged to an amount depending upon the IPD. But for proper placement of reading additions, CD is more important. To measure CD for near, a simple ruler is held on the nose bridge at the level where spectacles will be and fingers are rested on temples. The patient is asked to look into one eye of the examiner who is sitting 33 cm away. With the left eye, the examiner locates the nasal border of right pupil and moves the scale till it coincides with zero. Now with the same eye, he or she

locates the temporal border of left pupil and notes down the corresponding scale reading, which gives the near CD. As an alternative to these measurements, the CP can be placed 2 mm nasal and 8 mm down from the CP for distance.

PANTOSCOPIC TILT

In general, most spectacles are fitted with a downward tilt of about 7 to 8 degrees to the visual axis, meaning that the top of the spectacle lens is approximately 8 degrees forward as compared to its bottom. This pantoscopic tilt of spectacle lenses in the frames is to conform with the rotation of the eye on the optical axis of the spectacle lens.

Advantages of pantoscopic tilt

- This minimizes the effect of oblique astigmatism, an aberration that would be induced with down gaze, if the lenses were fit perpendicular to the distance visual axis.
- This also minimizes the vertex distance changes. Since the top of the spectacle lenses are intentionally tilted forward, this helps to achieve a place that allows a more constant distance between the back surface of the spectacle lens and the front surface of the cornea.

Consideration for pantoscopic tilt. Though the pantoscopic tilt is not an exact measurement, but still most opticians will incorporate this tilt when fitting spectacle lens. Therefore, the pantoscopic tilt should be taken into account when using either a refractor or a trial frame.

FACE-FORM

Spectacles are said to have positive face-form, if the frame is bent around the bridge with the temporal portion closer to the face. Positive face-form causes the optic axes to pass nasal to the centres of rotation of the eyes. This will effectively change the power of the lenses and degrade off-axis optical quality. The optic axes can be made to pass through the centres of rotation by increasing the separation of the optical centres, but this creates horizontal prism and is not advisable. For this reason, spectacle frames should usually have little face-form. If the design of a spectacle frame includes a large amount of face-form or wrap, the lens powers can be modified to compensate for the optical effects of the face-form. This is done by some manufacturers of sunglasses.

GLAZING

Glazing refers to the process of fitting lenses to a spectacle frame or a mount. It includes the following processes.

LAYING OFF

Before the lens is cut to fit in a particular frame, it must be marked so that its cylinder axis (if any) is set as specified by the prescription and its optical centre is in the correct position relative to the lens shape. This process is known as *laying off*. It can be performed utilizing a focimeter, marking devices and a specially designed protractor preferably of the domed type.

Figure 7.27 shows a lens with its axis at 70 degrees laid off for the right eye so as to give a decentration effect of 2 mm down and 3 mm in. It is customary to indicate the nasal extremity of the horizontal line by means of an arrowhead, as illustrated, and to mark the lens R or L to indicate right or left.

LENS CUTTING

Lens cutting is the process of scoring a slightly oversize outline of the desired shape on one surface of the uncut lens and removing the waste. Lens cutting can be performed entirely by hand or with the aid of a wheel cutter – an

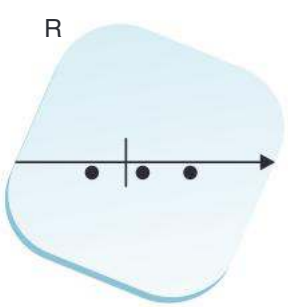


Fig. 7.27 *Lens laid off for the right eye to give a decentration of 2 mm down and 3 mm in.*

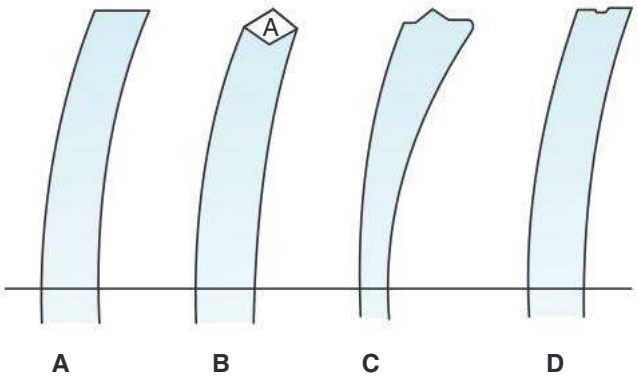


Fig. 7.28 *Common edge forms: A, flat edge; B, bevel edge; C, mid-bevel; D, grooved edge.*

outline having first been traced on the lens with Indian ink or a grease pencil. A number of more elaborate diamond-charged lens cutters are used in conjunction with the former.

LENS EDGING

Edging is the subsequent process of grinding the lens edge to produce the finished size and shape required at the same time, imparting the desired edge form. Various types of automatic edging machines are available for this purpose. Even though most of the work may be performed by automatic machines, hand edging is still an indispensable piece of equipment. Two grades of grit wheels are in common use for the hand machine. Diamond-wheel hand edges are also available and are in use.

Common edge forms used for fitting in the corresponding frames are flat edge, bevel edge, mid-bevel and grooved edge (Fig. 7.28).

SPRINGING IN AND RIMLESS FITTING

The final process of fitting well-edged lenses into rimmed plastic frames is known as *springing in*, and the fitting of lenses to rimless mounts is called rimless fitting.

VERIFICATION OF SPECTACLES

Many a time, the patients are not satisfied with the spectacles prescribed and the cause turns out to be faulty dispensing and/or fitting of spectacles. Therefore, verification of the spectacles by the prescribing ophthalmologist should be must before they are worn.

Verification of spectacles should include checking of lens power, cylindrical axis (if any), reading addition (if any), prism power and base setting (if any) and centration and observation for any lens surface defects. In addition, fitting of the lens in frames should also be verified. In practice, the amount of discomfort which may arise from fitting problems is too frequently forgotten.

LENS POWER AND AXIS

Commonly employed procedure, in clinical practice, to verify lens power, centring and cylindrical axis, if any, is by the use of a lensmeter. (For details of the instrument design and working of a lensmeter, see page 537.) Other technique to verify lens power is neutralization procedure. Every ophthalmologist should be familiar with this technique.

Neutralization Procedures

A. Spherical Lenses

Before starting the procedure, the type of lens should be found out. There are three methods:

1. Image of a distant object moves with or against the movement of lens in a concave (minus) and convex (plus) lens, respectively.
2. Lines of a crossline chart (Fig. 7.29A) will appear magnified in a plus lens (Fig. 7.29B).
3. *Straight edge test*. A ruler is placed vertically on the lens. If the ruler touches the lens only in the centre, then it is a convex lens whereas if it touches the periphery, only then it is a concave lens. This test is not of much use in meniscus lenses.

Important points that must be kept in mind:

- Target should be placed at the farthest convenient distance.
- It is preferable to keep the lenses at arm's length because small, transverse movements are then accentuated and, therefore, are clearly visible.
- Care should be taken not to scratch the lenses when in contact.

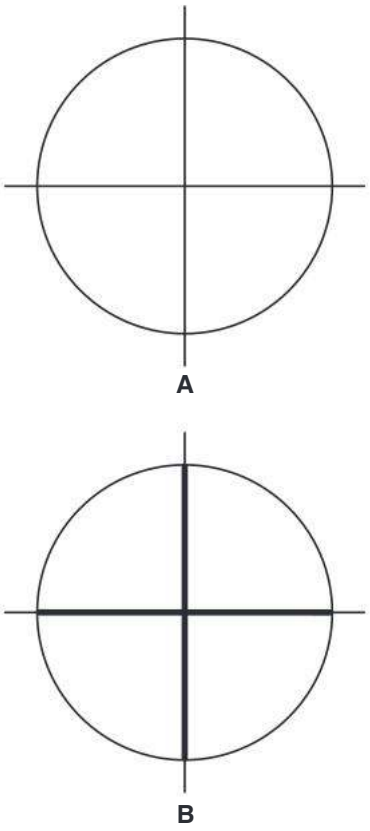


Fig. 7.29 *A, Normal crossline chart; B, magnified crossline chart as seen through convex lens.*

- Peripheral distortion in high-powered lenses may create confusion, so either the peripheral image is ignored or a card with 1 cm hole in the centre is placed before the spectacle.
- Neutralization is not the method of choice for meniscus lenses because BVP cannot be detected. This is so because a gap of 3–6 mm remains between the lenses. FVP, though, can be detected. It is almost similar to BVP for minus lenses but is quite different for plus lenses of more than +2.0 D. So, focimeter is preferred for these lenses.

Neutralization of spherical lenses is quite simple and is done by placing lenses of opposite sign and increasing power in front of the spectacles till the image stops moving.

B. Cylindrical Lenses

Cylindrical lenses show scissor-like movement of crossline chart when they are rotated (Fig. 7.30). To neutralize cylinder, first the lens is squared up with crossline chart (i.e. it is rotated till the lines are perfectly aligned with the image). Now the principal meridians are horizontal and vertical. Both the meridians are marked and then neutralized one by one, which can be done in two different ways:

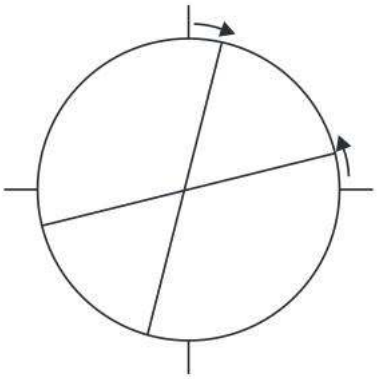


Fig. 7.30 *Scissor-like movement of the crossline chart seen through a cylindrical lens when it is rotated.*

i. ***Both the axes are neutralized by spherical lenses***. Movement of opposite axis is looked for (i.e. while neutralizing horizontal axis, breaking of vertical crossline is looked for).

- If horizontal axis is neutralized first, then

$$\text{Power} = \frac{\text{Horizontal sphere}}{(\text{Vertical sphere} - \text{Horizontal sphere})\ \text{cylinder} \times 180}$$

- If vertical axis gets neutralized first, then

$$\text{Power} = \frac{\text{Vertical sphere}}{(\text{Horizontal sphere} - \text{Vertical sphere})\ \text{cylinder} \times 90}$$

For example, if vertical axis is neutralized by +2.0 DS and horizontal axis by +3.0 DS, then the power is +2.0 DS/+1.0 DC × 90.

ii. ***One axis is neutralized as above by sphere and the other axis is neutralized using cylinder*** of residual power. Now the spectacles are placed on the protractor (Fig. 7.31) to read the axis, taking care to keep the front surface downwards because side pieces prevent it to be placed properly. The axis thus read is supplementary, so it is subtracted from 180 to get the actual axis.

The axis of cylinder can also be found out by reflection test. The spectacles are held horizontally,

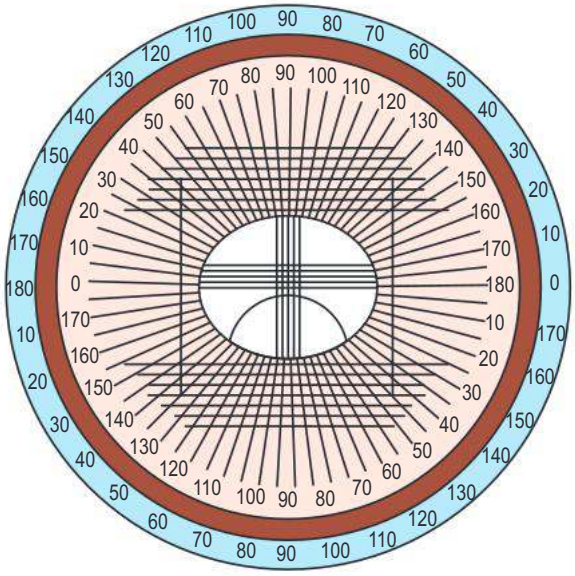


Fig. 7.31 *Protractor used for determining the axis of cylinder. Central markings can be used to determine the position of centration point.*

slightly below the level of lower eyelid and at 15 cm distance. Image of a point light source reflected upon the glass is noticed. If it is undistorted, then we are looking along the axis. If it is distorted and magnified, then it is a concave cylinder (magnification is different from that of lenses because reflection is being seen here). The spectacles are rotated till the image becomes undistorted. The axis is marked and read from protractor as outlined above.

C. Reading Addition

To detect the reading addition, first the distance correction is neutralized. At this juncture, the near segment may be obscured by the thumb. Now the near segment is neutralized. The difference between the near and distance power gives the reading addition.

If there is cylinder in the distance correction, then the distance portion is neutralized along the axis of cylinder. Now near segment is neutralized along the same axis. Difference of these two readings gives the reading addition.

For estimating distance correction on focimeter, BVP of spectacles is determined. But for measurement of reading addition, spectacles are placed in the focimeter upside down to detect FVP. FVP is determined instead of BVP because reading lenses are added on the front surface of the bifocals. First FVP of distance is calculated followed by FVP of near. The difference of these two readings gives the reading addition.

D. Prisms

For neutralization of prisms, first the direction of base is determined. This is done by focusing on a crossline chart and rotating the spectacles till one of the lines appears unbroken (Fig. 7.32). This line gives the direction of base–apex line. The other line will be deviated towards the apex. The prisms are now neutralized by placing various prisms from trial set in contact (base to apex) till no movement of crossline occurs.

LENS CENTRATION

Every spectacle frame has got a centre point, which is called standard optical centre or datum centre (Fig. 7.24). Normally, the CP or the optical centre of lens should lie on the datum centre and the distance between the CP of both eyes should correspond to the patient's IPD. If this is not so, then artificial decentration and prismatic effect may be introduced.

To verify the location of CP, first the vertical line of crossline chart is focused and the spectacle is moved horizontally till this line appears unbroken. At this point, the vertical line is marked in the centre of glasses. Now, similarly, the horizontal line is marked. Their intersection point gives the CP. When the spectacles are

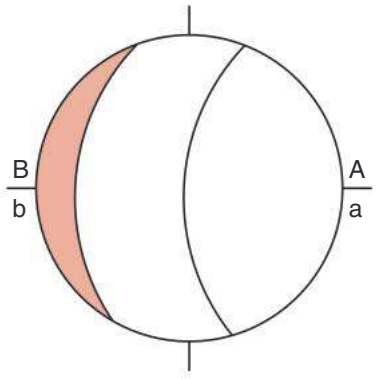


Fig. 7.32 *Crossline chart as seen through a prism (A, apex; B, base; BA, base–apex line).*

worn by the patient, the intersection points should correspond to centre of pupils.

SURFACE DEFECTS

All spectacle lenses should be free from abrasions, chips or waves, which could be seen with naked eyes under adequate illumination. These defects could lead to the problem of glare.

MEASUREMENT OF WARPAGE

When a plastic spectacle lens is inserted into a frame that is slightly too small, the lens often flexes or warps, altering the surface powers. The magnitude of this warpage is usually defined as the amount of cylinder present on the surface of the lens that should be spherical (the front surface of a minus-cylinder design lens). Warpage must be measured with a lens clock. A focimeter will not detect a power change. Warpage makes both lens surfaces toric but does not significantly alter the spectacle lens power, because the front and back surfaces warp (bend) by the same amount. Warpage may cause patients to have difficulty adapting to their spectacles. Adaptation problems may be related to changes in the lens aberration *distortion* caused by the warpage. Localized areas of warpage may cause bending or blurring of targets viewed through the lens periphery.

SPECTACLE-RELATED ASTHENOPIA

Spectacle-related asthenopia is not an infrequent complaint. Different causes of spectacle-related asthenopia can be errors at the part of the optometrist/ophthalmologist who has prescribed the glasses, the optician who has dispensed the spectacles, or the patient himself. Each and every factor needs to be reviewed to know the cause and suggest remedies.

FACTORS RELATED TO PRESCRIPTION

1. **Incorrect prescription.** Even slight error of power, especially, cylindrical or wrong axis may cause headache. So, due care must be taken while prescribing the power to every patient, especially those who are involved in reading, writing, watching TV for long hours or working on computer. Each patient responds differently to the same situation. Some patients neither appreciate nor have any complaint even if the residual refractive error is significant, while others may complain of headache or heaviness around the eyes even with insignificant error in power and incorrect degree of axis. This is sometimes related with the visual requirements of the patient, e.g. a student needs more accurate refraction as his/her visual requirements are more demanding as compared to an illiterate person who is involved in field job.

   Hence, it is advised that while checking for refractive error, sufficient time must be given to the patient so that he/she can appreciate the discomfort or heaviness around the eyes with the prescribed power in the trial frame.

   In addition, in high power lenses, there are peripheral aberrations, which cannot be removed completely even with the best form of lens manufacturing techniques. Counselling of the patient needs to be done regarding adjustment with the spectacles. Patients learn slowly to adjust with them in due course of time.

- *The distorting effect of cylindrical power lenses needs special mention*. If the axes of cylinder prescribed in two eyes is parallel, the distorting effect is minimized, hence easy for the patient to adjust, e.g. if axes of cylinders prescribed in two eyes is same, patient usually adjusts with the lenses easily. But if the axes in one eye is 90 degrees and the other eye is 45 degrees means the difference in the axes of cylinders prescribed in two eyes is more than 20 degrees, patient experiences slanting or sloping of images that produce headache. To avoid, centering of lenses must be done very accurately and preferably the spectacles for distance, near and computer distance should be made separate instead of bifocals or progressive glasses. If the difference is less than 10 degrees, the effect weans off with time. It is important to note that glasses should always be worn closer to the eyes to minimize these distortion effects.

- *Another important point to be noted is that if the axis of current prescription is slightly different from the previous prescription* and patient does not have any difficulty with the previous glasses, there is no need to change the prescription/glasses as it has been noticed that patient may not be comfortable with new prescription and we might need to revert to the old prescription.
- *Even if the refractive error is small*, some patients experience tightness around the eyes initially which settles with time. This is because a new relationship is being established between convergence and accommodation with glasses.

2. Over- or undercorrection of refractive error: Final prescription must be verified:

- *By using Duochrome test or Jackson's cross cylinder. Myopia should always be slightly undercorrected* to avoid minification and hence headache after using spectacles.
- *However, a patient of squint must be given full prescription in the first go.*
- Hypermetropia and astigmatism should always be fully corrected to avoid eye strain.
- Every patient should be encouraged to go for annual comprehensive examination of eye not only to detect any minor change in refractive error but also to detect any other pathology like primary open angle glaucoma (POAG) at the earliest. If patient comes for refraction after a long interval, chance of significant change in refractive error is always there. This might cause spectacle-related asthenopia with the new pair of spectacles. Growing children should be called for follow-up more frequently.

FACTORS RELATED TO DISPENSING

1. Power of spectacles does not match the power prescribed. In such cases, there is need to change the glasses as per prescription. It is advised that before edging of the lens, its power must be verified and if it does not match the prescribed power, the lens should be exchanged with the new lens with correct power. In this way, the optician can save not only the cost but also the agony of the patient as well. Although, the form of lens is usually decided by the manufacturer, but the optician may request any possible change if required. Base curve of the lenses being used, the vertex distance in high-power lenses, a change from spherical lenses to toric lenses or meniscus lenses are important aspects of dispensing, which may create headache if not taken care of.

2. Change in size of glasses sometimes makes the patient uncomfortable. Patient should be explained about the cause and frame may be selected accordingly. Here counselling of patient is very important. If the patient has changed the size of the spectacles, it might create some discomfort in the beginning. He/she again needs to learn how to use the present pair of spectacles of different size. With change in the size of the frame, the movement of head and eyes need to be adjusted, especially in case of bifocal or progressive glasses. If patient is using bifocal or progressive glasses for the first time, he/she should be advised not to use these glasses initially for a day or two while stepping up stairs and driving, as he/she might hurt himself while stepping up or stepping down the stairs due to lack of adjustment with the new bifocal or progressive glasses. Once he/she learns how to use bifocals or progressive glasses, he/she can carry out all his/her routine activities, including stepping up or down the stairs and driving a vehicle with the glasses on his/her eyes.

3. Poorly fitted frames might press on nose or temples and can cause headache. Hence, frame selection is very important. Patient must be satisfied with the looks of the frame, its size, shape, flexibility, etc. Hence, selection of frame should be done by a qualified professional.

4. Defective centering of glasses may also cause discomfort. Proper centering should be done. Ideally, all the glasses must be fitted with proper centering, but it becomes specially important if the power of glasses is more than plus or minus 3.00 D spherical or cylinder. As the power increases, the prismatic effect due to decentration also increases as per Prentice rule. More is the decentration, more are chances of headache. Thus, high myopes, high hypermetropes and

aphakic patients are the ones in which fitting of lenses must be done after proper centering.

5. Tilting of lenses introduces cylindrical power and changes effective power of the lens, which becomes a source of trouble. Sometimes a patient needs bifocals even if the power for distance is zero. This is because of his/her professional requirements. For example, a teacher who needs to see distant objects as well as near objects while teaching, needs bifocals but as the power for distance is zero, he/she goes for glasses for near only and wears the spectacles lower down the nose so that he/she can see distant objects over the spectacles. This is a wrong method of using spectacles because putting the spectacles lower down the nose increases its back vertex distance and thus the refractive error becomes overcorrected or undercorrected depending on the convex or concave lenses used. It becomes a source of eye strain. Hence while deciding power of prescription and making glasses, the style of the patient, the way he/she wants to use glasses, should also be given due consideration.

FACTORS RELATED TO PATIENT

1. If power of glasses is high like in aphakia or high myopia, there occurs peripheral distortion of image. Patient should be advised to look through the centre of the glass and not through the periphery of the glass. In addition, if the refractive index of the glasses is increased, the cosmetic appearance of glasses can be improved and hence confidence of the patient also gets better. It also helps to decrease peripheral aberrations and hence quality of image becomes better. CR-39 has a refractive index of 1.49. Lenses of refractive index 1.53, 1.61, 1.67, 1.71 and 1.79 are available in the market. However, it must be kept in mind that with increasing refractive index, although the lens becomes thinner and cosmetically better appealing but at the same time it becomes costlier and patient starts complaining of coloured fringes around the object. This is because, as the refractive index increases, the Abbe number or V value decreases and dispersive power of lens increases.

2. If best-corrected vision is less than required by patient, e.g. due to ARMD, anisometropia, amblyopia or corneal opacity, the patient might have some problem in doing near work for long hours. Patient needs to be made aware of this limitation and low vision aids can be prescribed after due counselling. Initially, when the patient is in the denial mode for low vision aids, he/she keeps on visiting one ophthalmologist after the other in search of a better glass. So, the ophthalmologist or the optometrist needs to have patience and give time to the patient so that he/she prepares himself mentally to accept the low vision aids.

3. A beginner takes time to adjust with bifocal and progressive glasses. He/she should be advised to wait for some time and try to adjust with the glasses. However, some patients cannot adjust in spite of all efforts. It is better for them to use separate pair of glasses for distance and near. Patients must be made aware that the movement of head and eyes should be normal whether the patient is using glasses or is working without glasses. When a patient uses glasses for the first time, he/she tries to do some experiments with the glasses and experiences headache. However, in due course of time he/she usually finds the correct way of using spectacles himself.

4. Some patients take time to adjust with new pair of spectacles, so if a person is well adjusted with previous glasses and there is not much change in power, advise him to continue with same glass. It has been seen with some patients that even change of frame keeping the same old lenses, sometimes makes the patient uncomfortable for some time. However, this settles with time.

5. Sudden change in power of glasses may sometimes cause trouble. So, give some time for adjustment. Hence, it is advised that refraction should be advised every 6 months for adolescents and every year for adults or even before if the patient has some problems so that the change in lens power is gradual and there is no issue of sudden change in power. However, if the change in power is remarkable and patient is not able to adjust with new power, counselling should be

done. Slight undercorrection may be done even if extent of vision is compromised to some extent for some days followed by the exact power of lenses a few days later.

6. **Hypermetropes usually take more time to adjust with glasses,** so wait and watch for some time is advised. Advise the patient to use glasses all day but if he feels headache after using glasses, he may take a break for a few minutes from glasses and reuse it once headache is over. With passage of time, he learns to relax accommodation and thus adjust with spectacles.

7. **Spectacles are worn in a wrong fashion.** In this way the back vertex distance is changed, e.g. too low or too high on nose, it causes trouble. Patient should be advised to wear glasses properly. As described earlier in this section that wearing glasses in a wrong fashion might also introduce cylindrical power in the spectacles and change its effective power, hence correct way of using glasses is very important and must be emphasized to the patient while doing refraction and dispensing of spectacles.

8. **Patient having exophoria may need muscle exercises.** Such patients usually complain of headache while doing near work. Convergence exercises should be advised. These exercises can be done on synoptophore as well as at home. Many studies conducted so far indicate that both the methods are equally effective.

9. **Patient is having some field defect** like hemianopia, scotoma or dyslexic anomaly, the problem in reading needs to be accepted as such and again the counselling of patient plays an important role. Need to prescribe prism is sometimes essential to relieve asthenopia symptoms.

10. **Contrast sensitivity of patient is decreased** due to cataract or glaucoma, so he is not satisfied due to fogginess of vision. He should be explained about the nature of disease and all efforts should be made to treat the underlying cause.

11. **Patient does not like glasses** or is not in a habit of using glasses. He should be explained the advantages of using glasses and should be encouraged to use glasses.

12. **Patient complains of glare, prescribe antiglare glasses.** This is especially more important if the patient works on mobile, laptop, computer or watches television for long hours or drives at night. Antiglare glasses not only prevent glare but also help getting rid of ghost images. Ghost images are experienced by low myopes due to reflection of light from front and back surfaces of spectacle lenses. These become more troublesome if the patient is looking at a small light source in a dark area, e.g. a street light at night. Antireflective coating, based on the phenomenon of destructive interference, is done on both front and back surfaces of lens to get rid of this problem. If patient has a field job and needs to move in day light, photochromatic or tinted lenses are a good option to avoid photophobia. Polaroid lenses are another good option for patients who have intolerance to light. This lens is based on the phenomenon of polarization of light. It allows lesser light to pass through the lens and hence photophobia is relieved. It can be identified by rotating the polaroid lens. While rotating the lens if we keep on seeing any object through the lens in one particular axis, it appears brightest but as we move towards the axis at 90 degrees to the brightest axis, it becomes totally dark and we cannot see the object at all. This is because the lens allows rays of light to pass through it that are vibrating in only one particular direction. Rest of the light rays are absorbed by the lens material.

8 Contact Lenses

Chapter Outline

INTRODUCTION

HISTORY

Contact lens is an artificial device whose front surface substitutes the anterior surface of the cornea. Therefore, in addition to correction of refractive error, the irregularities of the front surface of cornea can also be corrected by the contact lenses.

- The concept for development of contact lens came from Leonardo de Vinci (AD 1508), who conceived the idea of neutralizing the cornea by substituting it with a new refracting surface.
- History of contact lens development is very long. It took almost 400 years and hard work

of many researchers, when around 1946 the corneal contact lenses made of polymethyl methacrylate (PMMA) were popularized.

- Introduction of soft contact lenses made of hydroxyethyl methacrylate (HEMA), in the year 1961 by Wichterle, has revolutionized the use of contact lenses. Since then a number of products have been introduced.
- Development of rigid gas-permeable (RGP) contact lenses around the same period was also a major breakthrough.
- Now, contact lenses have come to occupy an important place in improving vision. Though refractive corneal surgery is making a great dent in the popularity of contact lenses, their importance cannot be ignored.

CONTACT LENS TERMINOLOGY

Various terms used in relation to different aspects of contact lenses can be grouped as follows.

CLASSIFICATION

Contact lenses have been variously classified as follows:

I. ***Depending upon the anatomical position occupied***

1. *Scleral contact lenses*, which cover cornea and conjunctiva overlying the sclera.
2. *Semi-scleral contact lenses*, which cover the cornea and bridge the limbus to lie partially on the conjunctiva.
3. *Corneal contact lenses*, which confirm to the cornea.

II. ***Depending upon the nature of material used for manufacturing***

1. *Rigid (hard) non-gas-permeable contact lenses*, e.g. those made up of PMMA.
2. *RGP lenses*, e.g. cellulose acetate butyrate (CAB) and silicone lenses.
3. *Soft contact lenses*, or the hydrogel contact lenses, e.g. those made up of HEMA.

III. ***Depending upon the mode of wear***

1. Daily wear contact lenses.
2. Extended wear contact lenses.
3. Disposable contact lenses.

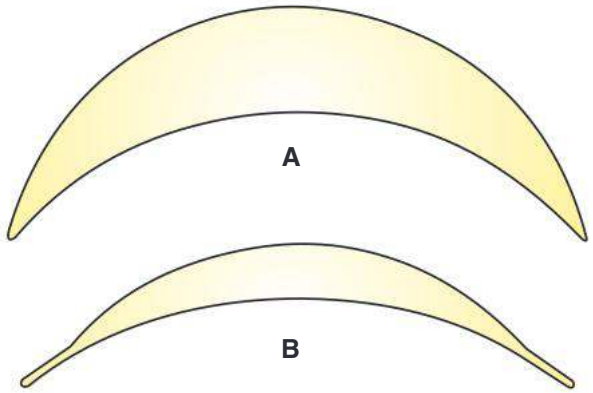


Fig. 8.1 *Single-cut (A) and lenticular cut lenses (B).*

IV. ***Depending upon the water content, the hydrogel lenses can be***

1. Low water content (0%–40%).
2. Medium water content (40%–55%).
3. High water content (>55%).

CONTACT LENS DESIGN

I. ***Single-cut lenses*** (Fig. 8.1A). In these lenses, front surface has a single continuous curve. The back surface consists of the base curve and peripheral curves as desired.

II. ***Lenticular cut lenses*** (Fig. 8.1B). In these lenses, front surface has a central optical portion surrounded by a peripheral carrier portion. The peripheral carrier portion is made thinner than the central optic portion and has a radius of curvature flatter than the central optic portion. The back surface of a lenticular cut lens has the same curves as a single-cut lens, i.e. base curves and peripheral curves as desired.

TERMS USED IN RELATION TO LENS MATERIAL PROPERTIES

1. ***Wettability.*** It is the adherence of a liquid to the surface of a solid despite the cohesive forces holding the liquid together. Lower the wetting angle better the wettability, and higher the wetting angle poorer the wettability:
   - Complete wetting – wetting angle 0 degree
   - Partial wetting – wetting angle 70 degrees
   - Non-wetting – wetting angle 150 degrees
2. ***Water content.*** Water content of a contact lens is the percentage of the contact lens that is

constituted by water. Contact lenses have pores that are formed by cross-linking of monomers. These pores absorb water, forming the water content of the lens.

- An increase in water content increases oxygen transmissibility.
- If water content is increased by 20%, oxygen permeability is doubled.
- Increase in water content also increases the thickness of the lens.
- Increase in water content increases mechanical strength.

3. ***Oxygen permeability.*** It is the property of the polymeric material to transmit gaseous substances. It is expressed as a coefficient of variable DK, where D is diffusion coefficient and K is solubility coefficient. It does not refer to oxygen passage through an actual contact lens. However, it is the unit from which oxygen passage for a specific lens is derived.
4. ***Oxygen transmissibility.*** It refers to the oxygen permeability for a contact lens of given thickness. This is expressed as DK/L, where L is thickness of the lens. However, one can use central thickness or an average thickness of the lens for oxygen transmissibility coefficient. Usually manufacturers refer to the thickness of a –3.00 D contact lens as a standard.

   For example, DK = 4.98×10^{-11} ($cm^3 \times cm$)/($cm^2 \cdot s \cdot mmHg$)

   L = 0.001 cm

   DK/L = 4.98×10^{-9} $cm^3/cm^2 \cdot s \cdot mmHg$
5. ***Light transmission*** is a measure of optical property.
6. ***Refractive index.*** It depends on the density.
7. ***Heat resistance*** is the ability of the material to withstand high temperature.
8. ***Dimensional stability.*** It depends on other external factors.
9. ***Flexure*** is a mechanical property.

CONTACT LENS MANUFACTURING

CONTACT LENS MATERIALS

The earliest material used was inevitably glass, but despite its excellent optical properties, it was a failure as contact lens material due to its weight, brittleness and difficulty in manufacturing. The true dawn of contact lens use may be said to have arrived with the introduction of transparent methyl methacrylate (MMA) by Obrig and Muller in 1938 and plastic contact lenses by Kevin Tuchy in 1948. Another giant leap forward in the development of contact lenses was made in 1961, with the introduction of hydrophilic soft lenses by Wichterle. Broadly, contact lens materials have recently been classified into two groups:

1. ***Focons.*** The term focons is used for the ***hydrophobic rigid lens materials***. These include the following:
   - PMMA and
   - All the materials used to manufacture RGP lenses. Focons have been grouped as Groups 1a, 1b, 2, 3, 4 and 5.
2. ***Filcons.*** This term is essentially used for the ***hydrophilic non-rigid lens material***. However, the silicone rubber elastomers, which are in fact very hydrophobic, are also classified as filcons. Filcons have been grouped as Groups 1a, 1b, 2a, 2b, 3a, 3b, 4a, 4b and 5.

IDEAL MATERIAL FOR CONTACT LENS

An ideal contact lens material should have the following properties:

1. *Biocompatibility.* This entails that the material must not be harmful by itself or should not contain material potentially harmful to the tissues of the eye.
2. *Optical properties.* Any material for manufacture of contact lens must obviously be transparent. In addition, a refractive index approximating to that of tears is of enormous advantage.
3. *Gas permeability.* The greatest bugbear of contact lens is the impairment of corneal respiration. If the material were to be freely gas permeable, then the tolerance and wearing time of contact lens can be enormously increased.
4. *Tolerance.* It depends mainly on the gas permeability of the material and/or the design characteristics.

5. *Moulding.* The ideal material should be amenable to easy shaping and manufacture methods so that the contact lens can be manufactured and duplicated easily.
6. *Sterility.* The material should be either resistant to contamination or easily sterilizable.
7. *Stability.* The curvature and thickness of the contact lens should be stable in order to cater for an efficient optical purpose, and yet at the same time soft like the surrounding tissues.
8. *Surface chemistry.* The surface chemistry of contact lens material should be such that it is easily wettable so that it can be covered by a continuous tear film.

It is a bitter pill to swallow that in spite of intensive research, spanning more than four centuries, the ideal material is still not within the realm of practical possibility. However, considerable strides have been made with regard to materials and methods of manufacture of contact lens. The research into polymers with stress on higher stability, flexibility, gas permeability and biological tolerance has made available several polymeric materials. The present-day contact lenses are made almost exclusively of polymers.

RIGID NON-GAS-PERMEABLE LENS MATERIALS

Hard lenses are manufactured from *plastic* or thermoplastic material. The first commercially available plastic contact lens material was PMMA. Since it is a derivative of acrylic acid (CH_2 = CH—COOH), it is also called acrylic.

Advantages of PMMA

- The PMMA has a high optical quality and stability and is light in weight.
- It has excellent moulding and machining qualities and so is easy to manufacture.
- Pure PMMA is non-toxic and does not excite allergic reactions.

Disadvantages of PMMA Hard Contact Lenses

- PMMA is practically impermeable to O_2, with DK value essentially zero, thus restricting the tolerance.
- Being relatively hard, it can cause corneal abrasions.
- Being hydrophobic in nature, it resists wetting, but a stable tear film can be formed over it.

A lot of efforts have been directed at improving the property of PMMA, specifically its oxygen permeability. Copolymerization of PMMA with other monomers has resulted in better materials. However, these materials no longer possess the properties of PMMA and cannot, therefore, be termed hard lenses.

Note. PMMA hard contact lenses are now obsolete.

RIGID GAS-PERMEABLE LENS MATERIALS

RGP lenses are made up of materials which are permeable to oxygen. They have the inherent rigidity similar to PMMA, but somehow due to their O_2 permeability, they have become popular by the name of *semi-soft lenses.* Materials used to manufacture RGP contact lenses are as follows.

RGP Lens Materials Used Earlier

1. ***Cellulose acetate butyrate.*** CAB, a class of thermoplastic material derived from special grade wood cellulose, was the first widely used gas-permeable rigid contact lens material. The lens surface, although having good wetting characteristics, is easily scratched. Other major disadvantage of this contact lens is its tendency to warp. Because of these disadvantages, CAB lenses are not much popular nowadays.
2. ***Silicone.*** Although pure silicone has the highest oxygen permeability, silicone lenses have not become popular because of the inherent lack of wettability in this material.
3. ***Styrene.*** T-Butyl styrene has also been tried to manufacture RGP lenses. This material has a high oxygen permeability. However, due to problems with surface durability and brittleness, this material has not been used to any great extent for contact lenses.

Presently Used RGP Lens Material

1. ***Silicone acrylate.*** RGP lenses are commonly manufactured from the copolymer of PMMA

and silicone-containing vinyl monomer. The cross-linking of silicone and PMMA copolymers have resulted in siloxanyl methacrylate lenses. The MMA content provides good wetting characteristics and the silicone content permits oxygen to migrate. By various combinations of the silicone content, these materials may be manufactured with a wide range of DK values (15–55) and oxygen permeability. As a rule, the higher the oxygen permeability with increased silicone content, the greater will be the difficulty with surface characteristics of the lens.

2. *Fluoropolymers.* RGP lenses made from the copolymer containing fluorine molecule have been quite popular. In fact, these lenses have been accepted for extended wear because of their high oxygen permeability (high DK value up to 150) and good surface characteristics. Furthermore, these lenses are not as prone to surface deposits as is the case with higher DK value pure silicone lenses. Presently, there are three subtypes of fluorine-containing contact lens materials:

- *Pure fluoropolymer* is cast moulded.
- *Fluorosiloxanyl methacrylate* copolymer is the most common form. It can be lathe cut into a contact lens.
- *Perfluoroalkylitaconate-siloxane* is available as the Alberta N lens in Canada.

HYDROPHILIC SOFT CONTACT LENS MATERIALS

Soft lenses are made from hydrogels. In contrast to PMMA, the hydrogels contain a hydrophilic group such as hydroxyl group. The hydrogels are cross-linked polymers and have a coherent three-dimensional polymeric network and can imbibe large quantities of water without dissolution. This material is not dimensionally stable like hard lenses and swells to form labile soft lens.

Hydrogels may be obtained by polymerization or copolymerization of hydrophilic monomers with a cross-linking agent such as ethylene glycol dimethacrylate (EGDM). Cross-linkage is not necessary in case of water-insoluble monomers, e.g. HEMA. Cross-linked polymers are more often utilized since they are more stable.

Characteristics of hydrogel lenses:

- *Amount of absorbable water (hydration) or equilibrium swelling* – which is defined as the balance between osmotic pressure of polymer segment and the elastic refractive forces arising in the chains between the cross-linkages – is important from the point of view of the utility as contact lens materials. In terms of hydration, the soft lenses can be
  - Low hydration lenses (38%–45% H_2O) or
  - High hydration lenses (up to 85% H_2O).
- *Hydration of soft lens varies with* the following:
  - Chemical composition.
  - Number and nature of hydrophilic groups.
  - Amount of cross-links in the network or cross-link density, or the solubility of non-cross-linked polymer.
- *Degree of swelling of contact lens* in a given aqueous solution depends on temperature and pH of the solution.
- *Average diameter of pore in hydrogel* increases with the water content; i.e. the greater the water content, the larger the pore diameter and consequently increased gas permeability.
- *Two basic principles of oxygen permeability in soft lenses are* important to understand:
  - The first is as water of hydration increases, there is a logarithmic increase in oxygen permeability.
  - The second concept is that oxygen permeability is also inversely related to centre thickness of a hydrogel material.
- *Hydrogel lens characteristics change* with external environment and can desiccate when not taken care of (i.e. in dry environment).

High Water Content Lenses

These lenses are preferable because of the increased access of cornea to the atmospheric gases. Thus, a higher oxygen delivery to cornea can be ensured by increased water content of lens and decreased thickness of lens. There are, however, limits to the thinness of lens – friability increases with thinness and there may be rippling of thin lenses on blinking, thus interfering with vision.

The presence of pores on the surface of polymer has certain drawbacks. Substances

of larger dimensions such as proteins, viruses and bacteria cannot penetrate the intact hydrogel but are deposited on the surface, impairing the efficiency of lens.

Hydrogel Lens Materials

Hydrogel lens materials, commonly used, are as follows:

1. ***HEMA lenses.*** HEMA is the original soft lens material and is still widely used. In India, most of the soft lenses are made of this material. These lenses are resistant to biodegradation or attack by any enzyme constituent of normal or abnormal tears and withstand chemical and thermal sterilization.
2. ***HEMA-VP lenses.*** The homogenous HEMA lenses have a maximum hydration of 40% and to attain a higher hydration, copolymerization with vinyl pyrrolidone (VP) (a non-acrylic) was tried. Polyvinyl pyrrolidone (PVP) is a water-soluble polymer. Random copolymerization of HEMA (80%) and VP (20%) and cross-linkage with EGDM yields a material known as PHP. Hydrocurve, Hydroflex, Flexicon lenses are made of this material with a maximum hydration of 45%. A common characteristic of VP-containing hydrogels is the tendency to colour with age.
3. ***MMA-PVD lenses.*** These are made of hydrophilic polymer PVP, monomer VP and hydrophobic MMA. A combination of various proportions of hydrophobic and hydrophilic moieties in cross-linked polymer, varieties of hydrogels of varying hydration, can be obtained, e.g.:
   - Sauflon 70 (68%–73% hydration),
   - Medigel 70,
   - Vizilens 70 and
   - Soflex 66 S and Soflex 88 copolymers of VP and MMA are commonly used in India.
4. ***Glycidyl methacrylate.*** Hydrophobic monomer is another hydrogel used in combination with HEMA and VP or with MMA and VP.

SILICONE HYDROGEL LENSES

A new generation of silicone hydrogel contact lenses have come up. These lenses have high DK value and low water content. Oxygen transmission in these lenses is function of silicone content.

MANUFACTURING PROCESS

Manufacturing Techniques

1. Lathe cutting
2. Spin casting
3. Moulding

1. Lathe Cutting

This method of manufacture is so-called because lathe is used to carve the anterior and posterior central curves. Different lathes are used for each surface.

- *Hard lens* is polished with convex (for posterior surface) and concave (for anterior surface) wax lens.
- *Soft lenses* are polished with aluminium oxide lubricated with distilled paraffin.
- The peripheral and intermediate curves and edges are modified.
- Contact lens is then verified against the parameters.

Advantages

There is a greater flexibility in the choice of power, posterior curvature and diameter, for individual fitting. This method can be utilized for manufacture of both hard and soft lenses. In case of soft lens:

- High-quality surface finishing at least equal to that of PMMA lenses can be obtained.
- High dimensional accuracy can be maintained by lens checking in a dry state.
- Lenses can be engraved for each identification.

2. Spin Casting

This is a process of centrifugal casting of hydrogel lenses wherein polymerization occurs simultaneously. A monomer solution, cross-linking agent and initiator are placed in a concave mould, rotating at a predetermined rate around its own axis. The polymerization and shaping of lens occur during the spinning of the mould. The outer surface of the lens is spheric and inner aspheric, and the curvature depends on the

shape and speed of rotation of the mould. The lens obtained is in a swollen state and the unpolymerized monomer and initiator are extracted by placing the lens in water for as long as 24 h.

Advantages

- Precision moulds and controlled spin speeds ensure accurate reproducibility.
- Free-formed fluid surface is the best optical surface and this process generates such surfaces.
- Since polymerization of thin film of monomer is done, a consistent, homogenous and thoroughly cross-linked polymer is obtained.
- Surface and interstitial imperfections are least with this process.

3. Moulding

The lens material is heated or cured to produce a mobile phase and it is placed in a mould to obtain desired contact lens form. This method is not widely utilized now.

Stages in Manufacture of a Contact Lens

1. *Contact lens blank* is a section of clear MMA, ethyl acrylate or copolymers of methyl and ethyl acrylate sheet or rod which comes ordinarily in diameter of 12.7 and 15.9 mm having a thickness between 3.00 and 6.5 mm.
2. *Semi-finished blank* is a contact lens blank with a proposed posterior curve.
3. *Semi-finished lens* is a lens that has an anterior curvature and a posterior curvature, both of which have been polished and are of optical quality and of known diameter.
4. *Finished corneal contact lens* is a finished lens that has been individually adjusted to a specific cornea by modification of the peripheral and intermediate areas of the posterior surface and of the diameter and edge of the lens.

TEAR FILM AND CONTACT LENS INTERACTIONS

The pre-corneal tear film plays a major role in the maintenance of the functional integrity of the cornea. It protects, nourishes and lubricates the cornea. The cornea is made up of the refractive elements. The transparency and health of cornea are of utmost importance. The contact lens necessarily interferes with the normal harmonious relationship between the cornea and the tear film – to a greater or lesser extent. This disturbance may not only result in the impairment in the health and functioning of the cornea but may also ultimately impair the efficacy and acceptability of the contact lens itself.

The interactions that take place between the tear film and contact lens are summarized below.

POSITIONING OF LENS AND TEAR FILM

The only logical approach to position the contact lens on the eye is to either somehow clamp the lens to cornea or by sticking the lens to the cornea. Both of these are not practically feasible, and the pre-corneal tear film with its properties of surface tension and viscosity functions as a reversible sheeting and glue to hold the contact lens to the cornea. As soon as the lens is inserted in the eye, conjunctival mucus is rubbed on to the lens surface after several blinks, and then the tear fluid will wet the lens with each blink. The tear film not only wets the lens, but the thin sheet that spreads over the lens anchors itself all around the periphery of lens to the surrounding tear film. The pre-lens tear film, like a sheet of plastic, tacks the lens to the eye due to the strong cohesive force among the water molecules in tear film and adhesive force between water and lens material. It has been experimentally observed that 11 g of force was necessary to dislodge a stationary contact lens. With the break in tear film covering the lens, the internal method of adhesion takes over. A negative pressure develops between the lens and the cornea – the tear film–air interface forms a collar between the edge of lens and cornea – and this tear surface membrane acts as a container for the lens. This negative pressure has been experimentally measured to be about 29 dyn/cm^2.

OPTICAL CONSIDERATIONS

The tear lens or the post-lens tear film plays a major role in supplementing the function of

contact lens. The back of tear lens fills the irregularities of cornea, thus presenting a uniform optical surface and the front surface of tear lens is shaped by the rear surface of contact lens. The refractive index of tears is 1.337 and that of cornea is 1.376. If these indices were equal, all degrees of corneal astigmatism and irregularity would be perfectly corrected with contact lenses. However, the difference of 0.04 in the refractive index implies that in astigmatism up to 5 D contact lens leaves a residual of 0.50 D only. However, with a high degree of astigmatism, the residual astigmatism may be proportionately higher. Further details of effect of tear lens on contact lens optics are described on page 268.

EFFECT OF CONTACT LENS ON CORNEAL NUTRITION

Contact lens can potentially embarrass the cornea in at least four ways. It can:

1. Retard the evaporation of tears and interfere with hypertonicity of tears.
2. Present a physical barrier for delivery of oxygen.
3. Trap wastes and interfere with waste disposal.
4. Traumatize the delicate epithelial cells of cornea.

Average hard lens covers 50%–80% of corneal surface and with normal lens mobility 70%–85% of this covered area is permanently covered. Hence, this area of cornea is dependent for nutrition on the tear film under the contact lens. This post-lens tear film has to be constantly renewed in order that the corneal oxygen needs are met. It has been found that under static conditions, the oxygen in the post-lens tear film is exhausted in about 90 s with hard lenses or with soft lenses with 40% hydration. Since the non-oxygen-dependent pathway for obtaining energy is only about 1/18th as efficient as oxygen-dependent pathway and further there is accumulation of lactic acid, the corneal nutrition suffers and there is corneal oedema and haziness.

The blinking provides a *pump mechanism* in the cornea–contact lens system, and the lid pressing on the lens expels the post-lens tear film which is formed again subsequently. Efficiency of tear pump depends on the following:

- Volume of tears behind contact lens,
- Percentage of exchange with each blink (20% required) and
- Frequency of blinking.

In soft lens, the large diameter of lens (11.5–15.5 mm) almost wholly covers the corneal epithelium. However, since soft lens is hydrophilic, an *aqualung effect* is seen. The post-lens tear film obtains oxygen from the tear film on contact lens surface. However, even here, in absence of blinking, the cornea suffers from lack of oxygen. The pump effect is not so evident in these cases. Oxygen delivery is only 1/10th that with hard lens. But the flexibility of lens permits a capillary layer of lacrimal fluid under the lens. Deturgescence of cornea may be impaired due to hypotonicity of tear film caused by the following:

- Excessive tear secretion,
- Impairment of evaporation and
- Altered blinking rate.

LENS EDGE FLARE

The contact lens is surrounded by patient's tears which produces a prism-shaped meniscus at the lens edge. If the edge crosses the pupillary area as with small hard lenses – especially with low- or high-riding lenses – there is formation of second out of focus image on retina. This phenomenon is known as *edge flare* or *ghost image*.

CONTACT LENS INTEGRITY

The tear fluid plays a role in maintaining the normal integrity of soft lenses. The hydrophilic soft lenses have a water content between 25% and 85%. These lenses when deprived of their water content become hard and brittle, and the refractive index and dimensions vary with the amount of hydration. It has been noted in HEMA lens (38% hydration) that after 2 min of loss from the eye, about 10% of its water content is lost and after 15 min, about 50% of water content is lost.

LENS SPOILAGE AND TEAR FILM

It is indeed ironic that the tear fluid which plays such a vital role in the acceptability of, adaptability to and functioning of soft contact lens is also responsible for the spoilage of soft contact lenses.

A soft contact lens is subject to deposits on its surface, which affect its optical properties. In most cases, these deposits diminish the efficiency of the soft lens within 6 months. These deposits are due to various causes as follows:

- Irregularities of lens surface due to manufacturing defects,
- Porosity of the lens,
- pH of the tears,
- Composition of tear fluid,
- Volume of tear fluid,
- Rapid break-up time and
- Blinking deficiencies.

Bulk of soft lens deposits appear to be derived from ocular secretions incorporated in tears. Main components of tears affecting soft lens are mucoid and proteinaceous elements including lysozyme, polysaccharides, chlorides, phosphates and calcium. In addition, products of normal desquamating epithelial cells or necrotic tissue and altered component of tear fluid in diseased state may also form deposits. pH of tears appears to play an important role in lens spoilage. Protein deposits occur when pH is low and mineral deposits occur when it is high. Gelatinous deposits are encouraged by dry spots while lysozyme deficiency (as in dry eye syndrome) may be associated with mucinous precipitate. Altered mucin due to hormones (oral contraceptives) seems to promote adhesion and precipitation of mucin. Discrete lens opacities on anterior surface, consisting predominantly of lipid derived from meibomian secretion, appear to be deposited due to combination of dryness and stress of blinking, which alters the structural integrity of lens. These deposits, apart from impairing the optical function, render the lens rigid and less permeable. The wettability is also impaired, which promotes dryness and thus a vicious cycle is set up.

OPTICS OF CONTACT LENS

Contact lens is held in close apposition with the eye in contradistinction to spectacle lens which is held 12–13 mm in front of corneal vertex. Spectacle lenses are separated from the eye by air and aim at changing the incident light so that the rays appear to come from the point for which the eye is naturally adapted, i.e. its far point. There is no change in the total refractive power of the corrected eye; i.e. vergence of the eye itself is not altered but only the vergence of rays is altered. Thus, spectacle lens has only an accessory effect on the refractive power of the eye. In contact lenses, the vergence of the eye is altered, or in other words, there is a change in refractive power of the eye. This is achieved by abolition of cornea as the initial refracting surface of the eye and by substitution of the contact lens system for it.

NEUTRALIZATION OF CORNEA

With contact lens in situ, there is a thin tear film that acts as a fluid lens. Refractive index of tears is taken to be 1.336 and that of cornea 1.376. The tear film would neutralize 1.336 or about 9/10th of the power of the anterior surface of cornea, reducing it from +48.83 to about +5.19 D. The power of posterior surface of cornea is unaffected, and on the whole refraction by cornea is either totally abolished or a small negative balance may persist. This tear film acts as a fluid lens. Thus, in contact lens we have (a) glass lens and (b) fluid lens. Ametropia is corrected by glass lenses by incorporating the spherical correction on anterior surface and residual astigmatism on posterior surface.

Ametropia can be solely corrected by means of liquid lens when the anterior and posterior curvatures of the contact lens are equal. This lens is known as afocal lens. Usually both the fluid lens and glass lens are utilized for correction of ametropia.

CORRECTION OF AMETROPIA BY CONTACT LENS

To understand the correction of ametropia by contact lens, it is essential to understand the

behaviour of rays passing through plastic contact lens and tear lens before hitting the cornea. When a contact lens is in place, four media of different refractive indices must be taken into account. Following the direction of incident light, these are air (RI 1.0), contact lens material PMMA (1.49), tears (1.33) and corneal substance (1.37). It is clear from the similarity of last three media that the most significant refractive power lies in the interface between air and lens, the front surface of which optically replaces the front surface of cornea. The curvatures of interfaces have equal importance in the refractive properties of the system. In this respect, the two basic principles of correcting ametropia by contact lens must be reviewed.

1. ***Afocal lenses.*** Here the correcting properties of optical system were imparted by different curvatures of surfaces of fluid lens. It is perfectly valid to regard the three elements (contact lens, fluid lens and cornea) as separated by infinitely thin air spaces. So, if the contact lens is afocal, the correction of ametropia is due to back vertex power of fluid lens in air. This power will be the sum of its front and back surface powers.
2. ***Powered lenses.*** Afocal lenses are now outdated therapeutically. The causes are that too many base curves are required to cover all the possible types of ametropia, and fitting technique has limitations. In modern practice, contact lenses are designed with posterior surface of their optical zone differing from anterior surface. So, the correction of ametropia is fundamentally due to difference in curvature of anterior and posterior surfaces of contact lens. Once the curvature of posterior surface is known, the optical problem is to decide on the curvature of anterior surface; this has an empirically decided relationship to corneal curvature which is determined. Back vertex power of contact lens in air is equal to ocular refraction, provided its posterior surface parallels the apical zone of cornea as is approximately the case in modern practice.

POWER AND MAGNIFICATION BY CONTACT LENS

The distance at which the correcting lens is placed in relation to the vertex plane determines the power and size of retinal image. Contact lens is placed at the vertex plane while spectacle lens is placed 13 mm in front of vertex plane. The effect is that in hypermetropia, a stronger contact lens is required and in myopia a weaker lens is required. The power of contact lens required to correct the ametropia can be calculated from the spectacles correction. For example, a +8.0 D spherical lens required for spectacles correction will have focal length of 125 mm. Since contact lens is placed 13 mm nearer back vertex distance, focal length of contact lens will be 125 – 13 = 112 mm; i.e. a lens with a power of +8.93 D will be required. *Myopia* –11.5 D in spectacle plane is equivalent to –10 D in vertex plane.

The size of retinal image depends on the site of the lens. At anterior focus, there is no change. Nearer than this it decreases in hypermetropia and increases in myopia. Thus, in aphakia, magnification is 22% with spectacle lens and 7% for contact lens, which is within tolerable limits for binocular single vision in most individuals.

In spite of the efforts made to reduce the axial thickness of a contact lens to a minimum, it should be considered as a thick lens because of the relatively marked curvatures.

In practice, refraction is often estimated with the trial lens in place; such a lens may be afocal or powered and spectacle refraction is determined to give maximum acuity. It is usually adequate to add to the back vertex power of the trial lens the effective power of cornea of the supplementary lens required in the spectacle plane. For lenses of power less than 4 D, effect at the cornea is only slightly altered and the change can be ignored. This may, however, give rise to a slight error, if high powers are involved or if thickness of trial lens is excessive. It is always preferable to assess the fit and refraction with a lens as close as possible in power to the final one.

INFLUENCE OF TEAR LENS (FLUID LENS)

Tear lens is formed between the posterior surface of the contact lens and anterior surface of cornea.

- Two variable factors concerning the fluid lens that bear upon its optical properties are its thickness and surface curvatures.
- The thickness is generally of no great optical significance, being less than 1.0 mm. For average curvature of cornea and contact lens, the converging power of liquid lens in air increases by about 0.12 D for every 1.0 mm increase in thickness.
- *Soft contact lenses* conform to the corneal curvature, so the tear lens formed usually have plano power.
- *Power of tear lens with RGP lens* varies with the base curve of the lens as follows:
  - *Plano power tear lens* is formed when the base curve of the contact lens (CL) is equal to corneal curvature (K reading).
  - *Plus power tear lens* is formed when the base curve of CL is steeper than K.
  - *Minus power tear lens* is formed when the base curve of CL is flatter than K.
- *Power of tear lens formed* for every 0.05 mm difference between base curve of CL and K is 0.25Δ.
- *To get final CL power, with steeper CL*, always subtract the tear lens power to the estimated CL power (pneumonic SAM, i.e. for steeper add minus).
- *To get final CL power with flatter CL*, always add the tear lens power to the estimated CL power (pneumonic FAP, i.e. for flatter add plus).

EFFECT OF CONTACT LENS ON ACCOMMODATION AND CONVERGENCE DEMAND

Compared to spectacles, contact lenses increase the accommodative and convergence requirements of myopic eyes and decrease those of hyperopic eyes in proportion to the amount of refractive errors. This difference is due to effect on the vergence of light rays as they pass through respective lenses. Contact lens corrected eyes have accommodation equivalent to the emmetropic eyes. So, basically contact lenses eliminate the accommodative advantage of myopic spectacles and disadvantages of hyperopic spectacles.

INDICATIONS AND CONTRAINDICATIONS OF CONTACT LENS USE

INDICATIONS

1. ***Optical indications*** include anisometropia, unilateral aphakia, high myopia, keratoconus and irregular astigmatism. In fact, as an alternative to spectacles, the contact lenses can be used for cosmetic purposes by every patient having refractive error.

   Advantages of contact lenses over spectacles:
   - Irregular corneal astigmatism which is not possible to correct with glasses can be corrected with contact lenses.
   - Contact lenses provide normal field of vision.
   - Aberrations associated with spectacles (such as peripheral aberrations and prismatic distortions) are eliminated.
   - Binocular vision can be retained in high anisometropia (e.g. unilateral aphakia) owing to less magnification of the retinal image.
   - Rain and fog do not condense upon contact lenses as they do on spectacles.
   - Cosmetically more acceptable especially by females and all patients with thick glasses as in high refractive errors.
2. ***Therapeutic indications*** are as follows:
   - *Corneal diseases*, e.g. non-healing corneal ulcer, bullous keratopathy, filamentary keratitis and recurrent corneal erosion syndrome.
   - *Diseases of iris* such as aniridia, coloboma and albinism to avoid glare.
   - In *glaucoma*, as vehicle for drug delivery.
   - In *amblyopia*, opaque contact lenses are used for occlusion.
   - *Bandage soft contact lenses* are used following keratoplasty and in microcorneal perforation.
3. ***Preventive indications*** include (i) prevention of symblepharon and restoration of fornices in chemical burns, (ii) exposure keratitis and (iii) trichiasis.

4. ***Diagnostic indications*** include use during (i) gonioscopy, (ii) electroretinography, (iii) examination of fundus in the presence of irregular corneal astigmatism, (iv) fundus photography and (v) Goldmann's three-mirror examination.

5. ***Operative indications.*** Contact lenses are used during (i) goniotomy operation for congenital glaucoma, (ii) vitrectomy and (iii) endocular photocoagulation.

6. ***Cosmetic indications*** include (i) unsightly corneal scars (coloured contact lenses) and (ii) cosmetic scleral lenses in phthisis bulbi.

7. ***Occupational indications*** include use by sportsmen, pilots and actors.

CONTRAINDICATIONS

- Mental incompetence or irresponsibility, and poor motivation.
- Diseases of lacrimal apparatus such as chronic dacryocystitis.
- Diseases of eyelids such as styes and blepharitis.
- Conjunctivitis.
- Diseases of cornea, like corneal dystrophies and degeneration.
- Episcleritis and scleritis.
- Iridocyclitis.
- Occupational hazards – which expose the patient to smoke, dust, etc.
- Seventh nerve palsy.
- Inability to use hands, e.g. crippling arthritis.
- Poor personal hygiene.
- Allergic patients.
- Dry eyes.

Certain conditions that reduce the likelihood of successful contact lens wear are as follows:

- Pregnancy, in which contact lens wear is problematic,
- Giant papillary conjunctivitis (GPC) and
- Strabismus, where spectacles are a better choice for cosmetic reasons.

DESIGN DESCRIPTION AND PARAMETERS OF A CONTACT LENS

The essential feature in the design of a rigid contact lens is that the posterior surface must conform to a greater or lesser degree with the shape of cornea; any significant disparity in this respect will lead to lack of stability of the lens over the cornea.

CONTACT LENS: NOMENCLATURES

To understand the contact lens specifications, designs and parameters, the following standard nomenclatures have been recommended (Fig. 8.2):

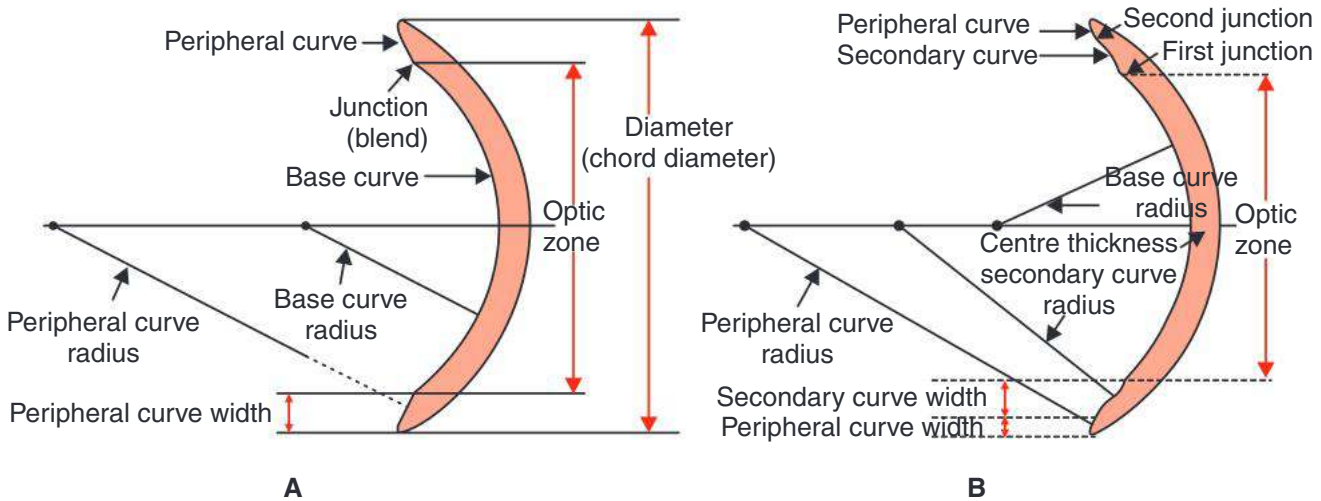


Fig. 8.2 *A, Standard bicurve contact lens and B, tricurve lens.*

1. ***Diameters of the lens*** are as follows:
   - **i.** *Overall diameter* or chord diameter of the lens is the linear measurement of the greatest distance across the physical boundaries of lens. It is expressed in millimetres (it should not be confused as being twice the radius of curvature). Overall diameters of contact lenses are as follows:
     - *PMMA lenses* (now obsolete) vary between 7.5 and 8.8 mm.
     - *RGP lenses* typically have a diameter varying between 9.0 and 9.8 mm.
     - *Soft contact lenses* commonly have a diameter between 13 and 15 mm.
   - **ii.** *Optic zone diameter* is the dimension of the central optic zone of lens which is meant to focus rays on retina.
2. ***Curves of the lens*** are as follows:
   - **i.** *Base curve* or central posterior curve is a curve on the back surface of the lens to fit the front surface of cornea. Within one particular design of lens, base curve radii may be available in a range commonly from 7.0 to 8.5 mm in 0.05 mm intervals.
   - **ii.** *Peripheral curves.* These are concentric to base curve and include intermediate posterior curve and peripheral posterior curve. These are meant to serve as a reservoir of tears and to form a ski for lens movements. The simplest form of the lens has a single peripheral curve, the radius of which is greater than that of optic zone; such a lens is known as bicurve lens (Fig. 8.2). Tricurve or multi-curve lenses are also available.
   - **iii.** *Central anterior curve* or front curve is the curve on the anterior surface of the optical zone of the lens. Its curvature determines the power of contact lens.
   - **iv.** *Peripheral anterior curve* is a slope on the periphery of anterior surface which goes up to the edge.
   - **v.** *Intermediate anterior curve* is fabricated only in the high-power minus and plus lenses. It lies between the central anterior curve and peripheral anterior curve.
3. ***Blend.*** Blend is a smooth area of transition of the radius of curvature from one curve to another. A blend could be classified as follows:
   - *Light*: The transition between two posterior curves is distinctly visible.
   - *Medium*: The transition between two posterior curves is just visible.
   - *Heavy*: The transition between two posterior curves is not visible at all.

   In the so-called continuous curve lenses, which flatten in non-spherical fashion from the axis onwards, the blends have been markedly reduced.
4. ***Edge of the lens.*** It is the polished and blended union of the peripheral posterior and anterior curves of the lens. The design of the edge of the lens is very important. A too sharp an edge may dig into the corneal tissue and too thick an edge may irritate the lids. The extent to which the curvature of most peripheral curve differs from that of the base curve radius is a measure of what is known as edge lift, also sometimes known as the Z factor. In PMMA lenses, the edge lift needs to be slightly more than that for gas-permeable lenses because of the greater need to ensure tear renewal. However, if the edge lift is excessive, stability of the lens may be compromised.
5. ***Power of the lens.*** It is measured in terms of posterior vertex power in dioptres.
6. ***Central thickness of the lens.*** It is usually measured at the geometric centre of the lens and varies depending upon the posterior vertex power of the lens.
7. ***Tint.*** It is the colour of the lens.

BRITISH VERSUS AMERICAN NOMENCLATURE OF VARIOUS PARTS OF CONTACT LENS

There exists a difference in British and American nomenclature of various parts and curves of the contact lens. So, it will be worthwhile to be familiar with both systems (Table 8.1).

RIGID CONTACT LENSES

Rigid contact lenses are of two types:

- *Rigid non-gas-permeable* lenses, as described above, are made of PMMA (also known as

Table 8.1 *Contact lens parts: British vs American nomenclature*

British nomenclature	American nomenclature
• Back optic zone	• Optic zone
• Back optic zone radius (BOZR) or back central optic radius (BCOR)	• Optic zone radius (OZR) or base curve radius (BCR)
• Back optic zone diameter (BOZD) or back central optic diameter (BOCD)	• Optic zone diameter (OZD)
• Back central optic portion (BCOP)	• Base curve (BC) or central posterior curve (CPC)
• Back peripheral optic portion (BPOR)	• Peripheral curve (PC)
• Back peripheral radius (BPR)	• Peripheral curve radius (PCR)
• Frontal central optic portion (FCOP)	• Optic cap (OC)
• Geometrical central thickness (GCT)	• Thickness
• Peripheral curve width (PCW)	• Peripheral curve diameter (PCD)
• Total diameter (TD)	• Overall diameter (OD)
• Front bevel (FB)	• Bevel

Plexiglas) (see page 261). These lenses are virtually obsolete today.

- *RGP lenses* are made up of various polymers, e.g. CAB, silicone acrylates, fluorine copolymers, pure silicone resin, polystyrene, polysulphone copolymer and butyl styrene (for details see page 261).

FITTING PROCEDURE FOR RIGID CONTACT LENSES

A standardized routine followed for fitting procedure of a rigid contact lens is described.

INITIAL PATIENT WORK-UP

1. ***History*** is taken in detail from the patient to exclude medical contraindications to the contact lens wear. In fact, patient selection criteria should be reviewed before proceeding further. Evaluation of the patient's emotional general status and the reasons for wanting contact lenses can be of particular importance in the overall success rate.
2. ***General ocular examination*** including slit-lamp biomicroscopy should be performed for a thorough inspection of anterior segment.
   - Special care should be taken to note any conjunctival or limbal injection or corneal infiltration.
   - *Tear film* should also be evaluated properly.
   - *Blink characteristics* are important to note, as a partial blink does not wet a rigid lens properly and does not provide adequate tear exchange under the lens.
   - *Measurement* of corneal diameter, pupil diameter and palpebral width are useful in deciding the overall diameter of the contact lens.
3. ***Refraction*** including retinoscopy and subjective verification should be carried out meticulously. Best corrected vision should be noted. In fitting a rigid contact lens, the ocular refraction is most conveniently expressed in spherocylindrical notation, using minus cylinders, and the necessary corrective power of the lens is specified by the spherical power only. The information about vertex distance is essential to determine the contact lens power at the corneal plane. Refractive errors of greater than ±4 D require a correction to zero vertex distance, because error of this magnitude will cause a significant variation in lens effectiveness at the corneal surface.
4. ***Keratometry*** is then performed to measure the corneal curvature in two principal meridians. Keratometry readings are important to choose the base curve radius of the contact lens. For details of keratometry, see page 175.
5. ***Trial lens fitting.*** The practitioner should have a trial set of pre-fabricated lenses. A complete inventory set should have available at least two different diameters lenses with increments of 0.25 D of base curve value (40–50 D range). The same trial set is usually appropriate for both PMMA and gas-permeable lenses. Since PMMA lenses are sparingly

used nowadays, so the fit is discussed for gas-permeable lenses.

SELECTING LENS FROM THE TRIAL SET

A trial lens with following parameters should be selected from the trial set:

1. ***Diameter.*** An overall diameter of 9 mm is appropriate for the fitting of gas-permeable lenses in a new contact lens wearer with an average corneal diameter and palpebral aperture. An overall diameter of 0.5 mm less or more may be selected, if the corneal diameter and palpebral aperture are small or wide, respectively.
2. ***Base curve radius*** is derived from keratometry. The usual practice is to fit the trial lens based on flatter 'K' reading (*fit 'on-K'*). However, in the presence of astigmatism, a base curve 'steeper than K' may be chosen. Suggested guidelines are as follows:
   - *If astigmatism is of 0.5–1.0 D*, base curve 0.25 D steeper than K is chosen. For example, if keratometry readings are 44 D/45 D, then base curve chosen is 44.25 D.
   - *If astigmatism is of 1.0–2.0 D*, a base curve 0.5 D steeper than K is chosen. For example, if keratometry readings are 44 D/46 D, then base curve chosen is 44.5 D.
   - *If astigmatism is of more than 2 D*, then one-third toricity should be added to 'K' for choosing base curve. For example, if keratometry reading is 44 D/47 D, then base curve chosen should be:

$$44 + \frac{47 - 44}{3} = 45 \text{ D}$$

3. ***Power of the trial lens*** should be as calculated from refraction. The spectacle refraction should be determined in minus cylinder form and then corrected for the power at the refracted (spectacle) vertex distance to a vertex distance of zero, since the contact lens is in direct opposition to the cornea. The following example demonstrates this:
   - Spectacle prescription = –9.25 + 0.50 × 90
   - Vertex distance = 15 mm
   - Minus cylinder form = –8.75 – 0.50 × 180
   - Correction for vertex distance of zero = –7.75 – 0.50 × 180

This vertex distance correction can be calculated by applying the appropriate formula. For a ready reference, tables are available for converting spectacle correction into contact lens correction with zero vertex distance. The spherical power determined in this way is used as contact lens power.

EVALUATION OF THE TRIAL LENS FIT

The selected trial lens is inserted into the eye and after an adaptation period (usually 15–30 min), it is evaluated (for the adequacy of the parameters to be ordered) by utilizing slit-lamp biomicroscopy and fluorescein pattern evaluation.

1. **Position of the lens.** Ideally optic zone must cover entire pupillary area adequately in all directions of gaze. Lens position may not be ideal and may differ in the following ways:
   i. ***Lens may ride high***; i.e. the upper edge of the lens crosses the upper limbus while looking straight. Common causes and their correction are as follows:
      - *Position of the lower lid* may be higher, thus pushing the lens up. Reduce the diameter of the lens, so that it lies within the limbus.
      - *Upper lid may be tight* and thus pulling the lens up due to excessive traction. Making the edge thin, so that it slips under the upper lid, will solve the problem.
      - If high-riding lens is due to both the above factors, fit a very small lens that lies within palpebral aperture or use a prism ballast lens.
      - High-riding lens due to a large lens or marked with-the-rule astigmatism can be corrected by making the lens small or steep and small.
      - *High minus lens* may also ride high and can be corrected by making the edge thin or by making a plus carrier lenticular lens.
      - Upward displacement of optic cap should be corrected by using the prism ballast or a large lens.

ii. ***Lens may ride low***; i.e. lower edge touches the limbus. Common causes and their correction are as follows:

- *Lens may be heavy*, as seen particularly in single-cut aphakic lens. The remedy lies in making a plain lenticular lens or a minus carrier lenticular lens.
- *Lens may be small in diameter or flat.* Correction is done by fitting a large or steep lens.
- *In exophthalmic eyes*, the lens may lag down. Fit a large lens or a steep and small lens.
- *Upper lid may be pushing* the lens down. It may be corrected by fitting a plain lenticular lens minus carrier lenticular lens.
- *Lens may ride low* due to inferior located optical cap. Replace the lens with a properly located optical cap.

iii. ***Horizontal decentring of the lens*** may occur either nasally or temporally. This is usually seen in corneal opacity, oblique or against-the-rule astigmatism. Centring of the lens can be achieved by fitting a steep and small lens.

2. Base curve determination. Once the position of the lens has been stabilized, check-up if the lens is ideal, steep or flat for a given cornea. In fact, base curve determination is the single most important factor in the science and art of fitting the rigid contact lens. On it depends the tear exchange – the most crucial factor for the health of cornea. Tear exchange is mostly due to pumping action; i.e. on blinking, the lens is compressed against the cornea and creates a negative pressure and on releasing, the new tear volume is drawn under the lens. This action is achieved, provided the base curve of the lens matches the curve of the cornea.

The characteristics of a flat, steep or ideal fitting lens are as follows:

i. ***Flat base curve.*** A flat fitting lens is characterized by:

- Excessive lens movement.
- High- or low-riding or horizontally displaced lens.
- *Fluorescein pattern* in a spherical cornea will show a black area over the corneal apex (indicating that there is no tear layer and the lens is touching the cornea) and a diffuse green pattern in the peripheral and intermediate zones (Fig. 8.3). The central bearing area will remain the same on movement of the lens. A flat fitted lens over an astigmatic cornea will have a broad area of optical touch (black band) overlying the flattest corneal meridian and the remainder of the area will be bright green in colour (Fig. 8.4D).

  When a flat fit lens is prescribed to the patient, it will touch the central portion of the cornea, resulting in corneal abrasion, irregularity or distortion due to inadequate tear flow at the points of contact of the lens with the cornea. Also, lens lag may be there on a flat lens. This will result in indentation near the upper limbus on conjunctiva, and the conjunctival staining will be present and will result in increased feeling of the lens to the patient. Other causes which may mimic a flat lens are a wide palpebral aperture or too small a lens or both.

ii. ***Steep base curve*** is characterized by:

- Little or no movement of the lens.
- Air bubbles may be seen under the surface of lens, if base curve is very steep.

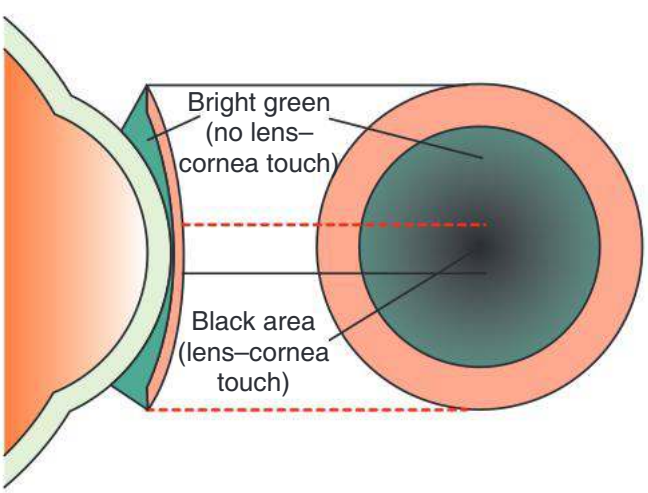


Fig. 8.3 *Fluorescein pattern in a flat fit contact lens on spherical cornea.*

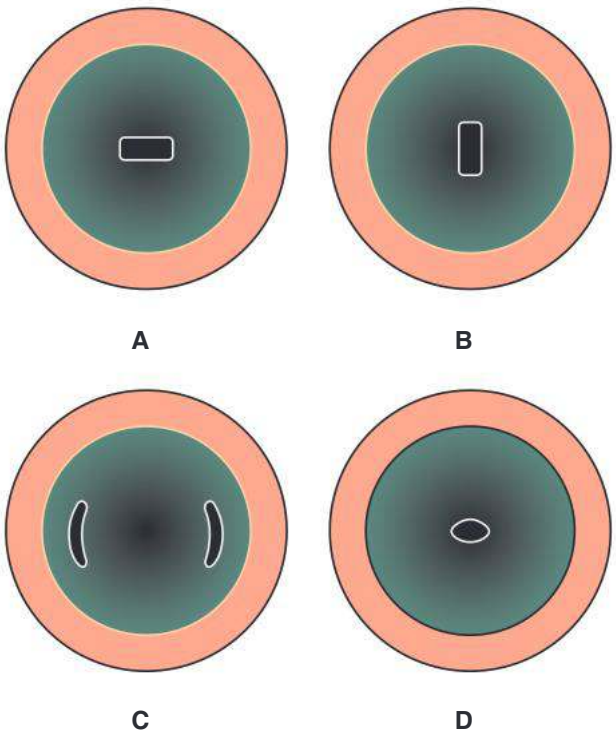


Fig. 8.4 *Fluorescein pattern in an astigmatic cornea: A and B, ideal fits; C, steep fit; D, flat fit. Dark areas indicate areas of touch.*

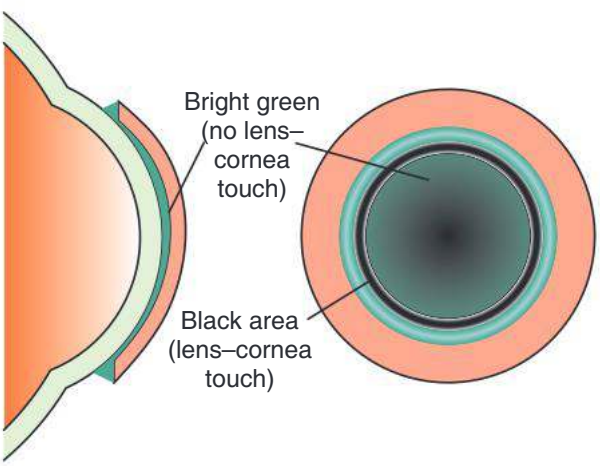


Fig. 8.5 *Fluorescein pattern in a steep fit contact lens on a spherical cornea.*

- Fluorescein pattern in a spherical cornea will show pooling of tear fluid in the central position (bright green central area), a bright green peripheral band and a broad black intermediate area indicating a heavy touch under the intermediate zone of the contact lens (Fig. 8.5). On blinking, there will be no or minimal exchange of tear fluid trapped under the lens because of the sealing effect of the lens over the cornea. A steeply fitted lens on an astigmatic cornea will show a black crescent under the intermediate zone and bright green centre and periphery (Fig. 8.4C).

  A lens fitted steeper will usually give rise to burning sensation, corneal oedema and hazy vision.

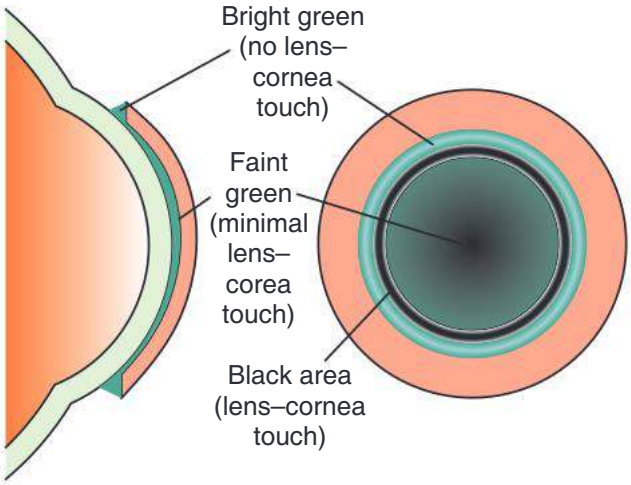


Fig. 8.6 *Fluorescein pattern in an ideal fit contact lens over a spherical cornea.*

iii. ***Ideal base curve.*** With an ideal base curve of the lens over the spherical cornea, one would see apical appearance, mid-peripheral touch and peripheral clearance; i.e. the periphery appears bright green and the central area appears faintly (Fig. 8.6).

In an ideal fit on an astigmatic cornea, there will be a black band in the central apical zone over the flattest corneal meridian, a faint green pool over the steeper meridian and a darker band over the intermediate zone; the periphery will be bright green (Fig. 8.4A and B).

3. Finalization of the overall diameter. The diameter of the lens initially selected may sometimes have to be changed with the change in base curve, as the diameter of the lens and the base curve have a direct correlation. A large lens should have flat radius to produce the same effect as that of a small lens with steep radius. One millimetre change in diameter is equivalent to 0.01 mm change in radius.

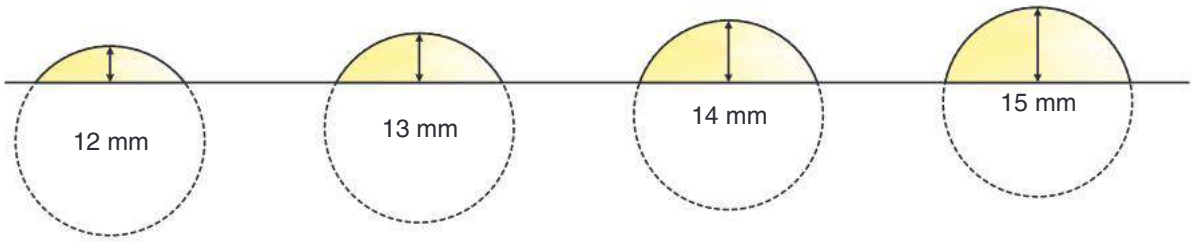


Fig. 8.7 *Lenses having same radii of curvature with different diameters have different sagittal depths.*

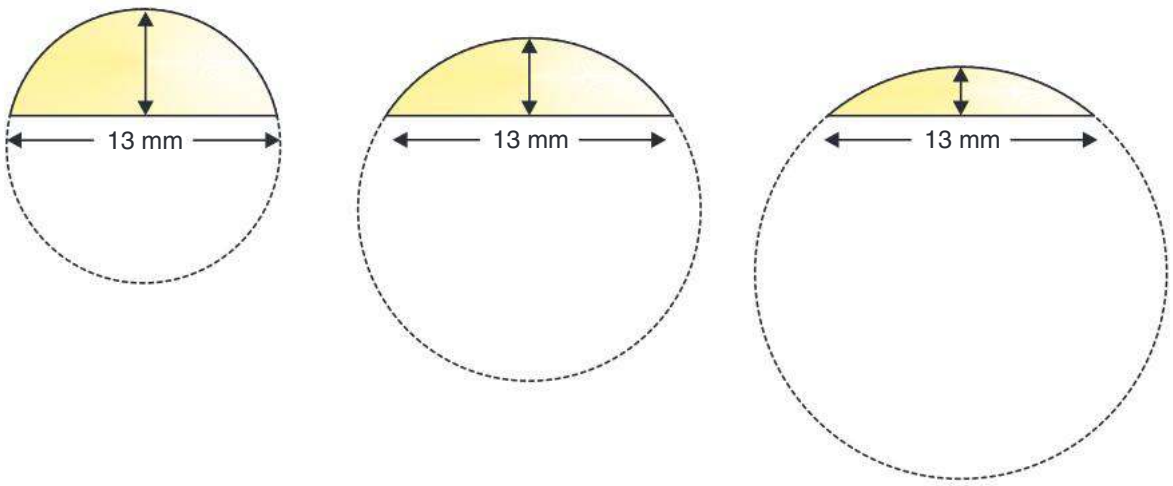


Fig. 8.8 *Lenses having same diameter with different sagittal depths have different radii of curvature.*

Lenses having the same radii of curvature with two different diameters will have different sagittal depths (Fig. 8.7). On the other hand, lenses having same diameter but different sagittal depths will have different radii of curvature (Fig. 8.8).

4. Finalization of the power. Once a lens of satisfactory fit has been found, the power to be ordered should be finalized. It may be advisable to carry out an over-refraction, particularly so, if the trial lens is very different from the patient's refraction. While finalizing the contact lens power from the lenses in trial frame, a due consideration should be given to effectivity correction.

POST-FITTING PATIENT MANAGEMENT

■ ORDERING RIGID LENSES

Once the parameters of the ideal fitting trial lens are finalized, the rigid lenses are usually ordered from a manufacturer's known style, specifying following variables:

- Base curve radius (e.g. 7.5 mm),
- Optic zone diameter (e.g. 7.0 mm),
- First back peripheral zone (e.g. up to 8.5 mm extension),
- First peripheral curve radius (e.g. 8.3 mm),
- Second peripheral curve radius (e.g. 9.0 mm),
- Overall diameter of the lens (e.g. 9.5 mm) and
- Power of the lens (e.g. –3.0 DS).

The *prescription* for a lens with above parameters is written as follows:

7.5: 7.00/8.30: 8.50/9.00: 9.5, power –3 DS.

■ EXAMINATION OF THE ORDERED LENS

The ordered contact lenses, when received from the manufacturer, should be examined meticulously before these are inserted into the patient's eye. Ideally, the examination of the

finished contact lenses received from the laboratory should include the following:

- *Overall diameter* should be measured with the diameter gauge.
- *Central lens thickness* should be measured with lens thickness gauge.
- *Base curve radius* should be measured using a radioscope.
- *Lens power* should be measured with a lensmeter.
- *Lens edges, peripheral curves* and lens quality should be inspected using a tubelight or a shadow graph.

EVALUATION OF THE ORDERED LENS FIT

On examination, if the finished contact lenses are found to be as per specifications, these should be inserted into the patient's eyes and after an adaptation period, the lens fit should be evaluated following the same procedure as described for evaluation of the trial lenses (page 272). In summary, to evaluate the rigid lens fit, following points need to be noted:

1. *Lens position*
   - Ideal fit – well-centred and
   - Anomalous fit – lens may ride high or low (page 272).
2. *Lens movements*
   - Ideal fit – adequate movement is marked by 1–2 mm of smooth vertical or lateral excursion on lateral or downward gaze.
   - Flat fit – excessive lens movement.
   - Steep fit – little or no lens movement.
3. *Fluorescein pattern* is the most important test for evaluation of a rigid contact lens. The typical fluorescein pattern seen in ideal fit, flat fit and steep fit are described on pages 273 and 274 (Figs 8.3–8.6).
4. *Quality of vision*. Vision should match the best corrected vision with glasses or should be better and stable throughout the blink cycle and not vary due to lens movement.
   - Over-refraction can reveal under-correction or over-correction of contact lens power.
5. *Comfort* should be evaluated after following the recommended wearing schedule (see rigid lens problem, page 280).
6. *Physiological response.* With an ideal fit, the corneal metabolism is not disturbed. Anomalous fit may reveal corneal disturbances in the form of desiccation, erosion and oedema.

EDUCATING THE PATIENT

After the lens fit is found satisfactory, the patient should be taught about the care of lenses and the technique of insertion, removal and recentration of the lenses, and also about the hygiene and wearing schedule.

CARE OF CONTACT LENSES

Careful and meticulous attention to contact lens hygiene should be paid, as the risks associated with their use are of paramount significance. The patient should be given the following instructions:

1. Hands should be thoroughly cleaned before handling the contact lenses.
2. Treat lenses carefully; never apply pressure. Remember they are only one-fifth of a millimetre thick, i.e. less than one-hundredth of an inch.
3. Lenses must be spotlessly cleaned before insertion.
4. Always clean lenses upon removal, before placing into the case – with concave (hollow) side facing upwards.
5. Use antiseptic wetting agent or cold water for cleaning (avoid cleaning under running tap water). Contact lenses should be disinfected with appropriate system. PMMA and RGP lenses are treated with chemical disinfection only, as these cannot withstand heating. Multi-purpose solutions are available in the market which can be used for soaking, cleaning, disinfecting and rinsing of contact lenses.
6. Before insertion, the contact lenses should be rinsed again with sterile saline.
7. Patients should not sleep (except with extended wear lenses [EWLs]) or swim with their contact lenses on.

IDENTIFICATION OF RIGHT AND LEFT LENS

Rigid lens has an 'R' engraved at periphery for the right eye, where there is a difference in specification between the two eyes.

INSERTION AND REMOVAL OF CONTACT LENSES

After teaching about care and handling of contact lenses, it is very important to train the patient in insertion and removal of contact lenses.

Insertion

Technique 1 (Fig. 8.9A). Place the wet lens hollow side up on the end of the middle finger of your right hand just above and towards the middle of the margin of your right lower lid. Pull your lower lid down and hold it firmly against the bone below it. Bring your left hand over your head and place the forefinger or middle finger just below and towards the middle of the margin of your right upper lid. Pull your upper lid up and hold it firmly against the bone above it. Insert the lens. To insert the lens on your left eye, your hands may be used the same way or you may alternate your hands.

Technique 2 (Fig. 8.9B). Spread the forefinger and middle finger of your right hand in the form of an open pair of scissors. Hold the right lower lid down with the middle finger and hold the right upper lid up with the forefinger. Place the wet lens with its concave or hollow side up on the forefinger of your left hand. This finger is held relatively parallel to the ground and the lens is inserted. To insert the lens on your left eye, your hand may be used the same way or you may alternate your hands.

Fig. 8.9 *Technique of contact lens insertion.*

Removal

Technique 1 (Fig. 8.10A). Bend over so that your head is relatively parallel to the floor. Cup your left hand under your right eye. Place the thumb, index or forefinger of your right hand at the outer corner of your eyelids. Look straight down and open both eyes wide. Pull the finger in an upward and outward direction. If the lens does not come out, it may be necessary to blink simultaneously while pulling. The opposite hands are used for the left eye.

Technique 2 (Fig. 8.10B). Bend over so that your head is relatively parallel to the floor. Place the middle finger of your right hand along the right lower lid margin and the forefinger of your right hand along the right upper lid margin. Cup your left hand under your right eye to catch the lens. Draw your lids away from the lens, hold them tightly against the eye and press them tightly together while looking straight ahead. An alternative method is to pull both lids to the side with the forefinger on the

Fig. 8.10 *Technique of contact lens removal.*

lower lid and the middle finger on the upper lid, or with the thumb on the lower lid and the forefinger on the upper lid. The opposite hands are used for the left eye.

Recentration of the Lenses

1. *When the lens is in the outer corner.* Pull your lids apart and locate the lens. Give pressure at the junction of the two lids and look in the direction of the lens. Now look straight, release the pressure, look down and leave the lower lid and the upper lid.

2. *When the lens is in the inner corner.* Pull your lids apart and locate the lens. Look in the direction of the lens, look straight, look down and leave the lower lid first and then the upper lid.

3. *When the lens is under the lower lid.* Pull your lids apart and locate the lens. With the help of the lower lid, try to move the lens in such a manner that the lower edge of the lens and the outer edge of the lower lid come in contact. Once the lens moves, look in the direction of the lens, look straight, look down and then leave the lids, leaving the lower lid first.

4. *When the lens is under the upper lid.* Pull the upper lid up. Holding it firmly, look down and give a few horizontal jerks. After a few jerks, look straight, look down and then leave the lids, leaving the lower lid first.

In all the cases, if the lens does not come back into position in one try, make a second attempt.

NORMAL WEARING SCHEDULES

- The patient should not wear lenses during the first 2 days but should frequently practise insertion and removal until reasonably proficient.
- It is essential to build up tolerance gradually.
- The patient should wear lenses 2 h a day for 2 days, preferably in the morning. Increase wearing time to 3 h for 2 days and then continue to add 1 h every third day in this manner for 2 weeks. From then onwards, add an extra hour every day until all-day tolerance is achieved. This will take about 3 weeks, if the timing is followed precisely.

Wearing schedule for a rigid lens is as shown in Table 8.2.

GENERAL ADVICE

- The patient should be advised not to pull lids or rub eyes as lenses may otherwise be pushed on the sclera.
- If blurring or misting sets in and persists, remove lenses, clean and reinsert.
- Perseverance is essential. It is important to keep to the wearing schedule as closely as possible. Initial reaction to lenses will differ widely and no undue emphasis need be placed on variation experienced for the first 1–2 months until the eyes have become fully adapted.

Table 8.2 *The wearing schedule for rigid contact lenses*

Day	Wearing time (h)
2nd	Practice insertion and removal
3rd	2
4th	2
5th	3
6th	3
7th	4
8th	4
9th	4
10th	5
11th	5
12th	5
13th	6
14th	6
15th	6
16th	7
17th	7
18th	7
19th	8
20th	9
21st	10
22nd	11
23rd	12
24th	13
25th	14

- Use germicidal soaking solution, if so advised.
- Swimming with corneal lenses may involve risk of loss.
- Progress report and check-up in 1 month – annual eye examinations are strongly recommended thereafter.
- The patient should be advised to always feel free to seek advice in case of doubt or if experiencing problems.

POST-FIT FOLLOW-UP

For a successful, comfortable and complication-free contact lens wearing, regular follow-up examination is most essential. The follow-up visits may be timed as follows:

- First visit after 24 h
- Second visit after 72 h
- Third visit after a week
- Fourth visit after a month
- Fifth visit after 3 months
- Sixth visit after 6 months
- Subsequent visits every year

The patients should also be instructed to report as and when they have any problem. It is better to plan a routine follow-up visit at the end of wearing period. Following routine may be adopted during each follow-up visit:

1. ***History.*** Enquiries should be made about the visual as well as the non-visual symptoms experienced by the patient. It is important to differentiate between the adaptive and abnormal symptoms; the former usually disappear after a fortnight or so, while the latter may persist and rarely may continue insidiously.
2. ***Visual acuity*** should be checked while the lenses are still in position. If the visual acuity is subnormal, pinhole test and over-refraction should be performed.
3. ***General inspection*** should be carried out to note the following:
   - Face turn or head tilt, if any,
   - Blinking note,
   - Lid swelling and
   - Congestion or redness of the bulbar conjunctiva.

4. ***Biomicroscopic examination*** should then be carried out, first with lenses in situ and then after having been removed. Biomicroscopic examination should include detailed examination of the contact lens, conjunctiva and cornea.

RIGID LENS PROBLEMS

Rigid lens problems which may be complained and/or noted during the follow-up visits include the following:

1. ***Blurred vision at the distance***

- In case the blurring of vision occurs early, the probable causes could be excessive watering, incorrect lens power or residual astigmatism, scratched lens and poor optical quality of the lens. These can be rectified by changing the lens or correcting the power. Residual astigmatism can be corrected by toric lenses or additional spectacle correction.
- *Warped lens* and corneal oedema are the causes of late blurring of the distant vision. Warped lens will have to be replaced.
- *Corneal oedema* can be physiological when the remedy is to flatten the lens or decrease the diameter or it can be mechanical when lenses should be made steeper or their diameter increased.
- *Oily or mucus deposits* can result in both early and late blurring of vision. These oily deposits are secretions from glands of lids or by the use of cosmetics. Such patient is asked to blink completely and clean the lenses properly.

2. ***Blurred vision for near***; i.e. with the contact lens, distance vision is clear but near vision is blurred. If it occurs in patients below the presbyopic age, blurring of near vision can be caused by defective power, decentred lens, decreased fluid interchange resulting in decreased movement of the lens and convergence insufficiency. Lens should be changed in case of defective power and decentred lens and the patient should be asked to blink frequently, if decreased fluid interchange is suspected. Convergence exercises can be advised to those with convergence insufficiency. In addition, a myope who is an early presbyope requires more accommodative effort with contact lens than with spectacles.

If the patient is of presbyopic age, then he or she is advised to wear additional glasses for near or bifocal contact lenses.

3. ***Blurred vision when contact lenses are removed and spectacles are worn.*** Realistically, this problem (of spectacle blur) is quite common and usually it should not last for more than 1 h after 12 h of wear. But when it is more than that, it should be treated accordingly because these patients are ideal candidates for overwearing syndrome.

Causes of spectacle blur:

- *Corneal oedema.* Commonest cause of spectacle blur is corneal oedema due to tight-fitting lens. In this case, fitting relationship should be changed.
- *Induced curvature changes.* Spectacle blur can also be because of induced curvature change, which when significant calls for the change of lenses. Induced curvature change most of the times results, if the lens is flatter. This may not be significant for those who have discarded their spectacles and are wholly dependent on contact lens for all their needs. This problem becomes very acute when the patients have lost or misplaced their lenses or have developed infection in eyes. Then they find it difficult to use their old glasses and new prescription of glasses can be given only after 2–6 weeks of discontinuation of contact lens.

4. ***Inevitable awareness of presence of lens.*** State of awareness of the lens is only relative and is more so during the adaptation period. Usual reason for this is that lens edges have been damaged or the *base curve* is too flat. It can also be due to thick, large or scratched lens. It calls for the change of the lens. It can sometimes be because of foreign matter on the lens or low-grade conjunctivitis which would increase the sensitivity to the lens. These would be corrected on their own merits.

5. ***Feeling of burn, hot and scratchy eyes.***
   - If it occurs immediately on insertion, then it is because of improperly cleaned lenses or contaminated cleaning solution.
   - But if it occurs about half an hour after the insertion, as is usually the case, then it is due to too tight a lens. In this case, flatter or smaller lens is given.
   - Other causes for this could be insufficient tears, inadequate blinking, exposure to poor environment like smoke and dust, low-grade conjunctivitis and eyestrain.

6. ***Feeling of lenses touching eyelids.*** It can occur when there is excessive movement of the lens as would be the case in small lenses or flat lenses especially when posterior curve is flatter. These can be remedied by proper fitting of the lens.

It would also be encountered when there is improper edge (too thick or too sharp) or when there is poor positioning of the lens. These should be corrected accordingly.

7. ***Uncomfortable feeling in the morning.*** It can be due to normal initial wearing reaction during adaptation period but is also encountered when the eyes are not cleaned properly or lenses are improperly handled (with dirty hands) or with use of irritating contact lens solution. Sometimes it is due to the residual corneal oedema or when too tight lenses are prescribed.

Occasionally, slight conjunctival congestion which is usually present in the morning may give rise to this symptom. In this case, eyes should be washed with cold water and lens worn as late as possible.

8. ***Tilting back of head*** when the movement of the lens is excessive (e.g. flat lens). The patient tends to tilt the head backwards so that more of the upper eyelid covers the lens and steadies it on the eyes.

Sometimes it is due to poorly finished edges (like excessive peripheral clearance) or due to the sensitive lids. These can be corrected by proper designing of the lens. Occasionally, head tilt can be because of poor pupil coverage by the optical zone or due to infrequent blinking. The patient should be motivated to look up during initial adaptation period.

9. ***Excessive blinking.*** This could well be an initial wearing reaction during adaptation, which is acceptable. But if it is excessive, the patient may be asked to look up during adaptive period.

Commonly, small lens produces excessive blinking which in turn helps to maintain the lens in the centre of the cornea. It can also be because of a foreign particle on the lens. Furthermore, fogging of the lens due to scratches or mucus deposits may produce frequent blinking or it could only be psychological.

10. ***Milky fluid coating over lenses in the morning.*** Such fluid on the lens could be a normal secretion consisting of mucus, sebum, proteins and epithelial cells or abnormal secretion (exudation) in cases of allergic conjunctivitis and low-grade infections of the eyes. For this, appropriate antibiotics and/or anti-allergic drugs should be prescribed along with proper cleaning of the lens. Such patients should keep the lens in wetting solutions.

11. ***Swelling of lids in the evening after all-day wear.*** Mild swelling of the lower lids may occur which is acceptable during adaptation. If it persists, it is usually due to the lens mechanically irritating the lower lid margin in between the blinks, usually resulting from loose lenses. If it is present in both the lids, it is due to tight lens. Poor edge finish will add to the factors mentioned. It is remedied by proper fitting of the lenses and readjustment of wearing schedule.

12. ***Difficulty in removing the lens.*** Firstly, the patient's lens removal technique may be improper. Secondly, lids are too lax as in aged or eyes are small or the posterior margin of the lids is rounded as in trachoma. Alternatively, the lens may be a tight fit. So, the patient should be taught alternative methods of lens removal. When the lens is tight, a flatter one should be prescribed.

13. ***Lenses fall out or too frequently get on to the white of the eye.*** The cause for this lies either in the lens or in the eyes. *Eye causes*: Prominent eyes, high astigmatism, excessive watering due to any cause. *Lens causes:* Loose lens, tight lens, small pupillary lens, thick lenses and single-cut lens for aphakia.

14. ***Discomfort in eye movements.*** Discomfort may be felt in eye movements during adaptation, but if it occurs later, loose-fitting lens or poor edge finish are to be blamed in most cases. Occasionally, it can be because of poor lens position. For these defects, appropriate remedial measures are instituted.

15. ***Persisting photophobia*** can be on account of too tight or too loose a lens, either of which will produce central corneal oedema. This oedema may be low grade and hence difficult to detect. If all is found normal, the patient is advised to wear sunglasses as in high minus contact lenses.

16. ***Fluctuating vision.*** Vision may fluctuate during adaptation period but if it occurs later, excessive lacrimation or small lens may be the responsible factors. Each of these should be taken care of on their own merits.

17. ***Better vision with change in head posture.*** It may be due to poor centration. If poor centration of lenses is found, then lenses with better centration should be given. Alternatively, this could be due to excessive movement of the lens when variable head postures are adopted to stabilize the lens.

18. ***Watering.*** The patient may complain that there is always water in the eyes with contact lens. Mechanical irritation on account of either poor edge finish or scratches on the surface of the lens is an important cause for such a complaint. Poor fluid interchange leading to corneal oedema, residual refractive error or inadequate blinking may also be responsible. It should be kept in mind that the patient has this complaint very often during adaptation period, and it also accompanies cold and sinusitis.

19. ***Pain immediately after putting lenses.*** Important factors causing pain immediately on insertion of lenses are poor technique of insertion, foreign substance on the back of the lens, improper edge, dry lenses and improper wetting solution.

20. ***Pain after a few hours of wear.*** It is probably caused by the induced corneal oedema or corneal abrasion due to tight lens fit. In these cases, cornea should be stained with fluorescein dye and the state of the cornea checked. Remedy lies in re-evaluating the lens fit after the cornea has returned to normal and then appropriate alterations should be made.

21. ***Severe pain 3–4 h after removal of lenses.*** It is a clear feature of overwear syndrome. Initially due to dullness of corneal sensations while wearing the lenses, the patient does not feel it but it occurs after 3–4 h of removal when corneal sensation is regained. It is due to tight lens fit, leading on to corneal oedema or corneal abrasion. The treatment should be as that for corneal abrasion, and a flatter lens is advised after 2 weeks.

22. ***Feeling of dryness.*** Such a feeling can be due to inadequate lacrimal secretion, poor blinking, dry hot environment and tight-fitting lenses. These can be remedied accordingly along with the use of artificial-tear eyedrop twice a day.

SCLERAL RIGID GAS-PERMEABLE LENSES

Scleral RGP lenses are large diameter lenses which rest on the sclera and create a tear fluid vault over the cornea. The new generation of scleral RGP lenses are made from a highly oxygen-permeable polymer, fluorosilicone acrylate, resulting in improved ocular health, increased wearing time and easier lens fitting.

TYPES AND INDICATIONS

Types of scleral RGP lenses available are as follows (Fig. 8.11):

- *Limbal lenses.* Diameter: 11.8–12.5 mm
- *Corneoscleral lenses.* Diameter: 14.5 mm
- *Miniscleral lenses.* Diameter: 16 mm
- *Scleral lenses.* Diameter: >19 mm

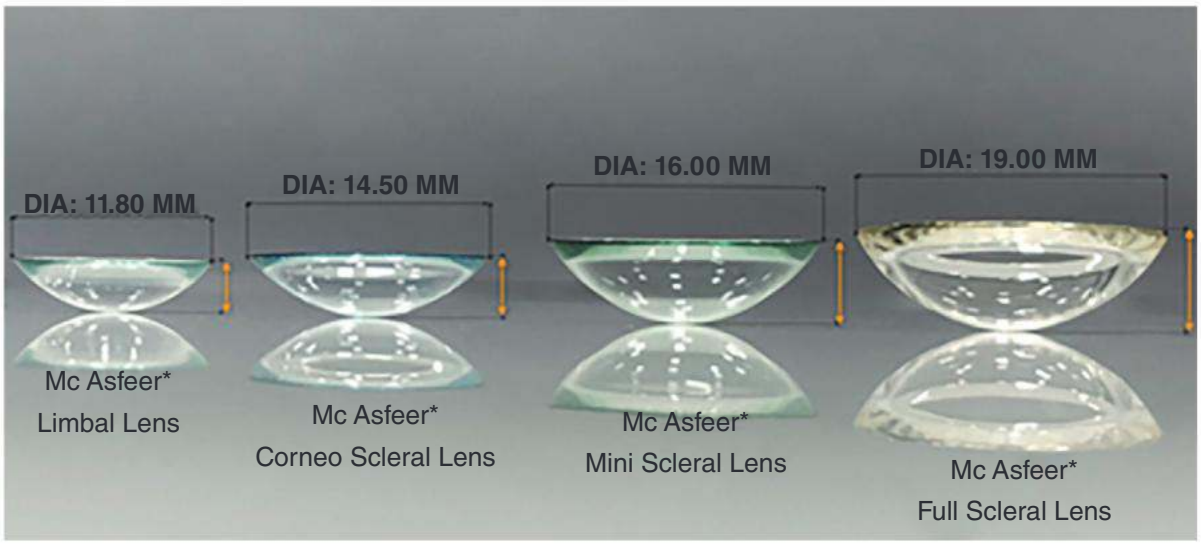


Fig. 8.11 *Types of scleral lenses: A, Limbal lens: B, Corneo-scleral lens; C, Mini- scleral lens; D, Full scleral lens.*

Indications include the following:

1. *Patients with irregular or abnormal corneal topography:*
   - High astigmatism due to keratoconus and other causes of primary or secondary corneal ectasia including post-corneal transplantation.
   - Traumatized eye with mechanical trauma or chemical or thermal burns.
   - Post-refractive surgery ectasia and irregularity of cornea.
   - Aniridia and microphthalmos.
   - Neurotropic keratitis and pellucid degeneration.
2. *Patients with high refractive errors with following problems:*
   - Centration difficulty.
   - Intolerance to corneal RGP or hydrogel lenses.
3. *Therapeutic applications of scleral RGP lenses include:*
   - *Severe dry eye conditions* such as cicatrizing pemphigoid, Sjögren syndrome and Stevens–Johnson syndrome.
   - *Lagophthalmos* due to poor lid closure or absence of lid closure.
   - *Intractable trichiasis* and lid margin keratinization.

ADVANTAGES AND DISADVANTAGES

Advantages of scleral RGP lenses include:
- Provides best visual acuity for irregular corneas,
- Comfort similar or better to soft contact lenses,
- Treats severe dry eye and cornea issues,
- Unlimited parameters/shape and
- Best/only treatment for some conditions.

Note: Because of the above advantages, the use of scleral RGP lenses is increasing in general.

Disadvantages of scleral RGP lenses are as follows:
- High cost,
- Fitting time consuming/more difficult and
- Insertion and removal challenges.

SCLERAL RGP DESIGN

Essential features of scleral RGP lens design are as follows (Fig. 8.12):

- Large diameter: 14 mm to 20+ mm.
- Much larger than corneal RGP.
- Designed to completely vault cornea and limbal area (Fig. 8.12A).
- Central vault limited to 200–300 µm is ideal.

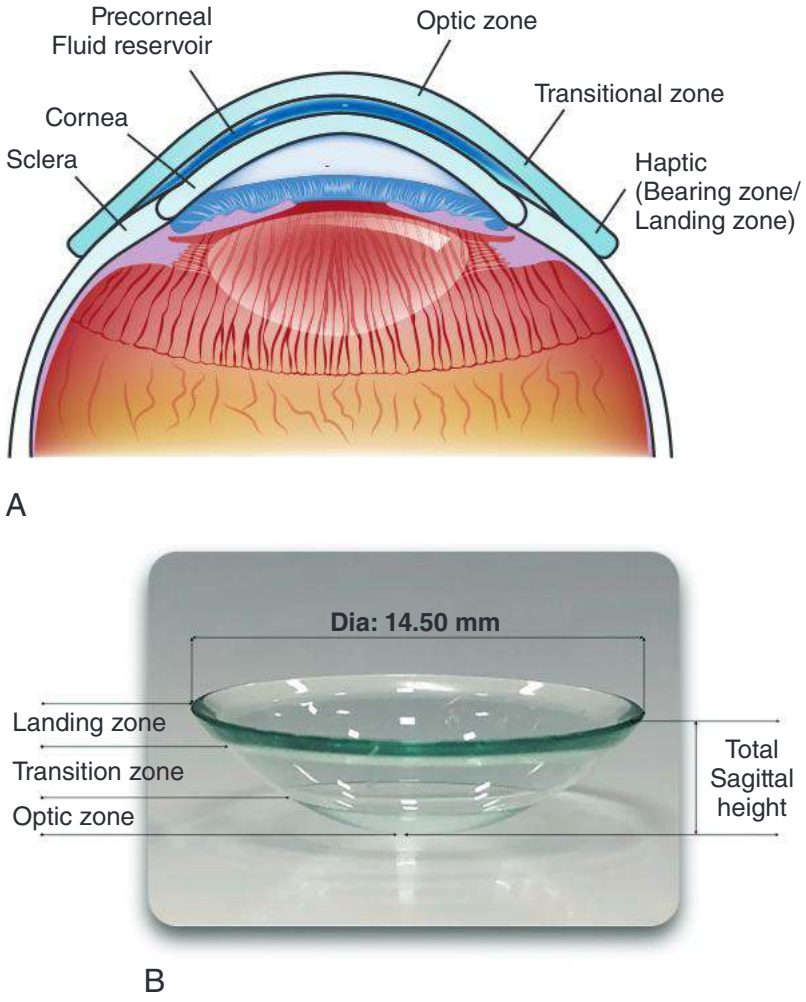


Fig. 8.12 *Scleral RGP lenses: A, Design, B, Parts/Zones.*

- Optic section with sodium fluorescein is used to evaluate vault.
- Vault is increased to eliminate any lens-cornea touch.
- Must wait 30 min with lens on eye for evaluation.
- Ideal design has peripheral curve parallel to the scleral contour.
- Small vessels should not be pinched by landing zone–peripheral curves.
- Try to avoid 'impingement'.

Parts (zones) of scleral lens

There are three main components of scleral lens (Fig. 8.12B):

1. ***Optic zone***. The optical zone is the centremost zone of the scleral lens that uses radii and lens power to produce the desired optical effect, vaulting the cornea and protecting its optical function.

2. ***Transition zone***. The transition zone between the optical zone and the landing zone of a scleral lens is also known as the mid-peripheral, intermediate or limbal zone. The transition zone raises and lowers the optical zone in relation to the eye and it is also required for limbal stem cell protection. This zone is significant as it determines the sagittal height of the lens.

3. ***Landing zone***. The landing zone refers to the area of the lens that rests on the anterior ocular surface. Haptic zone is another name for landing zone. The term 'haptic' comes from a Greek word that means 'to fasten' or 'to attach'.

FINALIZING AND ORDERING SCLERAL LENS

Steps include:

- Base curve selection
- Finalizing power of lens
- Evaluation of trial lens fit
- Ordering a scleral lens.

Base Curve Selection Based on Corneal Condition

The selection of the base curves is categorized into five main types:

1. *Very flat:* If the corneal astigmatism is severe, begin the trial with a flat base curve of 7.80.
2. *Normal*: Begin a trial with a common base curve of 7.60 for a normal corneal patient or if they have been diagnosed with early keratoconus, post-refractive surgery, corneal dystrophy, post-ulcer, dry eye, traumatic corneal changes or any epithelial defect.
3. *Moderate*: We should begin a trial with a base curve of 7.40 for patients with ectasia, mild keratoconus, pellucid marginal corneal degeneration (PMCD), post-C3R and post-PK.
4. *Steep*: 7.10^{6} Patients with moderate ectasia, moderate keratoconus, advanced PMCD or post-PK have been assigned a steep base curve.
5. *Very steep*: If the eye is diagnosed with high ectasia, advanced keratoconus or keratoglobus, a trial with the steeper base curve of 6.60 should be initiated.

Finalizing Power of the Lens

The trial lens's power should be calculated using refraction. The appropriate formula can be used to calculate the vertex distance correction. Only spherical power can be incorporated into a scleral lens. If the astigmatism is corneal, the scleral lens can correct it. If the astigmatism is lenticular, it can be treated with cylindrical spectacles over spherical contact lens.

Evaluation of the Trial Lens Fit

The chosen trial lens is inserted into the eye. To evaluate the vault clearance, fill the optic section with saline and a drop of sodium fluorescein while inserting the scleral lens.

Slit-lamp biomicroscopy. Evaluation of trial lens fit is done in following steps:

- Vault clearance
- Over-refraction
- Landing zone fit
- Movement
- Finalizing lens.

Ordering Scleral Lens

Once the parameters of the ideal fitting lens have been determined, it should be ordered in the form of: L3P | 7.50 | 4.13 | –3.00 | 14.50, where:

- L3 denotes the landing zone of the lens and P indicates the base curve.
- 7.50 is the lens's base curvature.
- 4.13 describes the sagittal depth height.
- –3.00 is the power of the lens.
- 14.50 denotes the overall diameter of the prescribed lens.

POST-FITTING PATIENT MANAGEMENT

Evaluation of Lens Fit

The ordered lens should be inserted into the patient's eye and after an adjustment period, the lens fit should be evaluated according to the guidelines:

- First, the visual acuity for both distance and near should be checked, as well as the clarity of vision in both room and daylight. If cylindrical power requirements exist, prescribe spectacles over contact lenses.
- Following that, the central corneal vault clearance and final lens limbal clearance should be checked.
- Following the recommended wearing time, the patient's comfort should be reviewed.
- Lens movement should be evaluated accordingly.
- The tear debris should be examined under slit-lamp biomicroscopy after 4–6 h of wearing time.

Educating the Patient

The most important aspect of successful lens wear is dispensing. We must keep the healthy

fluid reservoir in good condition. The user should be given adequate time to educate and should be required to practice multiple times.

Handling the scleral lens:

- Cleanliness is the first and most important aspect of proper lens care.
- Fingernails should be short and neat.
- Wash your hands thoroughly with a mild soap and dry with a lint-free towel or let them air dry before handling the lens.
- Avoid using soap that contains cold cream, moisturizers, lanolin or perfumes.
- Avoid use of oily cosmetics, waterproof eye liner etc., prior to handling scleral lens.
  - These substances can adhere to the lens surface causing dryness and visual discomfort.
  - Cosmetics may spoil the tear reservoir on the cornea which may affect lens performance and reduce the wearing schedule.
    - If the lens does not have different handling tints, then it is recommended to develop the habit to start with a single lens first.
    - Open only one compartment of your lens case at a time (better eye lens first) to avoid lens swapping.
    - Open the lens case (one side only) and empty it onto the palm of your non-dominant hand.
    - Check and make sure that it is free of any deep scratch, crack or chipped edges.
    - In case of similar handling tints of your lens, it is recommended to check the marking provided on the lens surface to distinguish the appropriate lens.

INSERTION, REMOVAL AND CLEANING

Insertion and removal tips for scleral RGP lenses include:

- Must use preservative-free 0.9% sodium chloride.
- Must have face parallel to floor to maintain bowl volume.
- Must insert without bubbles.
- Insert with plunger, fingers or another method (Fig. 8.13A).

A

B

Fig. 8.13 *A, Insertion with either large plunger or fingers, B, Removal of scleral RGP lenses with plunger (i) and with finger lid pressure (ii).*

- Removal is performed with small plunger or finger-lid pressure (Fig. 8.13B).

Cleaning and disinfection: scleral lenses are cleaned and disinfected with standard RGP solutions.

Wearing Schedule

The most important factor in achieving comfortable wearing hours is the cleanliness and hygiene of the tear reservoir. Even though the lens material is highly breathable, it is recommended that patient should not wear the lenses for more than 2 h at a time at first to ensure a hygienic reservoir. Despite being one of the most comfortable lens geometries, the scleral lens should be worn as directed.

- For the first 5 days, gradually increase the wear time from 2 to 5 h at 1 h intervals.
- After 5 days of successful wear and increasing confidence in wearing the lens without any lid interaction or air bubble, the wearing time can be increased to 6 h per day. Users can gradually increase it to 10–12 h after 6–8 months.

SOFT (HYDROGEL) CONTACT LENSES

FITTING OF SOFT CONTACT LENSES

The initial steps of soft contact lens fitting are identical to those described for fitting of a rigid contact lens. However, because of their importance, they will be repeated again with special reference to soft lenses. The final steps of soft contact lens fitting vary with the individual's choice out of the available manufacturer's series. However, the basic principles do remain the same here.

The main steps of soft contact lens fitting are described below.

INITIAL PATIENT WORK-UP

1. ***History.*** A meticulous history should be taken – as described in rigid contact lens fitting – basically to review the patient selection criteria. A special importance should be given to the following:

- The patient's emotional status and motivation to wear contact lenses.
- History pertaining to medical problems including allergic disorders.
- History of previous contact lens use and problems faced if any with special reference to allergies and reactions to contact lens solutions.

2. ***General ocular examination.*** A complete general ocular examination of anterior and posterior segments including slit-lamp biomicroscopy and ophthalmoscopy should be carried out to note any abnormality. Special care should be taken to make a note about following points.

- *Eyeball* is abnormally prominent or sunken.
- *Lids* are abnormally tight or loose.
- *Cornea* should be meticulously examined for any neovascularization, infiltrates, opacities, etc.
- *Tear film adequacy* should be adjudged.
- *Conjunctiva* should be evaluated for presence of abnormal hyperaemia, follicles, papillae and concretion, etc.

3. ***Refraction*** should be performed meticulously, and the resultant spectacle refraction should be expressed in minus cylinder. Vertex distance must be noted for effectivity consideration.

4. ***Keratometry*** should be performed and readings in millimetre noted (for details see page 175). The flattest reading of the two principal meridians is labelled a K-reading.

5. ***Corneal diameter*** may be measured with the help of a transparent rule. For all practical purposes, the horizontal visible iris diameter (HVID) is noted to denote the corneal diameter.

TRIAL LENS FITTING TECHNIQUE

Nowadays, recommendations for soft contact lens fitting are usually provided in brochures by the manufacturers for their particular series. So the contact lens practitioner needs to be familiar with the commonly available soft lens series in the local market. Most of the manufacturers provide a maximum of three choices of base curve and overall diameter and the choice is to be made by the practitioner. The basic principles involved in making the choices are discussed in the following.

SELECTING THE INITIAL TRIAL LENS

A trial lens with following parameters should be selected initially:

1. ***Overall diameter*** chosen is usually 1.5–2.0 mm larger than the HVID, but this figure is not absolute and may be greater, if the limbal sulcus is not very pronounced.

2. ***Base curve.*** Initial base curve chosen is flatter than K, and how much flatter depends upon the overall diameter chosen and the water content of the lens chosen. Following guidelines may be useful:

- For a lens with overall diameter of 13.0 mm, a base curve 0.3 mm flatter than flattest K may be chosen. For every 0.5 mm further increase in diameter, a 0.3 mm increase in flattening should be made.
- High water content lens needs slight steeper fitting than low water content lenses. For example, if a low water content lens of

diameter 14 mm may require base curve flatter by 1 mm than the flattest K-reading, then a high water content lens of same diameter may need to be flatter, say, by 0.8 mm.

3. ***Power of the lens.*** To determine the power of the initial lens to be chosen, the spectacle refraction is corrected for vertex distance. The spherical equivalent of this gives the contact lens power. If the spectacle cylindrical power is more than 1.5 D, then toric soft lenses are required or else they may not be used.

EVALUATION OF THE TRIAL LENS FIT

Having determined all the parameters, the sterilized and clean appropriate lens is inserted into the eye. The patient is asked to wait for 20 min for a low water content lens and 10 min for a high water content lens so that the lens hydrates properly and settles in the eye environment. Once the lenses are in the eyes and initial reaction has subsided, the 'evaluation of the lens fitting' with respect to its various parameters may be studied.

1. ***Evaluation of the base curve of the lens***. It is important to note that fluorescein is never used in soft lens fitting evaluation. It is carried out by taking the following factors into consideration:

a. *Movement of the lens over the cornea:*
- A lens with *ideal base curve* should not move more than 0.5–1.0 mm with the upward or downward movement of the eyeball or with each blink.
- A *flat or loose fit lens* moves rapidly over the cornea.
- A *steep or tight fit* lens moves very little or does not move at all with the movement of the eyeball. Presence of air bubbles under the lens further strengthens the diagnosis of steep fit.

b. *Centring of the lens over the cornea:*
- A properly fitted lens will centre well, extending symmetrically over the limbus around.
- A lens not centring well indicates an improper base curve.

c. *Effect of blinking on the clarity of visual acuity:*
- In an *ideal fit lens*, the vision remains equally clear before and after blinking.
- In a patient with *steep fit lens*, the vision clears immediately after the blinking.
- In a patient with *flat fit lens*, the vision blurs on blinking.

d. *Compression of blood vessels.* Examination of conjunctival blood vessels by slit-lamp is quite useful in fit evaluation:
- Compression of blood vessels by the lens edge indicates either a steep fit or a thick lens edge.
- Indentation of the sclera occurs after a prolonged wearing of steep lens.

e. *Effect of blinking on retinoscopic reflex:*
- In *ideal fit lens*, the retinoscopic reflex remains sharp and crisp both before and after a blink.
- In a patient with *steep fit lens*, the retinoscopic reflex becomes clear immediately after a blink.
- In a patient with *flat fit lens*, the retinoscopic reflex blurs after the blink.

f. *Effect of blinking on keratometer mires:*
Keratometer mires focused on the anterior surface of lens:
- Remain sharp and crisp before and after the blink if the fit is ideal.
- Become clear after the blink in a steep fit.
- Blur after the blink in a flat fit lens.

Lens with an ideal base curve, in nutshell, has following features:

- Maintains 0.5–1.0 mm movement.
- Maintains good centration.
- Does not cause compression of the conjunctival vessels.
- Maintains stable visual acuity with and without blinking.
- Maintains sharp and crisp retinoscopic reflex and keratometric mires before and after blinking.

2. ***Evaluation of the diameter of the lens.*** A lens with an ideal diameter should extend 1.0–1.5 mm over the cornea. The diameter of the lens and its extension over the cornea can be seen with naked eye and slit-lamp.

3. ***Evaluation of the lens power.*** If the power of the soft contact lens corresponds with the calculated power and the patient is seeing clearly,

then the lens power is alright. However, if the patient does not see clearly then the power may be undercorrected, overcorrected or distorted.

GUIDELINES FOR A CHANGE IN TRIAL LENS

If the trial lens selected initially is not found to be an ideal one, the new trial lens may be selected and again evaluated. No hard-and-fast rules can be given for changing the trial lens. However, based on the above evaluation, following are the guidelines:

1. *Centration* may be improved by increasing the overall diameter.
2. *Edge compression* may be diminished by flattening the base curve.
3. *Steep fitting* lens exhibiting no movement (steep fit) may be replaced by one with a smaller overall diameter or flatter base or both.
4. *Flat fitting* lens exhibiting excessive movements may be replaced by one with a larger overall diameter or steeper base or both.

Note:

1. These guidelines are just general indications and may not be absolutely correct for every style of lens and cornea. This is because the bearing relationship of soft lenses is complex, involving ideally touch of the lens not only to the apical cornea but also to the upper and lower limbal conjunctiva.
2. In addition, unlike rigid lenses, the base curve of the soft lenses ultimately conforms to the shape of the anterior central cornea; this in turn results in a change in the anterior curvature of the soft lens. The result is a negligible change in the net power of the soft lens. Therefore, changing the base curve of a soft lens does not usually require a compensatory power change.

POST-FITTING PATIENT MANAGEMENT

Post-fitting patient management is essentially on the same lines as that described for rigid lenses (page 285). However, some of the additional features and special comments about the post-fitting patient management are as following.

ORDERING SOFT LENSES

Once the parameters of the ideal fitting trial lens are finalized, the soft lenses are usually ordered from a manufacturer's known series, specifying the power required.

EXAMINATION OF THE ORDERED LENS AND EVALUATION OF THE FIT

The ordered contact lens received from the manufacturer should be examined meticulously with special reference to its diameter, power, thickness and base curve. The lens may have a bad or chipped edge, unblended or badly blended peripheral curves. Lenses can have bad optical quality. The ordered lenses – when found as per specifications and good in quality – should be inserted into the patient's eyes and the fit should be evaluated as described above.

HANDLING AND CARE OF SOFT LENSES

After the lens fit is found satisfactory, the patient should be taught about the care of lenses and technique of insertion, removal and recentration of the lens, and also about the hygiene and wearing schedule.

General Instructions

Cleanliness is the most important rule of contact lens use. Careful and meticulous attention to contact lens hygiene should be paid, as the risks associated with their use are of paramount significance. The patients should be given following instructions:

1. Hands must be washed, rinsed thoroughly and dried with a lint-free towel before handling the lenses.
2. Cosmetics, lotions, soaps and creams must not come in contact with the lenses since irritation of eyes may result. If hair spray is to be used, the eyes must be closed until the hair spray has settled.
3. Soft contact lenses must be stored only in normal saline solution. If left exposed to air, the lenses will dehydrate, become brittle and break readily. If by mistake a lens dehydrates, it should be soaked in normal saline solution until it returns to a soft, supple state.

4. Soft contact lenses must be cleaned and asepticized daily. It is always better to use a 'Soft-lens' Aseptor-Patient Unit.
5. The lens case should be cleaned by boiling in water and then rinsed thoroughly with normal saline. Never use soap for cleaning the lens case.
6. The patient should never sleep with lenses on.

Insertion and Removal

Insertion. Technique of insertion of soft lenses is exactly the same as that for hard lenses (page 277, Fig. 8.9A and B). A trapped bubble behind the lens may be managed out. This is done by gentle rubbing of the upper lid over the soft lens.

Before insertion, one should be sure that the lens is not inside out. This can be verified by gently folding the lens between the thumb and forefinger (*Taco test*). In normal circumstances, the lens edges should point inwards and look like a Mexican taco with the edges touching. When the edges roll outwards rather than inwards, the lens is inside out and must be reversed. It is important that the lens be grasped and folded near the apex of the lens rather than at its edges.

Removal. Technique of removal of soft lens is different from the hard lens. Right and left hands are used for removing the respective lenses (Fig. 8.10C). The steps of removal are as follows:

- The patient should hold the head erect and turn the eyes upwards.
- Lower lid should be retracted with the middle finger and the tip of index finger should be placed on the lower edge of the lens.
- The lens should be slid down to the white part of the eye and lightly compressed between the thumb and index finger.
- On rolling the thumb and index finger together, the lens can be pinched out of the eye.
- After removal, the lenses should be cleaned with normal saline and stored.

Normal Wearing Schedule

Soft lenses are comfortable from the beginning; therefore, there may be a tendency to overwear the lenses initially. However, the patient should be cautioned about it and instructed to follow the wearing schedule as shown in Table 8.3.

POST-FIT FOLLOW-UP AND PROBLEMS

For a successful, comfortable and complication-free contact lens wearing, a regular follow-up examination is most essential. It is essentially the same as that described for rigid lenses (page 290).

Table 8.3 *The wearing schedule for soft lenses*

Day	Wearing time (h)	Rest period (h)	Wearing time (h)	Rest period (h)	Wearing time (h)
1	3	1	3	1	3
2	3	1	3	1	3
3	4	1	4	1	4
4	4	1	4	1	4
5	6	1	6	1	4
6	6	1	6	1	4
7	8	1	8		
8	8	1	8		
9	8	1	8		
10	10	1	Remaining[a] working hours		
11	12	1	Remaining[a] working hours		
12	14	1	Remaining[a] working hours		

[a]Never wear lenses for more than 24 h.

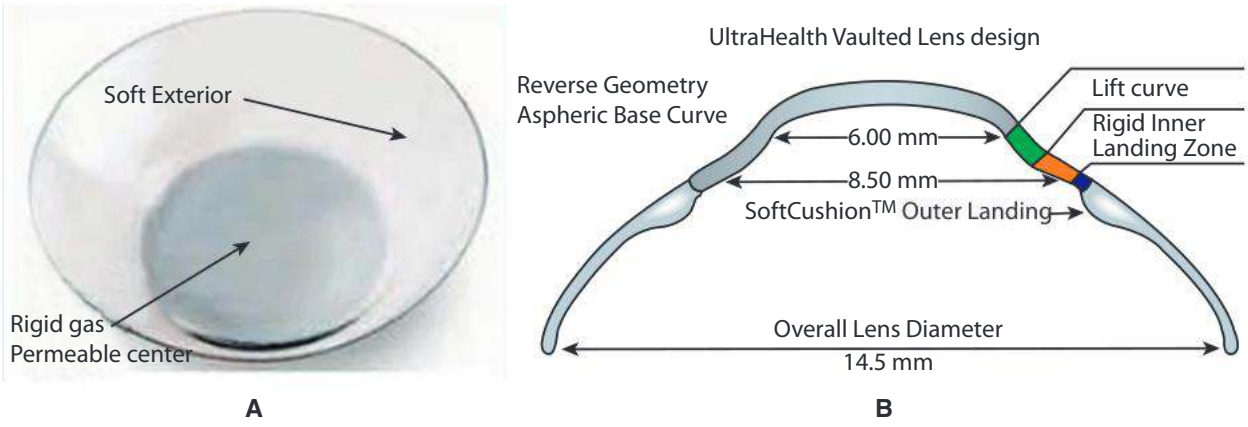


Fig. 8.14 *Hybrid contact lens: A, lens profile; B, diameters and curves.*

HYBRID CONTACT LENSES

Hybrid contact lenses consist of the RGP centre and silicone hydrogel skirt (Fig. 8.14). Older designs (SoftPerm) caused many complications due to lack of oxygen permeability and tight fit. RGP 8.5 mm diameter and over all diameter (OAD) 14.5 mm.

Commercially Available Hybrid Contact Lenses

- SynergEyes Duette
- SynergEyes Ultra Health
- SynergEyes KC, A, B

Indications

- Patients with astigmatism.
- Patients with unstable vision with soft toric contact lenses.
- Patients wearing RGPs with comfort issues.
- Presbyopic patients with astigmatism.
- Soft multi-focal wearers looking for better visual acuity.
- Irregular cornea patients looking for new options.

Advantages

- Improved comfort over RGP with same acuity.
- Much lower cost than scleral CLs for irregular corneas.
- Easier to remove than scleral and less chair time to evaluate.
- Visually more stable than soft torics.
- Available for presbyopic correction.

Disadvantages

- Cost is more than soft toric or RGP.
- Requires more chair time to fit.
- Requires replacement every 6 months.
- Insertion is difficult, similar to scleral RGP.

Hybrid Lens: Insertion and Removal

- Insertion similar to scleral RGP lenses with large plunger (Fig. 8.15A) or with tripod finger method (Fig. 8.15B).

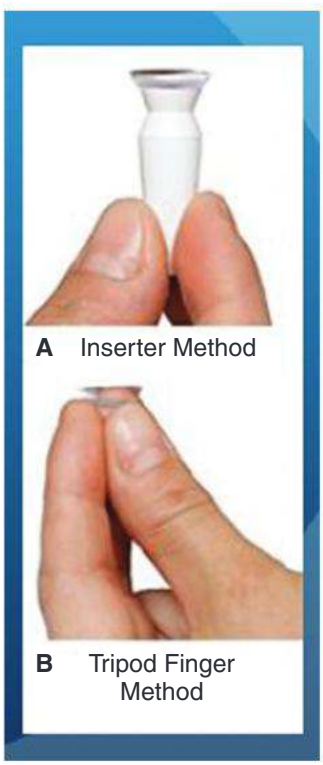


Fig. 8.15 *Methods of insertion of a hybrid contact lens.*

- Must fill bowl with preservative free saline with Ultra Health.
- Removal is done by pinch method with dry fingers similar to soft lenses.

EXTENDED WEAR LENSES

EWL refers to the concept of continuous wear day and night for several days, weeks or even months without removal. Lenses for extended wear are hydrogel soft lenses and RGP lenses.

A. EXTENDED WEAR HYDROGEL SOFT LENSES

INDICATIONS

In general, DWL (daily wear lens) concept is preferred over an EWL concept. However, EWLs may be indicated in some of the conditions:

1. Elderly aphakic patients having handling problems.
2. Younger patients to avoid frequent handling problems.
3. Patients not willing to comply with the routine of DWLs.
4. Patients having a profession with irregular waking shifts or working hours such as air hostesses, emergency staff (police and firemen), nurses and doctors.
5. Patients habitual of falling asleep with the lenses worn.
6. Habitual overwearers.

TYPES OF EWLs

Based on the percentage water content, the dry hydrogel lenses used for extended wear are of three types.

1. Low Water Content Lenses

The lenses with low water content (38%–45%) have to be very thin to be used as for EWL. The thinner the lens the greater will be the oxygen permeability. Therefore, such lenses are also called 'ultrathin lenses' or 'membranous lenses'. However, there is a limitation to have thin or membrane-like lens because the lens ripples on blinking causing distortion of vision. In addition, handling of extremely thin lenses becomes awkward. Examples of commercially available low water contact lenses are as follows:

i. CSI Lens

- It is a thin lens (thickness between 0.03 and 0.08 mm) with 40% hydration.
- It is durable and elastic, having very small optic zone requiring minimal movement and large lenticular zone.
- It is a non-HEMA lens made of glycerine, methyl acrylate and MMA.
- It is available in diameter of 14.8 mm and base curves of 8.6, 8.9 and 9.35 mm.
- Its power range is ±20 D.
- It equilibrates in 5 min and thus over-refraction is possible after this time.
- It is resistant to deposits, discolouration and effect of environment.

ii. Bausch & Lomb Lenses

When other lenses are not available, rarely Bausch & Lomb polymacon lens with 39% hydration and thickness of 0.35 mm have been used as EWLs.

2. Medium Water Content Lenses

These lenses contain 45%–60% water. Examples of commercially available such lenses are as follows:

i. Hydrocurve Lenses

- These are made of HEMA.
- Hydrocurve-I lens has a water content of 45% and 0.06–0.07 mm thickness.
- Hydrocurve-II lens has 55% hydration and 0.08–0.29 mm thickness.
- Hydrocurve lenses are available with the following parameters (Table 8.4).

Table 8.4 *Hydrocurve lens: parameters.*

Type of lens	Base curve (mm)	Diameter (mm)	Power (D)
Aphakic lens	8.5	14	+7 to +20
	8.8	14.5	
	9.2, 9.5, 9.8	15.5–16	
Cosmetic lens	8.5	14	0 to –12 and +0.25 to +7
	8.8	14.5	

ii. Softcon Lenses

- It is made of HEMA and povidone.
- Its hydration is 55% and its thickness varies from 0.17 to 0.64 mm depending upon the power. Thus, it is tougher, thicker and elastic.
- It is available with following parameters:
  - Base curve: 7.8, 8.1 and 8.4 mm.
  - Diameter: 13.5, 14 and 14.5 mm.
  - Power: –8.0 to +18.0 D including plano.

3. High Water Content Lenses

The higher the water content, the greater the oxygen permeability. The water content of such lenses is more than 60%. With very high water content, an EWL may be made fairly thick. While the thickness increases durability, the high water content polymer material is usually not very durable. Examples of commercially available high water content EWLs are as follows:

i. Perma Lens

- It is made of 2-HEMA VP and methacrylates.
- It is a lathe-cut lens having hydration of 71% and thickness varying from 0.24 to 0.43 mm.
- It is available with following parameters:
  - Aphakic lenses with base curves of 8.3, 8.6 and 8.9 mm in powers of +10 to +20 D and diameters of 13 and 13.5 mm.
  - Plano or lock power lens with 14 mm diameter can be used as therapeutic lenses.

ii. Sauflon Lens

- It is made of HEMA and N-vinyl-2-pyrrolidone.
- Its water content is 79% and thickness is 0.05 mm.
- It is available with following parameters:
  - Aphakic lenses in base curves of 8.1, 8.4 and 8.7 mm and diameter of 14.4 mm and power 0–20 D.
  - Myopic lenses in base curves of 7.8 and 8.1 mm and diameter of 13.7 mm and power 0–8.00 D.
  - Therapeutic lenses with base curves of 8.4 mm and diameter of 15.5 mm in plano power.

FITTING, FOLLOW-UP AND PROBLEMS

Fitting. The guidelines for fitting an EWL are similar to those for daily wear soft lenses but with a tendency to slightly more loose fit. Base curves of 8–9 mm and overall diameter of 13.5–14.5 mm are commonly used.

Follow-up. In order to avoid complications of extended wear hydrogel lenses, it is important to obtain the best initial comfortable fit for the proposed lens while in the office. Following routine for follow-up examination may be adopted.

- First follow-up visit should preferably be within 24–48 h. The patient should be observed for the presence of any corneal ocular response that is abnormal.
- Subsequent follow-up visits may be planned every 2 or 3 months, when the lenses should be inspected in situ and either replaced or removed for cleaning and re-insertion. However, if there is no symptom and no objective abnormal sign, the lens may be left in situ. When to remove an EWL depends on the individual's lens constituents and behaviour. An EWL should be removed when it shows significant deposits or lens damage. Every patient should be advised to report immediately, if anything untoward is occurring between the routine visits. The patient should also be taught to remove the lens at the first sign of trouble.

Problems. All complications known to occur with daily wear soft lenses may occur in patients using EWLs. However, EWL wearers are more prone to get

- Lens deposits,
- Infectious keratitis and
- Corneal vascularization.

The light lens syndrome is a peculiar problem associated with EWL use. It manifests as acutely developing painful red eye, commonly on waking and is characterized by an immobile lens which is partially dehydrated. It seems to be gripping a cornea oedematous on account of poor oxygenation. In addition to corneal oedema, anterior chamber reaction in the form of cells and flare may also occur in severe cases.

Treatment consists of abstaining lens wear for a week or two, followed by a use of looser fitting lens after the eye is normalized.

B. EXTENDED WEAR RIGID GAS-PERMEABLE LENSES

Rigid lenses made of copolymers with a very high oxygen permeability have taken a new importance in the concept of EWLs. New advances in high-DK lenses have permitted the use of silicone.

INDICATIONS

Indications of RGP extended wear (RGP-EW) lenses are similar to those of extended wear soft lenses. In addition, they are indicated in patients having following problems with soft lenses:

- Metabolic problems with hydrophilic extended wear,
- Visual problems with toric extended wear soft lenses,
- Allergic problems like GPC with soft lenses,
- Superior limbic keratoconjunctivitis due to soft lenses and
- All conditions where lenses are expected to be more thick such as high-power plus and minus lenses, toric bifocal and bigger diameter lenses.

FITTING, FOLLOW-UP AND PROBLEMS

Fitting. Patients selected for fitting RGP-EW lenses should be successful daily wearers and highly motivated with definite indication for use of an EWL. The selected RGP-EW lens should have DK value near 90. The fitting guidelines are almost similar to those for daily wear RGP lenses. The lens design should give alignment fit with minimal bearing, slightly wide edge with a clearance over 70 µm. The edge should be rounded.

Wearing schedule and follow-up. Patients should be advised to use the lenses as daily wear regime for the first week and then switch to an extended wear regime. Check overnight removal schedule, i.e. overnight removal every fifth night may be useful for a successful RGP-EW lens wear.

First follow-up visit should be on day 1 in the morning at 9 a.m. after an overnight wear. Subsequent follow-up visits may be planned after 1 week, 2 weeks and 1 month and then after every 3 months. A complete examination (as described earlier) should be conducted at such follow-up visits. A careful note should be made for the following:

- Persistent striae
- 3–9 staining
- Back surface debris
- Lens binding, arcuate stain and indentation
- Microcysts

Problems and complications of daily wear RGP lenses are known to occur more with EWLs. Problems that are much more pronounced with RGP-EW lenses are as follows:

1. *Adhesion phenomenon*. It occurs due to the lens behaving as a suction cup, causing first ring impression on the cornea and then adherence to cornea. This phenomenon is more likely to occur with the use of high-DK-value lenses, steep lenses and thin lenses.

2. *3–9 staining.* It occurs more with RGP-EW lenses than with DWL. Factors that increase the chances of occurrence of 3–9 staining are low-riding lenses, thick-edged lenses and partial blinkers. Therefore, furnishing a high-riding, thin-edge lens with good edge finish should correct the problem. Complete blinking should be stressed and demonstrated to the patient.

RGP-EW LENSES VERSUS SOFT-EW LENSES

1. ***Fitting.*** Fitting of RGP-EW lenses is more exacting and time-consuming than their soft counterparts. One has to exactly fit the RGP-EW lenses on the eyes rather than fitting the eye to the lenses as is the case with soft lenses.

2. ***Wearing comfort.*** Undoubtedly, initial wearing comfort is much more with the soft lenses – so they are more popular. However, by sleeping few nights with RGP-EW lenses, awareness may lessen considerably and patients are quite comfortable.

3. ***Optical quality.*** RGP-EW lenses provide a crisper type of vision and a better method of correcting corneal toricity than the soft hydrogel lenses. In soft lenses, hydration, dehydration

and flexure decrease the quality of vision. The patients usually complain that they do see everything, but the vision is not clear.

4. ***Lens durability and handling.*** RGP-EW lenses are more durable and easier to handle than soft lenses.
5. ***Change of lens parameters.*** After few months of wear, soft lenses become dehydrated and steep in fit, thus trapping tissue debris, metabolic wastes, lactic acid and pyruvate, resulting in acute red and sore eyes. RGP-EW lenses do not change their parameters even after years of use.
6. ***Lens deposits.*** Problem of lens spoilage due to lens deposits is much more common with soft lenses. In RGP lenses, deposits do occur but can be removed completely by organic solvents or polishing.
7. ***Oxygen performance.*** RGP-EW lenses have the added advantage over hydrogel lenses that there is much greater oxygen exchange through the tear interface in addition to the diffusion of oxygen through the lens itself.
8. ***Reproducibility.*** RGP-EW lenses can be fabricated to an accuracy of 1000th of a millimetre and are thus easy to reproduce. While there has been a problem to duplicate soft lenses in exact dimensions, this difficulty is more so for low-water ultra-thin lenses.
9. ***Adhesion phenomenon and 3–9 staining.*** As described earlier, these are the problems associated with the use of RGP-EW lenses. However, these are not difficult to manage.
10. ***Other complications.*** Incidence of other complications is comparatively more with soft lenses as given in Table 8.5.

Table 8.5 *Incidence of other complications with soft and rigid lenses: a comparison*

Complication	Incidence with	
	RGP-EW lens	Soft-EW lens
• Infectious keratitis	1 in 10,000/year	21 in 10,000/year
• Giant papillary conjunctivitis	2%	5%–30%
• Acute red eye	0%	4%–15%

RIGID VERSUS SOFT CONTACT LENSES

After knowing the characteristics of contact lens materials, fitting techniques and problems associated with them, it will be worthwhile to summarize the advantages and disadvantages of rigid contact lenses versus soft contact lenses (Table 8.6).

DISPOSABLE CONTACT LENSES

Disposable contact lens is a new concept which has been mooted with the idea to replace lenses before a problem develops.

WEARING AND DISPOSING SCHEDULE

Various wearing and lens disposal schedules have been adopted. Lenses can be worn on daily or extended wear basis and replaced weekly, biweekly, monthly or quarterly. A few of the schedules in vogue are as follows:

1. *A typical protocol* is to use the lens on daily wear basis with hydrogen peroxide disinfection overnight and dispose of the lenses every week or fortnight.
2. *Some recommend* an extended wear continuous use for 7–14 days before replacement.
3. *A balanced view* is to use continuously for two nights with overnight hydrogen peroxide disinfection every third night and dispose of the lenses after 2–4 weeks.
4. *Daily disposable*. The concept of 1-day disposables has been mooted as given below:
   - Fastest growing lens modality in the world.
   - Accounts for almost 30% of all contact lens prescriptions written worldwide.
   - Now available in high toric power and multi-focal powers.
   - Accounts for 24% of all contact lenses in the USA.

Types. Two types are available:

- Silicon based and
- Non-silicon based.

Table 8.6 *The advantages and disadvantages of rigid versus soft contact lenses*

Rigid contact lenses	Soft contact lenses
Advantages	**Disadvantages**
1. *Quality of vision* • Better.	• Variable vision despite good fit. May be result of lens dehydration, lens spoilage or deposits.
2. *Durability* • Comparatively more durable.	• Less durable, i.e. more susceptible to being scratched or torn. Therefore, need more frequent replacement than rigids.
3. *Correction of astigmatism* • Spherical rigid lens can correct moderate amount of astigmatism because of the increased amount of tears at the lens–cornea interface. Rigid toric lenses are best to correct high astigmatism as in patients with keratoconus.	• Spherical soft contact lenses often do not correct astigmatism as they mould to cornea. Toric soft contact lenses are available for astigmatism but rigid lenses are considered better.
4. *Deposit formation* • Rigid lenses are comparatively deposit resistant.	• Soft lenses are very much prone to develop protein, mineral and lipid deposits.
5. *Risk of infection* • Comparatively less risk of infection.	• Chances of corneal infection are more, if disinfection regimens are not rigidly followed.
6. *Modification* • Can be modified in office.	• Cannot be modified in office.
7. *Dry eye and often tear film irregularities* • Are not contraindications.	• Soft lenses are not suitable for patients with tear film abnormalities.
8. *Cost and handling* • Cost is less and handling is easy.	• Comparatively more costly and difficult to handle.
Disadvantages	**Advantages**
1. *Comfort* • Rigid lenses are less comfortable and more difficult to adapt.	• Soft lenses are very comfortable to wear and easy to adapt.
2. *Wearing problems* • Problems arise with wearing on an irregular or occasional schedule. Overwear of rigid lenses (particularly polymethyl methacrylate lenses) can lead to extremely painful reaction.	• Wearing problems are not much known with soft lenses. So, can be worn intermittently such as for occasional social or athletic events. Even overwear reaction tends to be much less severe.
3. *Spectacle blur* • Spectacle blur may occur with rigid lenses.	• Spectacle blur is not known with soft contact lenses.
4. *Lens stability* • Difficulty in achieving on-eye stability so are dislodged and lost comparatively more frequently.	• Soft lenses are larger and adhere more tightly to the cornea and thus are dislodged much less frequently.

■ ADVANTAGES AND DISADVANTAGES

Potential advantages of disposable lenses are as follows:

1. Problem of lens deposits is reduced.
2. Incidence of GPC is likely to reduce tremendously.
3. It seems that there will be a significant reduction in the incidence of preservative-related keratitis.
4. There is a definite convenience in care system.
5. Great for occasional use, travel and sports.
6. Reduced non-compliance.
7. Reduced severity but not frequency of complications.
8. Excellent for use in environments with high risk of infection, such as hospital.

Disadvantages include:

- Higher expenses if used 365 days in the year.
- Not for use with irregular corneas.
- Limited size parameters.

SPECIAL CONTACT LENS FITTING SITUATIONS

CONTACT LENS FITTING IN ASTIGMATISM

Astigmatism is not an uncommon condition. It can be corrected by both rigid and soft contact lenses.

■ RGP LENSES FOR ASTIGMATISM

1. Spherical RGP Lens

Such a lens may not prove sufficient in patients with moderate to high degrees of corneal astigmatism. However, some practitioners suggest to first fit the astigmatic wearer with a single vision rigid lens, even if there is high corneal toricity. They report that in a surprising number of wearers, the resultant vision is good, with very little residual astigmatism. Corneal astigmatism as high as 4.0 D has been reported to be corrected effectively with a single vision rigid lens in quite a few cases. It has been recommended that in such cases, the lens should be made 0.2–0.3 mm smaller in diameter than the standard routine lens diameter.

2. RGP Lens With Toric Peripheral Curves

Such a lens may be required in many patients with 1.5–2.5 D corneal astigmatism. In such patients, a spherical posterior surface lens may fit inadequately because the lens edge may lift over the steepest corneal meridian. This may lead to poor lens centration or frequent lens loss.

The standard peripheral curves are used in the flattest meridian, and in the steepest meridian, the peripheral curves are made steeper by an amount equal to the dioptres of corneal astigmatism. The lenses are ordered in the usual fashion with the notation *toric peripheral curves* and the dioptres of corneal astigmatism.

3. Bitoric RGP Lenses

Toric posterior curve lens is often necessary to provide an adequate lens fit in patients with higher degrees of corneal astigmatism, usually 2.5 D or greater. Such a lens is usually fitted with posterior curves the same as the keratometric readings. However, when a lens with toric posterior curve is placed on the cornea, unlike a spherical posterior surface lens, the lens–tear interface becomes a toric surface with a resultant *induced astigmatism.* Thus, in most situations when a toric posterior curve is used, an additional anterior toric curve will be needed to overcome the induced astigmatic error. Such a lens is called *bitoric lens.*

Guidelines for Prescribing a Bitoric Lens

i. ***Posterior central curve (PCC) and posterior optical zone (POZ):***
   - Both corneal meridians should be fitted with the 'on K' procedure.
   - An arbitrary initial value of 7.5 mm for the POZ is used as a reference point. For every 0.5 mm change in the POZ from the initial diameter of 7.5 mm, a compensatory change in both radii of curvature of the PCC by 0.05 mm should be made.

ii. ***Lens power:***
   - Ocular correction for the vertex distance is required for both corneal meridians. For example, a patient with spectacle correction at 12 mm vertex distance of

–6.25, –4.75 × 180 degrees will require –5.75, –4.00 × 180 degrees.
- When the PCC is fitted steeper, add minus to the spherical power only.
- When the PCC is fitted flatter, add plus to the spherical power only.
- For every 0.05 mm change in PCC, a 0.25 D of sphere power should be changed.

iii. ***Peripheral curves should also be made toric to have a round POZ.***

iv. ***Centre thickness*** should be calculated from the spherical thickness chart, using the spherical equivalent of the bitoric lens.

4. Front Surface Toric RGP Lenses

These lenses are required in patients having spherical corneas with significant astigmatism. Such an astigmatism is called *residual astigmatism* and it usually reflects the lenticular astigmatism. When a front toric lens is ordered for a spherical corneal surface, a special change in the shape of the contact lens is necessary to prevent it from rotating (i.e. to stabilize the relative cylinder axis). This can be accomplished by the following methods:

i. ***A prism blast*** may be added to the lens in its manufacture (Fig. 8.16). The amount of base-down prism needed is usually 1.50Δ, although more prism may be necessary to centre a high minus power lens.

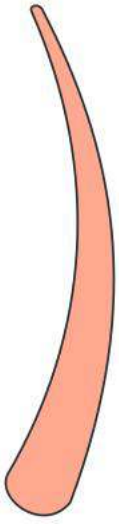


Fig. 8.16 *Cross-section of contact lens illustrating prism blast.*

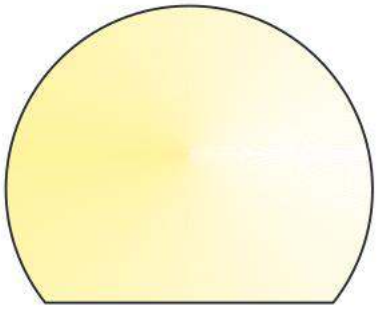


Fig. 8.17 *Truncated lens used to control lens rotation and stabilize the lens.*

ii. The lens may be formed ***truncated***, i.e. diameter of the lens in one meridian is shortened by cutting off the entire edge of the lens by 0.5–1.0 mm (Fig. 8.17). Truncation is usually used to modify an existing lens rather than as part of the initial lens design.

SOFT LENSES FOR ASTIGMATISM

1. Spherical Soft Contact Lenses

Spherical soft contact lenses may correct astigmatism of up to 1 D, provided the total astigmatism is not more than one-third of the spherical correction. For example, a patient with –5 DS and –1 DC prescription may be comfortable when fitted with a spherical soft lens, while a patient with –2 DS and –1 DC prescription may not be comfortable with spherical soft contact lens. Thinner spherical lenses correct less astigmatism than standard thicker lenses.

2. Toric Soft Lenses for Astigmatism

Toric soft lenses are required when astigmatism is more than 1 D and spherical soft lenses are not able to correct it, and the patient is unable to tolerate rigid lenses. Toric soft lenses have different radii of curvature in opposing 90 degree meridians. A wide variety of lenses are available with fitting guidelines provided by the manufacturer. Most important for a fitter is to ensure that the lens under consideration matches with the patient's refractive error accurately. The toric soft lenses need to be stabilized by any of the following methods:

- Double slab-off lenses (most comfortable)
- Prism blasting (provides the greatest stability)
- Truncation (single or double)

- Prism blasting combined with truncation
- Aspheric back surface

CONTACT LENS FITTING IN APHAKIA

An intraocular lens (IOL) is the treatment of choice for aphakia. Consequently, most of the patients are now implanted with an IOL during the cataract operation. However, where IOL has not been implanted, a contact lens is of great optical advantage over the spectacles.

RGP LENSES IN APHAKIA

Two basic types of contact lenses are used in aphakia:

1. ***A single-cut lens*** (Fig. 8.1A) tends to be very thick in the centre because of the high plus power required. Because of this thickness, a large lens tends to be heavy and will ride low. To counteract this, a small lens should be fitted, which will centre better. A standard single-cut lens usually will be 7.4–8.4 mm in diameter.
2. ***Large lenticular lens*** can be tried in aphakic cases where even small-sized single-cut lenses centre poor. The lenticular lens has a central optical zone anteriorly and a peripherally thinner flange (Fig. 8.1B). A flange with minus power will rise higher. A standard lenticular lens is about 9–10 mm in diameter.

APHAKIC SOFT CONTACT LENSES

- Aphakic soft contact lenses, particularly extended wear type, are of great help to patients, as aphakic patients are either elderly or small children (in which primary IOL implantation has not been done).
- Lathe-cut lenticular design has the best stability on the eye and provides sharpest and most stable vision.
- Aphakic patients, because of age, tend to be more prone to microbial corneal ulcer and thus need regular follow-up.

Note. Contact lenses in aphakic patients should be ordered with a grey tint to reduce glare and to act as a neutral density filter to reduce the excess light admitted by the absence of crystalline lens.

CONTACT LENS FITTING IN KERATOCONUS

In patients with keratoconus, the cornea is steep in the centre and usually much flatter in the periphery. Therefore, a contact lens of normal posterior surface design and diameter will either create a large area of central touch with flaring of the edges or an area of central touch with entrapment of an air bubble in the intermediate region of the lens.

Ideal CL fit for keratoconus should have the following:

- Minimal apical touch or apical clearance (three-point touch provides stable fitting and good vision).
- No excessive areas of tear/debris pooling beneath optic zone.
- Good circulation of tear film under lens.
- Good stability and comfort.
- Mid- or high-DK lenses for adequate O_2 permeability and good eye wettability (fluorinated silicone acrylate rigid CL preferable).

Contact lenses in use for keratoconus include the following:

- RGP,
- Soft contact lenses,
- Hybrid lens system,
- Scleral RGP lenses and
- Piggyback lenses.

I. RIGID GAS-PERMEABLE LENSES

Fitting Techniques/Philosophies

1. **Three-point touch design.** The three-point touch design is the most popular and the most widely fitted design for keratoconic patients. The aim is to distribute the weight of the contact lens as evenly as possible between the cone and the peripheral cornea. Three-point touch refers to minimal apical clearance in the centre, minimal area of touch/bearing in the mid-periphery with adequate edge clearance. This type of fitting works well for small central cones.
2. **Apical clearance fit (steep fitting).** In this type of fitting technique, the lens vaults the cone and clears the apex, resting on the

paracentral cornea. This type of lens was suggested as it was argued that apical clearance would minimize trauma to the central cornea. Apical clearance lenses are small in diameter (8.0 mm) and have small optic zones (5.8 mm). The apical clearance method works well on cones which have central apexes or on displaced apexes which are only slightly inferior to the visual axis.

This method, best for smaller cones, is impractical for large cones, such as a sagging oval cone or globus cone. The potential advantages of reducing central corneal scarring are outweighed by the disadvantages of poor tear film, corneal oedema and poor visual acuity as a result of air bubbles becoming trapped under the lens.

3. Apical bearing fit (flat fitting). This apical bearing fitting philosophy is useful for displaced apexes. As keratoconus develops, the apex of the cornea is generally displaced inferiorly. If a small lens is placed on an inferiorly displaced apex, the lens is generally positioned low, and the lid often dislocates the lens with each blink. In such cases, a lens of larger diameter (9.0–9.8 mm) is preferable. The fitting method positions the upper edge of the lens under the upper lid to prevent lens dislocation.

Good visual acuity is obtained as a result of apical touch. It has been reported that flat fitting contact lenses can lead to progression or acceleration of apical scarring.

RGP Special Lenses for Keratoconus

1. *Rose K lens.* It utilizes light apical touch with optimal peripheral clearance. Computer-generated peripheral curves are used. Toric surfaces are available on front, back and periphery. Characterized by multi-spherical posterior design with aberration control aspheric optics across back and front optic zone diameters.

2. *Rose K2 Lens.* The Rose K2 lens was created to address two critical areas of performance for the keratoconic patient – spherical aberration and small optical zones. The base curve of the Rose K2 lens has an aspheric (non-spherical) optical zone unlike the spherical optical zone found on the original Rose K lens. This aspheric optical zone controls spherical aberration found on all contact lenses in higher minus powers, typically present with keratoconus lenses. The incorporation of aspheric optics into the lens design improves vision performance and enhances wearing comfort. The aspheric optical zone is larger than that of the original Rose K reducing glare, haloes and flare, common for many keratoconic patients in dim illumination (night-time).

3. *Soper's technique* uses lenses with two posterior curves, one to fit the central cone and the other to fit the more normal cornea surrounding the apex of the cone. Bicurve lenses based on sagittal depth simulate a hat on the cornea. Three fitting sets are available:

- Mild (7.4 mm diameter, 6.0 mm OZ),
- Moderate (8.5 mm diameter, 7.0 mm OZ) and
- Advanced (9.5 mm diameter, 8.0 mm OZ).

Peripheral curve is constant. Peripheral alignment and apical clearance characterize these lenses.

4. *McGuine lens.* Prescribed for oval and more advanced cones. Goal is to achieve feather/minimal touch apical fitting relationship. It uses four peripheral curves (primary, secondary, tertiary and quaternary) with a wide blend.

II. SOFT LENSES

In general, soft contact lenses have a limited role in correcting corneal irregularity as they tend to drape over the surface of the cornea and result in poor visual acuity.

1. *Silicone hydrogel lenses* can be relevant here since the increase in rigidity compared to conventional hydrogels helps to mask the astigmatism and silicone hydrogel torics such as *Pure vision (Bausch & Lomb)* may be successful.

2. *Custom toric soft lenses*, i.e. soft lenses designed specifically for keratoconus such as *Kera*

soft (Ultra-vision) or *Soft K (Acuity contact lenses)* have a useful role in early keratoconus or where a patient may be intolerant of RGP. They afford higher levels of comfort and longer wearing times. One custom-made soft lens for keratoconus, manufactured by Flex lens is made of material with 45% water content and can be made in any power or curvature. When high-molecular-weight fluorescein is instilled in the eye of a patient wearing this lens, the fluorescein pattern under the lens is similar to that of a rigid lens. Lens movement is vital for a successful fit. Movement of this lens can be maximized by varying the secondary curve.

Disadvantages of soft lenses are corneal oedema and neovascularization if the lenses are overworn.

III. HYBRID LENS SYSTEM

It utilizes CLs with RGP central portion and a soft lens material skirt. These include:

1. ***Soft perm lens from CIBA vision***. One can choose from different peripheral curves. These lenses tend to be used in cases of RGP lens intolerance or for patients with displaced corneal apexes. Advantages of the soft perm lens are as follows:
   - Provides better comfort than the RGP lens,
   - Better centration and visual acuity and
   - Provides the comfort of a soft lens and visual acuity of a rigid lens.
2. ***SynergEyes hybrid contact lenses*** are the first FDA-cleared hybrid contact lens specifically designed for keratoconus vision correction. Utilizing revolutionary hybrid technology, SynergEyes has developed a family of lenses that provide keratoconus patients with the all-day comfort of soft contact lenses and the excellent visual clarity of RGP lenses. SynergEyes contact lenses for keratoconus are custom designed to meet the vision correction needs. There are two different lens designs, SynergEyes KC and ClearKone, to address all stages of keratoconus.

Disadvantages are frequent breakage of lens, GPC and peripheral corneal neovascularization.

IV. SCLERAL RGP LENS

Indicated in advanced keratoconus, where corneal lenses do not work and corneal surgery is contraindicated, completely neutralizes any corneal irregularity (e.g. RGP epicon LC, Boston lens).

Boston scleral lens (BSLPD – Boston scleral lens prosthetic device) is a specially designed fluid ventilated gas-permeable contact lens device that provides a non-surgical means of restoring vision in eyes affected with corneal disorders. The lens is about 18–23 mm in diameter and it rests entirely on the sclera and arches over the damaged cornea, thereby creating a space that is filled with normal saline or artificial tears. This fluid reservoir masks the distorted corneal topography and improves vision. It also functions as a unique liquid bandage by protecting the corneal surface from the desiccating effects of exposure to air and the friction of blinking. The presence of corneal oedema is a contraindication to wearing this device. The need to customize and design individual lenses makes these lenses expensive.

V. PIGGYBACK LENS

Rigid lens is fitted on top of a soft lens. RGP lens is fitted first with good centration. Slightly larger area of apical touch is acceptable as RGP will be cushioned by a soft lens. A silicone hydrogel soft lens should be used where possible, with good movement and coverage/centration as in a normal soft lens fitting.

Caring of the two types of lenses can be difficult in the long term. The cornea should be observed carefully for dryness and neovascularization.

RECOMMENDED CONTACT LENS DESIGN BASED ON DEGREE OF KERATOCONUS

Mild keratoconus (<45 D)

- Aspherics or multi-curve lenses
- Kera 1 and II (No. 7)
- Acuity K
- Rose K (David Thomas)

Moderate keratoconus **(45–52 D)**
- Kera II
- Quasar KNO7
- Rose K (David Thomas)
- Woodward KC3

Advanced keratoconus **(53–62 D)**
- Kera II/III
- Rose K (David Thomas)
- Profile K (J Allen)

Severe keratoconus (>62 D)
- Small diameter lenses
- S-Lim (J Allen)
- Dyna-intralimbal (No. 7)
- Scleral lens
- Gas permeable (innovative scleral)

CONTACT LENS FITTING IN HIGH MYOPIA

Patients with high myopia (more than –8.00 D) need contact lenses with a relatively flat anterior surface. These lenses tend to ride high because of the larger diameter and because of increased edge thickness. The thickness of the peripheral edge can be reduced by ordering a lenticular bevel. This minimizes lid irritation and reduces the gripping action of the lids on the contact lens surface.

CONTACT LENSES IN PRESBYOPIA

Presbyopes, who do not want to use glasses at all, can be given three options: monovision contact lenses, modified monovision contact lenses and bifocal contact lenses.

1. Monovision Contact Lenses

One eye is corrected for distance vision and the other for the near vision. Brain learns to suppress the blurred image and so the patient adapts to see clearly for distance as well as near with the alternative eye. However, the patients do suffer from lack of binocularity and concomitant loss of depth perception.

2. Modified Monovision Contact Lenses

In this technique, one eye is corrected for distant vision and the other eye is fitted with a bifocal contact lens. In this method, the patient gets advantage of binocularity for distance vision.

3. Binocular Bifocal Contact Lenses

Bifocal contact lenses are expensive and a bit difficult to fit. These are available in both rigid and soft materials. Four types of bifocal contact lenses are in vogue:

i. ***Annular bifocal lenses.*** The distance and near optical elements are arranged concentrically. These are available in two designs: a 'centre-distance' or a 'centre-near' element (Fig. 8.18). Figure 8.19 shows the focusing for a distance

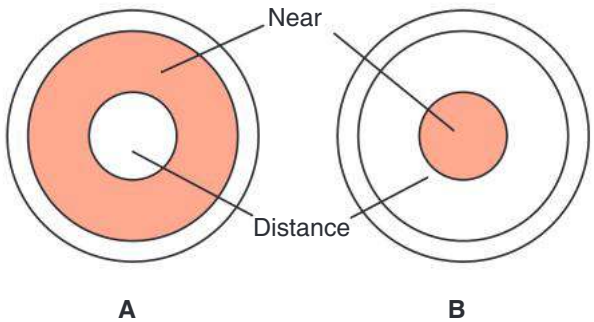


Fig. 8.18 *Annular design bifocal contact lenses: A, centre-distance; B, centre-near.*

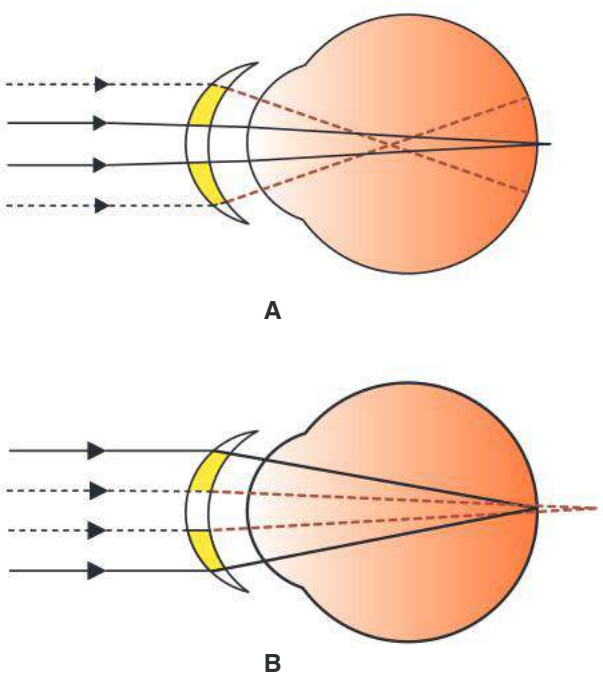


Fig. 8.19 *Focusing for distance (A) and near (B) by a centre-distance contact lens.*

object and a near object by a 'centre-distance' type of the bifocal contact lens.

Advantages include:

- Both foci are formed simultaneously, so lens does not have to move on the eye.
- Lens design is axially symmetrical, so axial rotation is not a problem.

Disadvantages include:

- Performance of annular lenses is highly dependent on pupil diameter. In bright light when pupil constricts, rays of light from the peripheral portion of the lens may not reach the retina.
- Because both foci are formed simultaneously, so the contrast of in-focus image is reduced and there occur other optical effects.

ii. ***Segmental bifocal lenses.*** Upper two-thirds portion of these lenses is for distance vision and lower one-third for the near vision. Performance of these lenses depends upon the translatory movements of the lens over the cornea. While looking down, the contact lens should move up so that the reading segment covers the pupil. Orientation of these lenses can be maintained by any of the two methods, i.e. by adding prism blast (base-down prism) or by truncating the lens.

iii. ***Aspheric bifocal lenses.*** These lenses have distance correction in the centre with gradually progressive add for near towards periphery. So, theoretically, these act as varifocal lenses and thus there is correction for distance, near and all intermediate distances.

iv. ***Diffractive bifocal lenses.*** These lenses have concentric diffractive rings which focus approximately equal amounts of light from both the near and distance objects (Fig. 8.20). So, each image is only half as bright as it would be with standard unifocal lenses. Thus, a good light source is always required to achieve satisfactory visual result. However, these lenses do not need to translate (cf. segmental bifocal lenses), and their performance is not dependent on the pupil size (cf. annular and aspheric bifocal lenses).

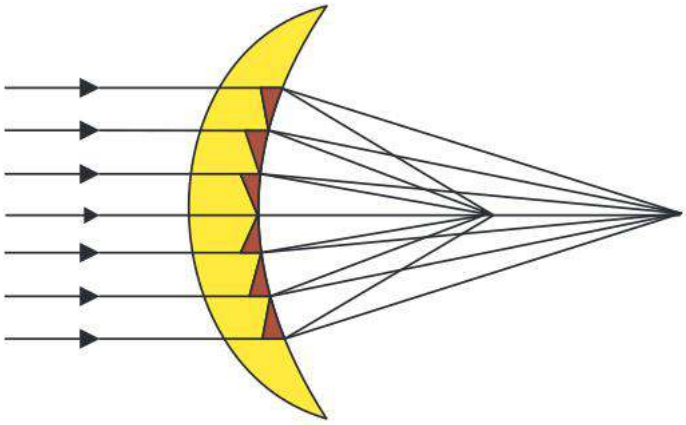


Fig. 8.20 *Diffractive bifocal contact lens.*

ORTHOKERATOLOGY

The term Orthokeratology is derived from the Greek word meaning 'the science of correcting the cornea'. It is a reversible and non-invasive technique of reshaping the cornea by wearing specially designed RGP lenses over a period of time. It is mainly used for the correction of myopia.

Overnight Ortho-K lenses are the most common type. They are worn during sleep for around 8 h leading to corneal flattening and then not worn during daytime when the myopia remains corrected. These are FDA approved for myopia correction (corneal refractive lenses). Effect is temporary and cornea will return to original shape when these are discontinued. Reverse geometry designs have been introduced. Central zone of these is flatter than needed for cornea, intermediate zones are steeper to provide peripheral bearing and peripheral zones are designed to provide necessary clearance and edge lift.

EVALUATION OF ORTHO-K LENS

Evaluation is done, as for any rigid gas permeable (RGP) lens, by noting the fluorescein pattern.

In ideal fit Ortho-K lens, the fluorescein pattern should demonstrate on slit-lamp examination:

- Bull's eye pattern with lens centred on cornea
- 3–4 mm treatment zone

- If bubbles attempt re-insertion with artificial tears to see if consistent
- Uniform lens landing
- 0.5–1 mm uniform edge lift

Poorly fit Ortho-K lens may demonstrate any of the following characteristics:

- Poor centration
- Absence of central bearing
- Absence of paracentral clearance
- Excessive paracentral clearance with bubbles in the return zone
- Heavy bearing [black arc] at junction of the return zone and peripheral landing zone
- Heavy bearing through the peripheral landing zone
- Excessive clearance in the peripheral landing zone.

Note. The presence of any of the poorly fit patterns is followed by failure to obtain optimum treatment. A well-fit lens pattern must be achieved through diagnostic lens fitting prior to lens ordering.

- Lens centration is the key for successful orthokeratology.
- Refractive change usually occurs in less than 2 weeks of wear.

CONTACT LENS ADVANCES IN NEAR FUTURE

In near future, contact lenses with following advances may be available:

- Anti-bacterial contact lenses that resist contamination.
- Soft contact lens that may slow progress of myopia.
- Customized CLs to correct individual ocular irregularities.
- New products: 'bio-inspired' by nature.
- CLs with embedded circuitry for monitoring IOP in glaucoma.
- CLs that measure glucose levels in people with diabetes.
- Drug delivery contact lenses.
- Three-dimensional contact lenses for gaming.

THERAPEUTIC CONTACT LENSES

Soft contact lenses can be used for therapeutic purposes in various ocular diseases. In general, therapeutic contact lenses (also known as bandage lenses) are used to

1. Provide mechanical support to the corneal surface,
2. Facilitate wound healing,
3. Help to maintain proper surface hydration,
4. Reduce discomfort from corneal surface disorders and
5. Act as drug delivery system.

Types and Choice of Lenses

Most therapeutic lenses are made of hydrogels that consist of an acrylic polymer matrix and an aqueous component. Silicone rubber has also been utilized for the manufacture of therapeutic contact lenses. Hydrogel therapeutic lenses may be:

1. *High water content thick lenses*. These are indicated in
   - Descemetocele for support,
   - Aphakic and pseudophakic bullous keratopathy and
   - Co-existent corneal or anterior segment inflammation.
2. *Moderate water content*, intermediate thickness lenses.
3. *Low water content*, ultra-thin or membrane lenses. These are indicated
   - In epithelial defects in a relatively dry eye and
   - When minimal lens movement is required.

COMMERCIALLY AVAILABLE THERAPEUTIC LENSES

These are depicted in Table 8.7.

FITTING OF THERAPEUTIC LENSES

Since keratometry is usually not possible or may give irregular mires in diseased cornea; the *trial fitting* is most appropriate. The ideal lens for therapeutic purposes is the Plano-T (ultra-thin lens), which provides an optimal lens–cornea

Table 8.7 *Commonly used therapeutic contact lenses*

Type	Material	Water content (%)	Thickness (mm)	Base curve (mm)	Diameter (mm)
Hydrogel lenses					
Plano-T	Polymacon	38	0.17	8.3	14.5
Plano-O_4	Polymacon	38	0.06	8.5	14.5
Softcon EW	Vifilcon	55	0.13	8.1–8.7	14.0–14.2
Perma lens	Perfilcon	71	0.24	7.7	13.5
				7.8	14.2
				7.9	15.0

relationship, is comfortable and does not require a fitting technique. It can be used in conjunction with various topical medications. After inserting the chosen therapeutic lens in patient's eye, fit should always be evaluated under slit-lamp biomicroscope.

- Flared edges may cause discomfort while adherent edges may indicate a tight lens.
- A therapeutic lens should undergo 1 mm excursion with blinking to allow tear exchange and clearance of debris. Thin membrane type lenses may move less than 1 mm and still fit well.
- Extreme flat or steep fit lens should be avoided.

INDICATIONS

1. ***Dry eyes***, secondary to Sjögren syndrome (keratoconjunctivitis sicca), Stevens–Johnson syndrome, ocular pemphigus, pemphigoid, etc., wherein the lens keeps the cornea moist, especially when saline or artificial tears are instilled along with the lens application, prevents evaporation of tears, is protective, aids epithelialization, gives relief from pain and prevents symblepharon formation. The frequency of instillation of saline or artificial tears can be decreased. It is extremely helpful for filamentary keratitis resulting from drying syndromes, where with the lens in situ there is improved vision due to elimination of astigmatism, relief from pain due to protection of naked nerve endings and also rapid disappearance of epithelial filaments by continuous protection of cornea and a bandage effect of the lens.
2. ***Neuroparalytic corneas*** resulting from V nerve lesions, herpes zoster ophthalmicus or following acid or alkali burns of cornea, along with protection of the anaesthetic cornea from extraneous trauma, it aids in relief of pain, helps epithelialization and prevents symblepharon formation in acid and alkali burns of cornea.
3. ***As keratoplasty splint.*** Soft lens may be used following keratoplasty as splints to support penetrating grafts. They are designed to lie entirely within the limbus. The immediate function of a splint is to serve as an intervening rigid membrane between the lid and graft, ideally allowing graft retention without sutures in the graft. It should be thin and have peripheral fenestrations to secure the graft to the peripheral cornea with thin suture material. It is debatable whether suturing techniques should be used only on the splint, and the peripheral host cornea and the graft itself contain no sutures. It is especially useful to protect the graft from injury and irritation by a scarred or deformed lid as in trichiasis or entropion in old-standing cases of trachoma and pemphigus.
4. ***As protective lens.*** It plays a role in protection of cornea in exposure keratitis from any cause and prevents drying of cornea. In trichiasis, it prevents rubbing of eyelashes on the cornea and helps in healing of the erosions already present.
5. ***As bandage contact lens.*** Soft lenses act as a bandage in cases of indolent ulcers, descemetocele, leaking wounds, recurrent erosions and Thygeson superficial punctate keratitis. In these cases, it helps by protecting the denuded cornea

and the newly formed epithelium from action of lids and exogenous trauma. It prevents epithelial breakdown in cases of recurrent erosions and provides a scaffolding over which the epithelium can grow.

In Thygeson superficial punctate keratitis, it is used in two groups of cases – those requiring corticosteroid therapy for relief of symptoms over a prolonged period and corticosteroid-dependent patients.

6. ***Bullous keratopathy.*** The insertion of lens along with hypertonic saline instillation results in relief of pain and improvement of vision by eliminating astigmatism. It is especially used in cases of aphakia with vitreous touch on the back of cornea, resulting in bullous keratopathy.

7. ***Corneal dystrophies.*** Soft lens is very helpful in improving vision in astigmatism and to relieve the pain in primary dystrophies of cornea such as Meesman juvenile epithelial dystrophy, Reese–Buckler dystrophy, fingerprint dystrophy, anterior membrane dystrophies, macular and lattice dystrophies. Fuchs' epithelial and endothelial dystrophies are also benefitted.

8. ***As drug delivery system.*** Recently, soft lenses have been used as a drug delivery system for drugs like pilocarpine, corticosteroids, idoxuridine, anti-fungal agents and antibiotics. Lenses with higher water content (60%–70%) allow increased permeability of drugs.

Soft lens provides drug to the cornea in a more efficient manner than conventional drops and so greater amounts of drug penetrates the cornea per given dose. The drug delivery depends on molecular weight of drug, thickness of the lens and water content of the lens. Clinical trials have shown that this method of drug delivery is especially useful in cases of acute and secondary glaucomas, for treatment of herpes simplex keratitis, indolent ulcer and fungal ulcers.

AFTERCARE AND GUIDELINES FOR USING A THERAPEUTIC CONTACT LENS

1. Always give importance to water content of the lens and the lens fit as per the requirement of the pathology for which it is indicated.
2. After fitting a therapeutic lens, always look for proper fit after 1 and 24 h of fitting.
3. Cleaning and disinfection of the lens should be done at least once in a month.
4. Do not allow the same lens in place for more than 3 months.
5. It is preferable to use a broad-spectrum prophylactic antibiotic.
6. Do not use phenylephrine, fluorescein, rose bengal, hypotonic saline, suspensions or any gels when therapeutic lens is in place.

COLLAGEN SHIELDS

- Collagen shield, a biodegradable therapeutic contact lens, is a comparatively new concept.
- As the collagen shields are biodegradable, so once used, there is no need to remove them for cleaning and disinfecting.
- Currently available collagen shields are made from pig sclera and are available in different forms that can last for 12, 24 or 72 h (or longer).
- The collagen shields may be used to protect and/or lubricate the cornea, or act as reservoir for delivering drugs to the eye. When used primarily to deliver antibiotics, these should be hydrated in the desired antibiotic solution.

COSMETIC SOFT LENSES

Cosmetic contact lens is a tented/painted lens used to enhance or alter the appearance of a normal eye. Hard corneal cosmetic or prosthetic contact lenses of various designs do not centre well, and their excessive movement and frequent dislocation from the corneal surface because of their excessive weight and smaller diameters mostly prove to be ineffective to achieve the desired results. Therefore, cosmetic and prosthetic soft lenses have been successfully produced by many laboratories. Soft lenses can be coloured by several techniques and used for prosthetic purpose. The technique should not affect the purity, safety, quality and leaching out of the colour substance used. These lenses should stand to heat treatment.

INDICATIONS

1. *Disfigured corneas* producing an ugly eye are the most common indication.
2. *Vision-disturbing conditions* requiring coloured contact lens are albinism, aniridia, iris colobomas, photophobia and diplopia, where vision is very much disturbed.
3. *Occlusion therapy*. In orthoptic treatment where occlusion of the pupil is required, the soft cosmetic lens with black pupil is recommended, especially in small children.
4. *To change the colour of the eyes.* Cosmetic soft lenses can be fitted to normal eyes to change their colour to give special effects for plays, movies and just for cosmetic purpose. Lens is made of clear pupil with the required power and of clear periphery not showing off the colour of the lens on the sclera. Diameter of iris can be made as per individual requirement. Blind eyes can be fitted with different types of lenses to give better cosmetic appearance.

FITTING TECHNIQUE

1. ***Firstly, a trial should be given by using a standard soft lens*** made of identical material which will later be used by the manufacturer to process cosmetic lens. Thickness and diameter should also be the same as far as possible. The exact power can be determined in the normal way as standard soft lenses are prescribed.
2. ***While fitting the lens in one eye, the colour and diameter of good eye is taken into consideration*** as a sample, and sometimes photographs prove to be quite useful to obtain a good match. The pupil diameter is measured mostly when the patient is working at close distance. This can be better measured with pupillometer. While placing the order to the manufacturer, diameter of the visible iris, pupil diameter and colour should be mentioned.
3. ***Common types of cosmetic contact lenses.*** In order to facilitate their easy fitting, some manufacturers have made small sets of cosmetic and prosthetic soft lenses of various types to fit different patients as follows:
   - *Black pupil lens*. It has a black central area of 5 mm, base curve 8.40 mm, diameter 14.30 mm (Fig. 8.21A). It is used for 'occlusion' for amblyopia therapy (patching), anti-suppression therapy, diplopia (pathological or physiological), mature non-operable cataracts, lens subluxation and iris hypertrophy.
   - *Clear edge with light brown tint lens*. It has base curve 8.70 mm, diameter 14.30 mm, tinted iris diameter 12.00 mm (Fig. 8.21B). It is used for cosmetic enhancement only.
   - *Clear pupil and clear edge with dark brown iris*. It has brown iris of diameter 11.50 mm, base curve 8.70 mm and total diameter 14.80 mm (Fig. 8.21C). It is used for photophobia, albinism, handling aid for aphakia, keyhole pupil, post-surgical glaucoma and cosmetic, polycoria and microcornea.
   - *Lens with black pupil and brown iris.* It has black pupil of 4 mm diameter, base curve 9 mm, diameter 14.80 mm with dark brown iris of 11.50 mm (Fig. 8.21D). It is used as cosmetic prosthesis in patients with corneal disfiguration, corneal scarring and decentred pupil.

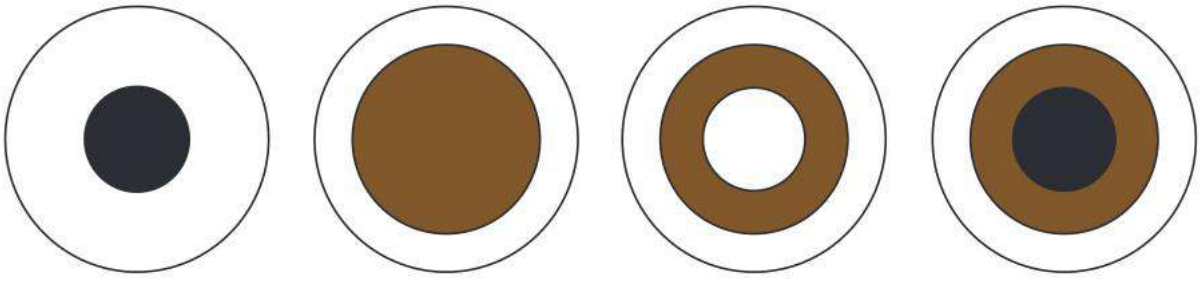


Fig. 8.21 *Common cosmetic contact lenses: A, black pupil lens; B, clear edge with light brown tinted lens; C, clear pupil and clear edge with dark brown iris; D, lens with black pupil and brown iris.*

Base curve, diameter of pupil, iris and overall diameter can be made to suit the requirements and on the basis of assessment that one makes after giving trial with one of the above-mentioned lenses.

CARE AND MAINTENANCE

Care and maintenance of these lenses is similar to other soft lenses. These lenses are quite safe and can be heat sterilized. The colour can withstand chemical disinfection and enzyme cleaning, but use of hydrogen peroxide or chlorine-releasing agents should be avoided. The tints are not affected by ultraviolet light and so the patients living in a hot, sunny climate are quite safe.

PROBLEMS AND THEIR MANAGEMENT

1. ***Toxic effects.*** In some cases, certain dyes used to colour or tint the finished lenses cause toxic effect, and most water-soluble dyes will not bind with the polymer for long period, hence the fading starts.
2. ***Corneal oedema.*** In certain cases, due to excessive thickness of the lens (because of painted portion having been sandwiched in between the polymer layers), oxygen transmission is reduced and chances of developing the oedema are there. However, this may not be a problem for the hopeless eyes.
3. ***Other problems*** are almost the same as faced with standard soft lenses such as protein, lipid and other deposits build-up, discolouration of clear portion at the pupil and periphery, drying of lenses, blanching of vessels, if fit is tight and movement is restricted. Lenses should be deproteinized like standard soft lenses. Practitioners' instructions should be strictly followed for the type of disinfecting system to be used.

COMPLICATIONS OF CONTACT LENS WEAR

With advances in contact lens manufacturing techniques, lens materials and improved hygienic measures, the frequency of complications related to contact lens wear has decreased. However, contact lenses do cause a variety of insults to the cornea and conjunctiva, including hypoxic changes, chemical toxicity, hypersensitivity reactions, mechanical trauma, desiccation and infections. These in turn can lead to a number of clinical complications.

Corneal Complications

1. Epithelial Oedema

Minor degrees of epithelial oedema is the commonest and earliest corneal change. It occurs due to hypoxia of corneal epithelium and is usually reversible.

2. Epithelial Microcysts

Pathogenesis. These are associated with a depressed corneal epithelial metabolism sustained over a period of weeks to months. These occur frequently with soft contact lenses and most commonly with EWLs.

Clinical features. Epithelial microcysts appear as fine dots of variable density and may be indistinguishable from Cogan microcystic dystrophy.

Management. These usually clear after the lens is removed. It is advisable to switch from extended wear basis to daily wear, or change from daily wear soft lenses to gas-permeable lenses.

3. Corneal Abrasions

Pathogenesis. These may be caused by mechanical injury from the lens itself or by traumatic insertion or removal. Occasionally, a foreign body embedded in the lens substance may also be responsible for corneal abrasions.

Clinical features. The patients usually complain of pain, redness and watering from the eyes. Fluorescein staining confirms their presence.

Treatment. Contact lenses should be removed and the patient should be treated with topical antibiotics. Patching is not recommended nowadays in contact lens-related abrasions due to danger of infection. After the abrasion heals, contact lenses can be reused, starting with 1 h a day and then gradually increasing the wearing time over a month.

4. Superficial Punctate Keratitis

Pathogenesis. Superficial punctate keratitis in a contact lens wearer may occur because of following factors:

- *Mechanical* injury from lens or traumatic insertion and removal.
- *Chemical toxicity* from contact lens solutions usually causes diffuse punctate keratitis. This may be due to preservatives in the saline solution, improper rinsing of the lenses after the use of surfactant or enzyme cleaner or failure to neutralize hydrogen peroxide disinfectant.
- *Associated external diseases* such as dry eye and blepharitis.

Management. Patients with punctate keratitis should discontinue contact lens wear until the epithelium heals. Lubricating drops and ointments can promote epithelial healing. Look for the probable cause and treat accordingly before reusing the lenses.

5. 3 and 9 O'clock Staining

Pathogenesis. It is caused by desiccation of the cornea due to interruption of tear flow or disruption of the tear layer at the nasal and temporal cornea. It may be associated with poor lens edge fitting, limited lens movements, low-riding lens, poor blinking, pinguecula and lens adherence. It occurs most commonly in RGP lenses.

Treatment. The recommended measures are refit with a larger-diameter lens, change of lens design, improvement of blinking frequency and quality, change of lens care system to improve wettability and use of eye lubricants.

6. Sterile Corneal Infiltrates

Pathogenesis. Sterile corneal infiltrates are the result of an inflammatory response to a specific antigen with resultant corneal infiltration of leucocytes from the limbal vessels. Preservatives in contact lens solutions have been identified as possible antigenic sources.

Clinical features. The sterile corneal infiltrates are usually small peripheral opacities, which may be located within the epithelium, subepithelially or in the anterior stroma. They are usually asymptomatic and detected during a routine follow-up examination. However, note that a corneal infiltrate may be an early manifestation of microbial keratitis.

Management. They usually disappear once contact lens wear has been discontinued. When they resolve, the patient may return to contact lens wear after switching to a non-preserved saline solution.

7. Corneal Neovascularization

Pathogenesis. Corneal neovascularization is often the result of chronic hypoxia, from excessive deposit formation on the lenses or from tight or thick lenses.

Clinical features. Corneal neovascularization may be superficial or deep, sectorial or extending 360 degrees into the cornea. Small amount (1–2 mm) of peripheral superficial vascularization is relatively common in extended and therapeutic lens wear. Greater than 2 mm of progressive vascular ingrowth or that involving the middle or deep stroma is uncommon.

Management. It is always better to prevent occurrence of neovascularization by careful fitting, regular follow-up examinations, use of high-oxygen-transmission lenses and discontinuation of contact lenses, if significant neovascularization is seen.

8. Microbial Keratitis

It is the most serious, but fortunately not very common complication of contact lens wear. It may occur with soft or rigid contact lenses but occurs with greater frequency with soft lenses in general and more so with extended wear contact lenses.

Pathogenesis of microbial keratitis involves an epithelial defect in the corneal surface, caused by a traumatic or hypoxic insult in the presence of microbial contamination. *Predisposing factors* for microbial contamination are poor personal hygiene, inadequate lens disinfection, contaminated lens cases or lens care

solutions, swimming while wearing contact lenses and associated external diseases like dry eye and blepharitis.

Causative organisms most frequently involved in lens-related corneal infections are *Pseudomonas aeruginosa* and *Acanthamoeba*. In addition, other gram-negative or gram-positive bacteria may also be associated with lens-related keratitis.

Clinical Features

Bacterial keratitis should be suspected in any patient with an acute onset of severe pain, regardless of the size of infiltrate. Clinical signs may include an ulcer covered by thick, adherent mucopurulent discharge. *Pseudomonas* corneal ulcers are characterized by a wide area of stromal oedema surrounding the ulcer, presence of a ring infiltrate around the ulcer and a hypopyon in advanced cases.

Acanthamoeba keratitis is more common in patients using home-made saline, swimming while wearing contact lenses and those with exposure to tub or tap water.

- *Early clinical features* of acanthamoeba keratitis include severe pain out of proportion to the clinical finding, irregularity in the epithelium and a patchy stromal infiltrate.
- *Late clinical features* include ring stromal infiltrate, radial keratoneuritis and elevated non-branching corneal epithelial lines.

Management. Every effort should be made to prevent this catastrophy. Overnight wear, which is a major risk factor for corneal ulcer in lens wearers, should be avoided. Better hygiene and compliance to cleaning and disinfecting procedures reduce the risk of corneal ulceration. It is also imperative that the patient receives proper instructions about early warning signs of corneal infection, so that it can be diagnosed early.

Once keratitis occurs, it should be treated energetically.

9. Corneal Warping

Corneal warping resulting in severe and permanent astigmatism may occur in some eyes as a response to chronic hypoxia, e.g. following prolonged wear of impermeable hard lenses.

10. Corneal Endothelial Changes

Both short- and long-term endothelial changes are reported to occur in contact lens wearers.

Pathogenesis of endothelial changes is not clear exactly. They are thought to be secondary to hypoxia which leads to lactate accumulation, elevated carbon dioxide levels and reduced pH.

Clinically two types of changes are seen:

- *Endothelial bleb response* is reported to occur minutes after use of a thick soft contact lens or rigid contact lens. This effect is transient and does not leave behind any sequelae. These changes resolve slowly after about 30 min of lens wear or rapidly after lens discontinuation.
- *Endothelial polymegathism and pleomorphism*, i.e. variation in cell size and shape is reported to occur after larger period of contact lens wear. These changes may be associated with an increased risk of corneal decompensation following intraocular surgery.

Prevention. The magnitude of endothelial changes can be reduced by encouraging the use of daily wear contact lenses over the extended wear contact lenses and the use of RGP lenses over rigid PMMA lens.

■ CONJUNCTIVAL COMPLICATIONS

1. Allergic Conjunctivitis

Pathogenesis. It is a common problem with thiomersal-containing contact lens solutions. Fewer soft lens care solutions now contain thiomersal.

Clinical features. The patient presents with redness, burning and itching soon after lens insertion. These symptoms may develop within days to months following the initial exposure to thiomersal. Examination reveals conjunctival hyperaemia and a fine papillary conjunctival reaction.

Treatment involves the avoidance of solution containing thiomersal. Diluted steroid eyedrops may be used for 3–4 days.

2. Giant Papillary Conjunctivitis

Pathogenesis. GPC has an immunological origin in which contact lens deposits, especially proteins, act as allergens. The incidence of GPC is influenced by patient susceptibility, wear schedule, care regimen and lens factors such as material and design. Soft lenses are most frequently implicated in causation of GPC. Patients with asthma, hay fever or animal allergies may be at increased risk.

Clinical features. Symptoms begin to appear after months or years of lens wear. These include ocular itching, increased mucus production in the morning, photophobia and decreased lens tolerance. Cobblestone-like giant papillae seen on the upper palpebral conjunctiva are the hallmark of full-blown picture.

Management. Occurrence of GPC can be minimized by having proper lens fit, frequent use of enzyme cleaners, regular replacement of lenses, avoiding heat disinfection and avoiding sleeping with lenses on regular basis.

Once GPC occurs, the measures include no lens wear for 1–2 months and use of sodium cromoglycate and steroid eyedrops. When the condition subsides, refit with new lenses may be made with adoption of above-described measures to prevent its recurrence.

3. Superior Limbic Keratoconjunctivitis

Pathogenesis. Superior limbic keratoconjunctivitis is reported to occur as hypersensitivity to thiomersal or other preservatives in contact lens solution.

Clinical features. The condition is usually bilateral but asymmetrical. The patients may complain of a foreign body sensation, redness and contact lens intolerance. Clinical signs include inflammation and hypertrophy of superior bulbar conjunctiva that stains with rose bengal, punctate staining and micropannus of the superior cornea, and a fine papillary reaction of the superior tarsal conjunctiva.

Treatment. The patient should be advised to discontinue wearing contact lenses and to use the lubricating eyedrops frequently. When the condition subsides, the patient may be given a new pair of properly fitting lenses and advised to use non-preserved saline and perform frequent lens cleaning.

CONTACT LENS-RELATED COMPLICATIONS

Contact lenses can be damaged/spoiled with time and create problems of various types. Lens spoilage may be physical due to alteration in the lens geometry and chemistry. The contact lens spoilage includes the following changes:

1. **Physical damage** to lens in the form of chipping or fracture may occur while handling, i.e. during insertion, removal or storage. Physical damage to lens may occur due to biochemical degradation of lens plastic which tends to get easily fractured or chipped.
2. **Discolouration of lens** may occur following topical use of fluorescein and phenylephrine and systemic use of rifampicin.
3. **Lens loss** occurs more often in children than adults. It is reported to occur more frequently in hard than soft and in EWLs than DWLs. A loosely fit lens which moves much more during blinking is more likely to get lost.
4. **Lens deposits.** Occurrence of lens deposits is not an uncommon problem. Deposits may occur with all types of lenses, i.e. extended wear soft lenses, daily wear soft lenses, RGP lenses and hard lenses – in order of the decreasing frequency.

Pathogenesis. Deposits originate from the tear layer, lens handling, cosmetics, topically instilled drug and the atmosphere pollutants like dust and fumes. Factors that affect the occurrence of lens deposits are as follows:

- Personal hygiene
- Defects on the lens surface, ageing and decaying of plastic
- Contact lens care regime
- Associated ocular diseases like blepharitis, meibomitis, lagophthalmos and dry eyes

Types of deposits. Mainly these are of two types:

- *Protein deposits* initially occur as clear transparent film that loses transparency and becomes a

diffuse milky coating over the entire surface of the lens.
- *Lipid deposits* occur as minute drop-like deposits, loosely bound to lens surface. A thick coating leads to poor wettability.

Effect of lens deposits. Lens deposits may produce following deleterious effects:

- *Physical lens damage.* Deposits may degrade the lens polymer, leading to lens distortion, lens discolouration and disturbed lens fit.
- *Physiological effect.* Lens deposits may impair the diffusion of gases across the lens.
- *Optical effects* of lens deposits include hazy vision, halos, distortion, polyopia, photophobia, aberration and astigmatism.
- *Toxic effects.* The lens deposits may accumulate toxic concentration of preservatives causing damage to cornea.
- *Infective effect.* The lens deposits are known to harbour bacteria and fungi responsible for infective keratitis.
- *Allergic effects.* Altered proteins of the deposits are well-known immunogens and are known to cause GPC, sterile corneal infiltrates and allergic conjunctivitis.

Management. The lens should be replaced when deposits are clinically significant. Ideally, DWLs should be replaced at least every 6 months and EWLs every 3 months.

Prevention. Deposits can be prevented by proper care and maintenance procedure including mechanical cleaning and regular enzyme cleaning. A proper follow-up and monitoring is of utmost importance.

CONTACT LENS SOLUTIONS AND CARE OF CONTACT LENSES

CONTACT LENS SOLUTIONS

Different types of solutions are used in contact lens practice. Some solutions are used only for hydrophobic rigid contact lenses and some for hydrogel soft contact lenses, while a few of them may be used for both types of lenses. In general, the various solutions available can be grouped as follows:

- Wetting agents,
- Cleaning agents,
- Storage (soaking) agents and
- Rewetting agents.

Sometimes these are provided by separate solutions, sometimes by one multi-functional solution (which is a combination of two or more of the above functions). Multi-functional solutions certainly enhance compliance by reducing the number of solutions the patient has to use.

All solutions contain components that are peculiar to the particular function of the solution, e.g. cleaning agent in cleaning solutions, the vehicle, buffering agents and preservatives at varying concentrations. Contact lens solutions, as distinct from other ophthalmic solutions, are usually formulated to contain as low a concentration of preservatives as possible in order to reduce the risk of any eye irritation. The range of preservatives includes benzalkonium chloride, chlorobutanol, thiomersal, chlorhexidine, ethylenediaminetetraacetic acid (EDTA), sorbic acid and potassium sorbate.

Initially when the gas-permeable materials were introduced, practitioners were concerned about the presence of benzalkonium chloride in the wetting/soaking solutions. But laboratory studies indicate that properly formulated hard lens care products do not absorb, affect the parameters or adversely affect the surface wetting properties of the presently available gas-permeable materials.

With the introduction of soft and gas-permeable lenses and contact lenses for prolonged wear, a great need of care systems that incorporate the use of surfactant cleaners, enzymatic cleaners, soaking solutions, heat for disinfection and chemical disinfecting has arisen.

1. WETTING SOLUTIONS

A wetting solution is an agent that coats the contact lens uniformly with a film which is intended to minimize the friction of contact lens against the palpebral conjunctiva and the cornea. This solution acts as a buffer or 'cushioning agent' but

only during a brief initial period, since it soon disintegrates to be replaced by the lacrimal fluid. This solution must meet accepted standards as regards to sterility, isotonicity, non-irritability and stability, and for initial comfort it should be buffered to pH of tears.

Essential Characteristics of a Wetting Agent

1. Should wet thoroughly and spread over entire surface of lens, rendering it hydrophilic.
2. Should form a film sufficiently tenacious so that it will not be washed away during the wearing period by tears.
3. Should be non-irritating and non-sensitizing.
4. Should not leave a residue of film on the lenses or around the skin.
5. Should have a cleaning and antiseptic action and should be self-preserving.
6. Should not interfere with wetting by the lacrimal fluid.
7. Should have the proper degree of viscosity for efficient lubrication.
8. Along with its function of wetting, cushioning and preservation, it should allow the lens to stick on fingertip during insertion and also should not allow oil of finger to get on lens.

Wetting Agents Commonly Used

- Polyvinyl alcohol
- Polysorbate 80
- Polyethylene oxide
- Cellulose-like derivatives (e.g. methylcellulose, etc.)
- PVP

2. CLEANING SOLUTIONS

It is self-evident that such a solution has two functions: that of a detergent which helps remove the lacrimal film and mucus deposits and that of a bactericidal agent. Moreover, it should not be detrimental, if accidentally instilled into the eye. In present day practice, two types of cleaners – the surfactant cleaner and enzyme cleaner – are used.

Surfactant Cleaners

At present, most of the cleaners in the market are *non-ionic surfactants*, functioning as a surface active cleaner. Most of them are preserved with thiomersal, potassium sorbate or sorbic acid. Some surfactants with polymeric beads are also available – tube polymeric beads acting as an abrasive on the lens surface for removing surface debris.

As we all know, the single most important event in debulking the lens of protein and debris on the surface is daily surfactant cleaning; this form of cleaning should be forcibly recommended for all types of lenses. There are also solutions of concentrated surfactants available for weekly cleaning, with a special cleaning container which has the 'washing machine' type of action on the contact lens – shaking off stubborn deposits.

Since the cleaning product is not meant for direct instillation in the eye, slightly stronger agents than those that can be tolerated by the eye may be used. The cleaning agents emulsify lipids, solubilize debris and remove accumulated contaminants most favourably in an alkaline environment (pH more than 7.4). Household cleaners should not be used like laundry detergents, dishwashing compounds, skin cleaners and hair shampoos because of their harsh action on lens surface or potential for damage to cornea.

Enzymatic Cleaners

Enzymatic cleaning is by far the best break the soft contact lens industry has achieved. The cleaning of bound protein and lipids from the surface of the soft and gas-permeable contact lens has solved a lot of problems of red eye and GPC, which the practitioners faced before. As enzyme cleaners, the tablets that have been around the longest are papain. Recently, the incorporation of the enzyme lipase has proven useful.

3. SOAKING SOLUTIONS

The soaking solution should possess adequate bactericidal properties since it serves as an antiseptic storage medium. The soaking solution maintains the lenses in a hydrated state. This may have some merit, although the question has not been settled as yet.

4. REWETTING AGENTS

Rewetting agents/artificial tears are used to rewet the corneal surface of eye or lens device while it is on the cornea, if required, by those lens wearers who cannot well tolerate the daily wearing schedule. Thus, these agents are of particular use in cases having.

- Feeling of lens awareness,
- Blurring of vision and
- Peripheral horizontal (3–9 o'clock) staining, which may be due to inability of tear film to distribute evenly over the lens. Rewetting solution may contain a viscous agent like polyvinyl alcohol or methylcellulose.

Commonly Used Agents

A few of the commonly used agents in various contact lens solutions are as follows:

1. ***Benzalkonium chloride.*** It is a cationic, surface active, quaternary ammonium germicidal agent. It is used in concentration varying from 0.004% to 0.01%. Cotton fibres render it inactive. This is the rationale for eliminating sponges from soaking kits. Strong solutions can cause superficial punctate disturbance in the corneal epithelium.

Soaking solution is designed to kill (whereas wetting solution is not); so benzalkonium alone would not appear satisfactory as soaking solution. EDTA is said to enhance the anti-bacterial action of benzalkonium.

2. ***Chlorobutanol.*** It has a synergistic action with benzalkonium chloride. It has many disadvantages when used as wetting solution:
   - It is unstable, so the concentration may fall below the desired level.
   - It dissolves only at higher temperatures.
   - It breaks into hydrochloric acid and hydrocarbons when pH is less than 6.
3. ***Thiomersal*** (0.04%). It is effective but the danger of sensitization is high and has a very slow rate of killing organisms.
4. ***Chlorhexidine*** is the most widely used. It is provided as a single solution to be used for both storage and disinfection, which means that the patient is not tempted to omit the disinfection step. This convenient method prolongs the life of the soft lens for about 2 years. The main disadvantage of chlorhexidine is the intolerance.
5. ***The hydrogen peroxide and povidone–iodine systems*** are double-step two-solution procedures requiring a neutralization step in each case. These more complex procedures are considered confusing and inconvenient by some wearers.
6. ***EDTA.*** It inactivates the metals in solution and prevents discolouration due to trace metals.
7. ***Polyvinyl alcohol.*** It provides good adhesiveness and affords great surface contact time.

CARE OF CONTACT LENSES

Whenever a person is prescribed contact lens, he or she must also be given detailed but easy-to-follow instructions regarding the care of the lenses. This is very important because damage to the lens may cause, apart from monetary loss, poor optical result and/or damage to the eyes. The patient must be instructed how to properly store the lens, how to clean the lens, how to maintain sterility of the lens in order to prolong the life of a contact lens and prevent any damage to the eye or lens.

There are many controversies regarding the storage, cleaning, etc. of lenses, but the following methods are quite satisfactory.

1. PERSONAL HYGIENE

The most important step in the maintenance of the quality of the lens is good personal hygiene. Hands should be thoroughly dried before contact lens is handled. Fingernails should be clipped and cleaned. The use of soaps with a hand cream or cold cream base should be avoided as these agents may deposit grease or oil on the lens.

2. REMOVAL OF LENS

The hands need to be meticulously washed with soap and rinsed well with water before attempting the removal of the lens. The hands should be thoroughly dried before lenses are

touched. The lens should also be cleaned before storage in the case.

3. STORAGE OF THE LENS

Hard lenses should be kept in a dry state in a simply shaped, preferably flat, case to fit in a pocket or purse. Lens case should be cleaned thoroughly at least every week. *Soft lenses* are stored in a wet state. For these, numerous types of hydrating kits are available, containing various combinations of solutions of thiomersal or chlorhexidine or quaternary compound. A good hydrating kit should not contain any sponge and inaccessible recesses. Lens should be put in hydrating kit after thorough cleaning and the kit should be filled with sufficient soaking solution to cover the lens. The hydrating kit should be cleaned thoroughly with soaking solution (or by boiling) twice a week.

4. ROUTINE CLEANING

Rigid lens. After the hands have been thoroughly washed and dried, the lens should be placed on the palm with its concave side up. The wetting solution is added on the lens till it overflows. The solution is rubbed for 15–30 s with the fingers of the other hand. The lens is then held between finger and thumb and held in the running water.

Soft lens. A soft lens is not washed with water. For this purpose, normal physiological saline or hypertonic saline should be used.

Lenses should not be dropped on hard surfaces, such as floor. If a lens drops on the floor, wet the finger and touch the lens lightly and pick it up. The lens should not be slid along the floor. A dry lens should not be rubbed as this sets up electrical charge which would attract foreign bodies.

After cleaning, the lens is held against the light to see any dry spots, foreign particles, oil/grease, etc. If any such thing is found, the entire process of cleaning is repeated. Cleaning is meant to remove the contaminants and hence prepare the lens for adequate disinfection – a dirty lens being more difficult to disinfect than a clean lens.

The cleaning solutions contain saline, buffer, hydroxyethyl cellulose, polyvinyl alcohol and preservatives like thiomersal and EDTA. The cleaning solution should be such that in case, by mistake, the lens has been stored in it or after cleaning the lens has been inserted directly into the eye, it should not cause ocular damage.

5. ENZYME CLEANING

This may be used for cleaning the lens once a week. Commonly used enzyme is papain. The enzyme tablet is dissolved in distilled water and the lens is left in this solution for 4 h. The lens should not be placed directly into eye after enzyme cleaning but should be rinsed clear of the enzyme. It is more effective when used in combination with heat disinfection, probably because denatured protein is more easily attacked by enzymes. It is more effective for protein coating. However, the enzyme cleaning also decreases the incidence of heavy coating with lipids because a layering of protein leads to formation of lipid–protein complexes which bind effectively with lens surface. Heavily coated lenses are often not restored to full use by enzyme system alone. Tendency of the lens to decentre is more marked after repeated enzyme cleaning.

6. DISINFECTION

Disinfection involves destruction of vegetative microorganisms – with only limited effect on sporing microorganisms – in contrast to sterilization, which means removal of vegetative and sporing microorganisms. Two techniques are available: moist heat disinfection and chemical disinfection.

Thermal Disinfection

There are several types of saline (0.9% sodium chloride) solutions available – most of them are used for rinsing only. *Sterile thiomersal, potassium sorbate-preserved salines* are normally recommended for heat disinfection. A new saline-based solution of thiomersal with EDTA is now being encouraged for heat disinfection as the EDTA helps in removing the calcium off the lens surface. Boiling the soft lenses in this

preserved saline before cleaning them in the enzymatic cleaners has shown to clean the lens much better, and also prevents the build-up of protein on the lens surface due to the absence of rough surface created by the calcium crystal deposits on which the proteins and lipids tend to bind. Due to increasing thiomersal hypersensitivity, the most popular saline for heat disinfection is the unpreserved saline. Boiling can be accomplished as follows:

- Boiling in a container with saline solution at 80°C for 10–15 min, so that vegetative forms of bacteria and fungi are inactivated.
- Suspending lens case in a column of steam forms boiling distilled water, say, in a tea strainer.
- Refinement of above procedure so that a temperature of more than 100°C is achieved with 5 lbs of steam pressure.

A saline rinse of lens before insertion is necessary to ensure hydration.

Chemical Disinfection

Cold disinfecting systems are very popular nowadays. Due to the binding problem of the *chlorhexidine*-based solutions, there are now very few solutions available with chlorhexidine as a preservative. The most popular ones are with *thiomersal-alkyl triethanol ammonium chloride* and *thiomersal-sorbic acid* or *potassium sorbate.*

- There is also the *hydrogen peroxide system* which is recommended for hypersensitive eyes.
- Hydrogen peroxide 3% for 10–15 min is used. Neutralization of hydrogen peroxide should be done by rinsing several times in normal saline and soaking in 2.5% sodium thiosulphate for 15 min. Residual hydrogen peroxide usually does not cause corneal damage but causes burning of the eyes. However, it can cause punctate keratitis. No greater lens deterioration has been experienced by this method of disinfection.
- The introduction of the *chlorine tablets used with distilled water* has also proved a great success as no preservative is required.
- *Iodine-based solution*. Iodine is reduced to iodide, which is the active disinfecting agent. It has excellent anti-microbial capabilities and is a non-binding preservative. The colour of the solution indicates the functional disinfectant state of the solution – when colourless, it has only preservative action.

7. SOME SPECIAL LENS CARE TECHNIQUES

i. ***In women.*** The problem is contamination with cosmetics. The users should insert the lens before cosmetics are applied. For make-up, liquid, non-greasy material should be used. Compact powder is better than cream with oil base – but powder should be applied very carefully as tiny particles can act as a foreign body.

- Mascara, if used, should be of waterproof variety and applied only at the tip of lashes.
- Nail polish and perfumes should be used very cautiously because these stains are difficult to remove.
- Hair spray should not get into the eyes as it may actually damage the eyes.

ii. ***In men.*** The problem is contamination of the lens by hair oils. Men should be cautioned against the contamination with occupational oils, gasoline or tobacco stains.

iii. ***In children.*** The problem is carelessness of the child. The parents should supervise and set a strict daily routine for the child to follow.

8. SPECIAL CLEANING

Occasionally, a lens becomes contaminated with grease, paint, nail polish and so requires special cleaning. Materials for removing such contaminants must necessarily be a strong detergent or solvent, which could be dangerous, if handled wrongly. Therefore, special cleaning should be left to the laboratory.

9

Intraocular Lenses: Optical Aspects and Power Calculation

Chapter Outline

GENERAL CONSIDERATIONS

Presently, intraocular lens (IOL) implantation is the method of choice for correcting aphakia. Its advantages and disadvantages over spectacles and contact lenses are discussed in the description of aphakia (see pages 78–80). The first implant was attempted in about 1795 by the Italian ophthalmologist Casamata, who used a glass lens. However, the IOL implant history had its real beginning on 29 November 1949, when Harold Ridley, a British ophthalmologist, implanted a lens made of polymethyl methacrylate (PMMA). Since then the history of IOLs has always been exciting, often frustrating and finally most rewarding.

TYPES OF IOLS

During the last 70 years, a large number of different types and styles of lenses have been developed. Undoubtedly, reviewing the evolution of IOLs in the last half century will be fascinating but, unfortunately, it is beyond the scope of this

chapter, which is devoted to the optical aspects of IOL. However, it will not be out of place to mention that from Ridley's first lens implantation to the present day, the evolution of IOL can be arbitrarily divided into eight generations:

- The rigid posterior chamber IOL (PCIOL) belongs to the fifth generation,
- The foldable IOL to the sixth generation,
- Multifocal IOLs to the seventh generation and
- Phakic refractive lenses (PRLs) and accommodative IOLs to the eighth generation.

Presently available IOLs can be grouped as follows.

I. BASED ON THE METHOD OF FIXATION

The major classes of IOLs based on the method of fixation in the eye are as follows:

1. *Anterior chamber IOLs (ACIOLs).* These lenses lie entirely in front of the iris and are supported in the angle of anterior chamber. ACIOL can be inserted after intracapsular cataract extraction or extracapsular cataract extraction. These are not very popular due to comparatively higher incidence of bullous keratopathy. When indicated, 'Kelman Multiflex' (Fig. 9.1A) type of ACIOL is used commonly.

2. *Iris-supported lenses.* These lenses are fixed on the iris with the help of sutures, loops or claws. Iris-supported lenses are of two types: prepupillary and retropupillary.

- *Prepupillary iris claw lenses* are not very popular due to a high incidence of postoperative complications. Example of iris-supported prepupillary lens is Singh and Worst's iris claw lens (Fig. 9.1B).
- *Retropupillary iris claw lenses* are fixed/clawed behind the iris (Fig. 9.1C). Cosmetically, these are more acceptable and it is very difficult to differentiate these

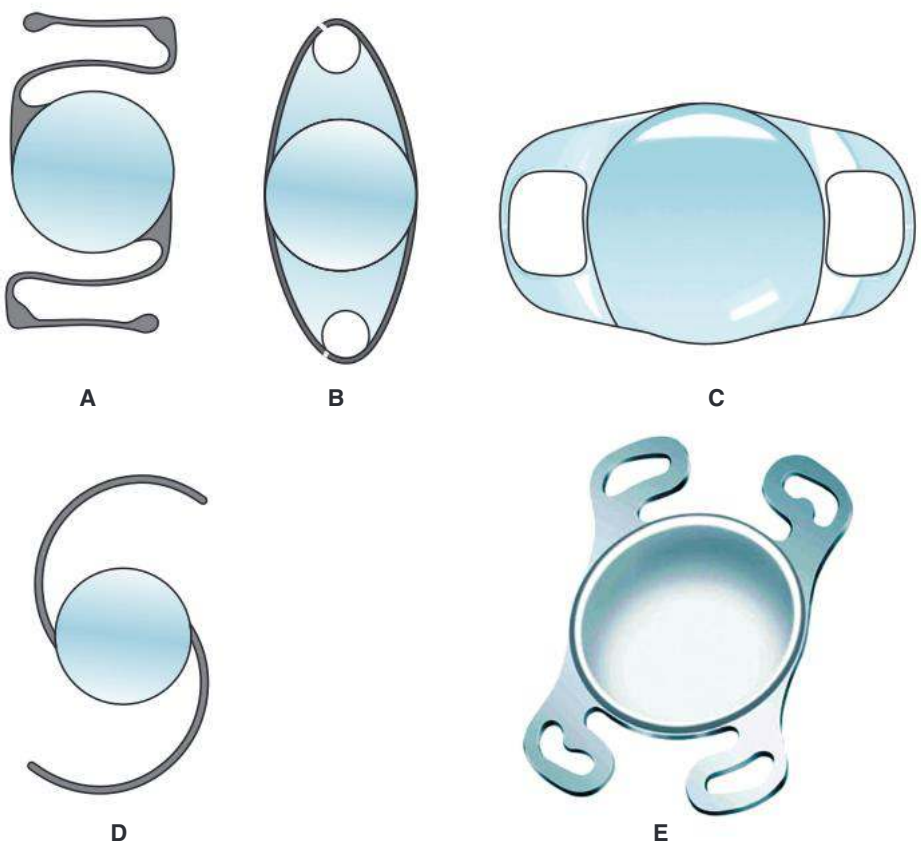


Fig. 9.1 *Types of intraocular lenses: A, Kelman Multiflex (an anterior chamber IOL); B, Singh and Worst's iris claw lens; C, retropupillary iris claw lens; D, posterior chamber IOL – modified C-loop type; E, Posterior chamber quadriloop.*

from PCIOLs. In addition, these are not associated with anterior segment/angle complications. Since posterior pigment epithelium of iris is more resistant so that less chances of iris chafing and displacement/loss of IOL. Long-term safety and efficacy of these retropupillary iris claw lenses are still under study/evaluation. These IOLs are useful in the absence of capsular support.

3. ***Ciliary sulcus and capsular bag supported PCIOLs.*** These lenses rest entirely behind the iris. They may be supported by the ciliary sulcus or the capsular bag. Recent trend is towards 'in-the-bag-fixation'.

- *Based on the haptic style,* the PCIOLs may be divided into loop haptic IOLs and plate haptic IOLs.
- *Commonly used models of PCIOLs* are modified J-loop, modified C-loop (Fig. 9.1D) and quadriloop (Fig. 9.1E).

4. ***Scleral-fixated IOLs.*** These IOLs are used in the absence of capsular support. There are two main techniques of scleral fixation of IOLs:

i. Sutured scleral-fixated IOLs. Commonly used IOLs are:

- *Standard one- or three-piece PCIOL.* Some suture fixation techniques involve tying knots directly to the haptic of a one- or three-piece IOL.
- *Special scleral-fixated IOLs with eyelets* in the haptic include:
  - Alcon CZ70BD PMMA lens contains eyelets along the haptics that facilitate suture fixation and requires a 7 mm incision, as it is not foldable.
  - Bausch and Lomb Akreos AO60 hydrophilic acrylic lens contains four eyelets through which suture can be passed, providing 4-point fixation.
  - Bausch and Lomb enVista MX60 IOL is a hydrophobic acrylic IOL that contains eyelets at the two haptic-optic junctions.
  - Zeiss CT Lucia 602 is a three-piece hydrophobic acrylic IOL with polyvinylidene fluoride (PVDF) monofilament haptics.

II. BASED ON THE MATERIAL USED FOR MANUFACTURE

The commonly used materials for manufacturing of IOLs are described here. Their advantages and disadvantages are summarized in Table 9.1.

1. Rigid PMMA IOLs. The commonly used material for manufacture of IOLs is PMMA. It is a rigid, chemically stable compound. Its excellent optical properties have been demonstrated through years of experience with PMMA contact lenses. PMMA has a relatively high index of refraction (IR). As with other lens materials, it may vary somewhat with temperature and water absorption. The specific gravity of PMMA is about 1.2 and thus is much closer to neutral buoyancy than the much heavier glass. The use of glass as an implant material has been abandoned because of its weight and its tendency to shatter when subjected to laser irradiation in the course of secondary laser procedures.

2. Foldable IOLs. These lenses have become popular after the success of phacoemulsification technique of lens extraction through a small incision. The foldable lenses are available in many different designs and are made up of silicone, acrylic or hydrogel.

i. *Silicone IOLs.* These are made from a number of formulations of polyorganosiloxane. Silicone polymers have a lower IR (n = 1.43) than PMMA (n = 1.49) and thus must be thicker for the same refractive correction.

ii. *Hydrogel IOLs.* These lenses are generally manufactured from polyhydroxyethyl methacrylate. Like silicone, hydrogel lenses are sufficiently flexible to be inserted through a small incision. The IR of hydrogels is also 1.43. Hydrogel lenses have a water content of approximately 3.8%. They are smaller in their dry state and swell upon hydration. For instance, a 4.3 mm dry optic can expand to 6 mm when implanted.

iii. *Acrylic IOLs.* Currently acrylic is the most commonly used material group; these

Table 9.1 *Advantages and disadvantages of commonly used IOL materials*

IOL materials	Advantages	Disadvantages
PMMA	High optical quality Large optical centre Proven biocompatibility Possibility of surface modification Good laser resistance	Large incision wound Not autoclavable Mild foreign body reaction
Soft acrylic	Foldable Controlled unfolding Good laser resistance Good biocompatibility Good optical quality	Limited experience Possible damage during implantation Sticky surface can adhere to instruments
Hydrogel	Good laser resistance Good biocompatibility Good optical quality Easy handling	Lack of long-term experience
Silicone	Good biocompatibility Less CME	Irreversible adherence to silicone oil Can tear Slippery when wet Limited control during Implantation Long-term discoloration

polymers of acrylate are foldable under room temperature. They are of two types:

a. *Hydrophilic*, as the name suggests, absorbs and retains water. Water acts as a plasticizer for the polymer chains and polymer folds. It is the consistency and the ability of the material to take up and retain the water. Hydrophilic material does not possess tackiness. The reason is simple – water is not tacky. It makes hydrophilic IOL freely movable and easily injectable. However, since it does not easily adhere to the capsule, it has a higher rate of posterior capsular opacification (PCO).

b. *Hydrophobic* material absorbs water to minimal amount. The molecular orientation of hydrophobic material, even if varies from batch to batch, may not lead to significant change in its applicable characteristics, as these characteristics are not dependent on the molecular orientation but on the molecules themselves. Hydrophobic material is tacky. Such a lens will not move easily in bag once implanted. It also adheres well to the capsule reducing the rate of PCO.

3. **Rollable IOLs or ultrathin IOLs**. These lenses are required to be implanted through a –2 mm subincision after microincision cataract surgery or the so-called phakonit technique. Some examples of commercially available ultrathin IOLs for microincision cataract surgery are as follows:

- ***Acri. Smart*** lens is a hydrophilic acrylic lens with 25% water content and a hydrophobic coating. The overall design is that of a plate haptic lens with square edges.
- ***UltraChoice 1.0 Rollable Thin Lens (ThinOptX, Abingdon, Virginia).*** It is a recently developed lens that can be inserted through a sub–2-mm incision (1.45 mm). It is manufactured from a hydrophilic acrylic material with 18% water content. The refractive index (RI) of the material is 1.47. The dioptric power of this lens ranges from –25 to +25 D. The optical thickness is 300–400 µm, with a biconvex optical configuration having a meniscus shape. The overall diameter of the lens is 11.2 mm,

and the optical diameter is 5.5 mm. Ultrathin properties of the lens are attributable to its optical design. The optic features three to five concentric optical zones with steps of 50 µm. Each Fresnel-like ring or segment of the lens has a small change in the radius to correct for spherical aberration (SA). The difference in radius is stated to ensure that each ring of the lens focuses light at nearly the same point as the prime meridian.

- ***Medennium Smart lens***. It is made of thermoplastic hydrophobic acrylic gel polymer.
- ***SlimFlex lens***. It is made of 26% hydrophilic acrylic material. It is not of plate haptic design but has a 360-degree square edge optic, four haptics and 5-degree angulation between optic and haptics.

Other rollable IOLs include AcriFlex MICS 46CSE IOL (Acrimed GmbH, Berlin, Germany); CareFlex IOL (W2O Medizintechnik AG, Bruchsal, Germany); SuperFlex and C-flex IOLs (Rayacryl Rayner Intraocular Lenses Ltd., UK); IOLtech microincision lens (IOLtech S.A., Zeiss Meditec A, Jena, Germany); and TetraFlex KH-3500 microincision lens (Lenstec Inc., Florida, USA).

Injector system for ultrathin IOLs. These lenses are injected into the eye using specially designed systems such as the Acri. Smart Glide System (Acri. Tec GmbH) for Acri. Smart IOLs. The system includes a special cartridge (Acri. Glide cartridge) and a specially designed injector. The Acri. Smart Glide System facilitated the injection of the lens through a sub–2-mm incision.

III. BASED ON FOCALITY (FOCUSING ABILITY)

Based on focusing ability, the IOLs are of two types:

1. ***Monofocal IOLs*** are the conventional IOLs having unifocal power. Depending upon the power of IOLs implanted, these can make the patient emmetropic, myopic or hypermetropic.
2. ***Multifocal IOLs***, as the name indicates, have optics to focus for distant as well as near vision. These are based on either refractive optics or diffractive optics. These are also called simultaneous vision lenses. (For details, see page 321.)
3. ***Pseudoaccommodative IOLs***. For example, the AcrySof ReSTOR (MA60D3 or SA60D3) with its apodized diffractive optic provides to the patients an excellent near visual acuity without compromising distance vision. This IOL has an anterior conventional refractive surface that provides the distance-vision power and a posterior concentric diffractive plate that provides additional near-viewing power ranging from +2.5 to +4.5 D.
4. ***Accommodative IOLs***. These IOLs exhibit anterior movement of the optic to improve near vision. Example of accommodative IOLs is Crystalens. (For details, see page 335.)
5. ***Extended depth-of-focus (EDOF) IOL***, e.g. TECNIS Symfony IOL, which allows extended range of vision due to an elongated focus area (instead of several focus areas of multifocal IOLs).
6. ***Trifocal IOLs.*** These are newer lenses which allow distant vision, intermediate vison and near vision. Examples include Alcon PanOptix trifocal IOLs and Zeiss AT LISA Tri.

IV. APHAKIC VERSUS PHAKIC REFRACTIVE LENSES

In addition to the aphakic IOLs, which are implanted after lens extraction, special phakic IOLs have been developed which are placed between the cornea and the crystalline lens. Three types of PRLs are available.

1. ***Posterior chamber sulcus-fixated PRLs*** are designed to vault the crystalline lens. Examples of posterior chamber PRL are as follows:
   - ICL by STAAR Surgical and
   - PRL by IVI-Medennium.

   (For details, see page 430)
2. ***Angle-supported PRLs*** are designed to have long legs (haptics). The best-known lens is NuVita MA20, a third-generation Baikoff lens design, by Bausch & Lomb Surgical, France.

3. ***Iris-supported PRLs***. The best known as of today is *Artisan lens.*

V. BASED ON SPHERICITY AND TORICITY

These include spheric IOLs, aspheric IOLs and toric IOLs.

1. Toric IOLs now provide the opportunity to correct corneal astigmatism, offering patients with pre-existing astigmatism optimal distance vision without the use of spectacles or contact lenses with a cylindrical correction. Shimizu *et al*. presented the first toric IOL in 1994. This was a non-foldable three-piece toric IOL made from PMMA.

Currently available toric IOLs are foldable, some of the examples are as follows:

- AcrySof (Alcon) – Hydrophobic acrylic
- T-flex (Rayner) – Hydrophilic acrylic
- STAAR (STAAR Surgical company) – Silicone
- Acri. Comfort (Carl Zeiss) – Hydrophilic acrylic

Indications for toric IOL implantation. Patients with regular astigmatism (otherwise having good vision potential and without any coexistent ocular pathology) which might need correction for astigmatism, should be considered for toric IOLs.

Toric IOL power calculation. It requires accurate keratometry and consideration for surgically induced astigmatism (SIA), which depends upon the size of the incision. AcrySof toric IOLs require a 2.2 mm incision for IOL implantation. These incisions have been shown to induce an SIA of 0.2–0.3 D for temporal incisions and 0.4 D for superior incisions. (For details of IOL power calculation for toric IOLs, see page 362.)

Technique of toric IOL implantation. IOL implantation requires a proper pre- and intraoperative marking of axis:

- The first step consists of preoperative marking of the horizontal axis with the patient in upright position to correct for cyclotorsion. This may be done with the patient seated at the slit lamp and with a coaxial thin slit turned to 0–180 degrees.
- Another technique to mark the horizontal axis is by using a bubble marker, such as a Nuijts/Lane Toric Reference Marker (ASICO) or by using a gravity marker with a calibrated horizontal position.
- Intraoperatively, the preoperative horizontal marks are used to position an angular graduation instrument. The actual alignment axis is marked using a toric axis marker.

Newer techniques to ensure accurate intraoperative toric IOL alignment described are as follows:

- *Iris-fingerprinting technique*, described by Osher, in which preoperative detailed images of the eye are obtained. The desired alignment axis is drawn in this image.
- *Intraoperative wavefront aberrometry* is a device connected to the operating microscope and enables intraoperative measurement of residual refraction.
- *Verion image-guided system* uses real-time eye tracking, based on iris and blood vessel characteristics. Preoperatively, a detailed image of the eye is captured, in which blood vessel and iris characteristics are visible.

Rotational stability is a crucial factor in the safety and efficacy of toric IOLs, since as little as 10 degrees of axis misalignment reduces the efficacy of the astigmatic correction by 33%. *Factors responsible for rotational stability* include:

- *IOL material.* Hydrophobic acrylic lenses have the highest bioadhesion property between the IOL and the capsular bag followed by hydrophilic acrylic, PMMA IOLs and finally silicone IOLs. Fibronectin is the primary extracellular protein involved in adhesion to the bag in hydrophobic acrylic lenses, which provides high rotational stability.
- IOL design. Currently available toric IOLs have a total IOL diameter ranging from 11 to 13 mm, which has been shown to be effective in avoiding IOL rotation. Prinz *et al*. recently compared plate-haptic and loop-haptic acrylic IOLs and did not find a significant difference in early and late rotation.

Post-operative assessment of the axis. If there is a misalignment of more than 10 degrees, then repositioning may be required. Realignment of a rotated toric IOL should ideally be performed preferably before 2 weeks because of the formation of adhesions between the capsular bag and the IOL optic.

2. Aspheric (negative spherical) IOLs have been designed to reduce SAs. SA occurs when parallel rays of light do not focus on one point. The refractive power in the periphery of the lens may either be too weak or (usually) too strong. When the peripheral rays of light focus in front of the central rays, it is called positive SA, and if behind the central rays, it is called negative SA. The cornea has positive SA which in young patient gets compensated by negative SA of the lens. The lens grows over in lifetime. In the process, it gets thicker. Its refractive error also increases. Hence, the lens develops a positive SA with age. So overall, the eye has positive SA in old age due to additive effects of the SA of cornea and lens leading to reduced contrast sensitivity. Conventional spherical IOLs have a positive SA, resulting in reduced contrast sensitivity under mesopic and scotopic conditions. Aspheric IOLs like the TECNIS (AMO), AcrySof IQ (Alcon) and Akreos AO (Bausch & Lomb) minimize the SA resulting in improved vision. Initial clinical results with these lenses have shown improvement in contrast sensitivity under low luminance and high spatial frequencies when compared with fellow eyes implanted with conventional IOLs and has improved patients' night driving simulator performance. However, decentration greater than 0.5 mm will decrease the functional vision when compared to spherical IOLs.

VI. BASED ON EDGE FINISH

Based on edge finish the IOLs are of the following types:

- Ridge IOLs,
- Square edge IOLs and
- Sharp edge IOLs.

VII. SPECIAL FUNCTION IOLs

The IOLs have been developed to provide some special function in addition to correcting aphakic special function IOLs. Examples are as follows:

1. ***Aniridia IOLs.*** These lenses were devised to cosmetically cover the defects of aniridia or partial iris loss in cases like trauma. The following two lens models are available:
   - For partial iris damage, a ring with one black segment added to it can be implanted in the damaged area.
   - For extensive iris damage, a multisegmented ring is available. These lenses are best used, if these are secured within the capsular bag or when suturing of the lens is done.

2. ***Implantable miniature telescope***. The implantable miniature telescope, manufactured by VisionCare Ophthalmic Technologies (Saratoga, California), is a unique visual prosthetic device designed specifically to improve vision of patients suffering from late-stage age-related macular degeneration (ARMD). The second-generation telescope is a wide-angle version of the device that allows for a larger view of the central visual field than previous models. This device is an optical apparatus comprised of two main components: a pure glass optical cylinder and a carrying device constructed from standard biocompatible materials suitable for implantation in the eye. The optical portion contains ultraprecise, wide-angle microlenses that provide retinal image enlargement of the central visual field. Two models are available, allowing for a magnification of ×2.2 or ×3, with an enlarged retinal image produced over approximately 52–60 degrees of the central retina. The carrying device is comprised of a clear carrier and a blue light restrictor. The carrier has two modified C-loops that hold the prosthetic device in the capsular bag. Once secured inside the bag, the anterior window of the optic extends marginally through the pupil. It is designed to allow a clearance of approximately 2–3 mm from the corneal endothelium.

3. ***Piggyback IOL.*** An eye with a shorter axial length (AL) requires a stronger IOL. As IOL powers become too high however, the lens becomes too spheric and image quality decreases. Using two lenses to obtain a needed high-power correction results in an optically superior image compared with that obtainable by a single lens of required power. Thus, for short or nanophthalmic eyes so-called piggyback IOLs represent a viable solution. Piggyback minus lenses have been used in eyes of long ALs alone or combined with high corneal curvature to achieve minus powers commercially unavailable in a single lens. Piggyback IOL can also be inserted in two stages, with the second IOL inserted (in the ciliary sulcus) to correct an undesirable refractive result following the initial IOL implantation. Refractive results in adding a piggybacked IOL as a second procedure should be superior to that of an IOL exchange for several reasons. First, the power of the second IOL is based only on the postoperative refraction. Second, the surgeon cannot be certain that an exchanged IOL would be in exactly the same plane as the IOL it replaced. Third, the accuracy of the power labelling of the first IOL is irrelevant, because of the first reason. Fourth, these added IOLs tend to be of lower power, and vergence distance changes are less important with lower power lenses. One occasional curious finding in piggyback lenses is an apparent increase in the depth of focus.

These advancements in IOL have transformed cataract extraction to a refractive surgery nowadays. Now the patient demands beyond 6/6 distant visual acuity from IOL implantation. Each IOL has its own pros and cons and judicious reasoning is required while deciding which IOL to implant to a particular patient. Still there is no substitute that provides all the functions of the natural lens and further research and development is required for the creation of an ideal IOL.

4. ***Smart yellow IOLs.*** These are the photochromic lenses, which have an ultraviolet (UV) near blue absorption curve similar to blue blocking lenses but only in photopic condition. Thus, they behave like a clear lens in mesopic and scotopic conditions. These are made up of hydrophobic acrylic material.

5. ***Blue blocking IOLs.*** These IOLs are based on the concept that normal human lens turns yellow with age due to oxidation of tryptophan and glycosylation of lens proteins which leads to progressive absorption of blue range wavelength. This protects the lipofuscin containing retinal pigment epithelial (RPE) cells from blue light damage, which may result in reducing the risk of ARMD.

Examples include AcrySof SN60AT IOL, which has hydroxybenzophenone, and hydroxyphenylbenzotriazole as chromophores absorbs visible blue light (200–550 nm). This may cause decrease in night vision since blue light is important for scotopic vision.

OPTICAL ASPECTS OF IOLS

Various optical aspects of the IOLs which need emphasis are as follows:

- Optical correction of aphakia with IOLs,
- Optical factors in IOL design,
- Optical goals in IOL implantation,
- IOLs and near vision,
- Optical aspects of IOL – spectacle combination,
- Optical results of IOL implantation and
- Optics-related complications of IOLs.

OPTICAL CORRECTION OF APHAKIA WITH IOL

The capsular bag fixated PCIOL is the most physiological method of optical correction of aphakia. IOLs avoid most of the optical problems associated with other corrective modalities, viz. spectacles and contact lenses (see also pages 78–80).

Optical advantages of IOLs are as follows:

- Image size approximates the baseline.
- Visual field changes are essentially avoided.

- Prismatic effects of thick spectacle lenses are eliminated.

OPTICAL FACTORS IN IOL DESIGN

The optical factors in IOL design which affect the quality of the optical image produced by the IOL are as follows:

1. ***IOL power.*** The power of IOL is the main factor affecting the image produced by it. The calculation of IOL power will be discussed later. Optical defects in an IOL related to power are as follows:

- Incorrect power specification, which may cause post-operative under- or overcorrection,
- Built-in astigmatism and
- Built-in double vision, which may cause monocular diplopia.

2. ***IOL optic design.*** The lens optic shape or design will influence its A-constant and post-operative anterior chamber depth (ACD) and thus will affect the IOL power. Theoretically, it has been suggested that the ideal IOL should be located in the posterior chamber and should be a biconvex lens in which the posterior curve should be approximately three times steeper than the anterior; i.e. the configuration of the lens should be similar to the normal crystalline lens. It has also been pointed that a biconvex lens will have fewer reflections from the lens surface as compared to a lens with plane surface. Some workers have recommended the use of aspheric IOLs to minimize SA. On the other hand, it has also been suggested that an aspheric lens might suffer more image degradation from decentration than a biconvex lens.

3. ***Optical effects of positioning holes.*** Optical aberrations may be produced by the positioning holes even by high-quality well-centred IOLs when the pupils are relatively dilated, such as at night. Slight asymmetric placement or decentration may pose this problem even with undilated pupil. The problem due to centring holes is more seen in IOLs of 6 mm optic size as compared to those of 7 mm. The factors related to positioning hole complaints are as follows:

- Size of the hole,
- Size and reactivity of the pupil,
- Diameter of the clear optical zone of the lens and
- Distance between the posterior surface of iris and the anterior surface of IOL.

4. ***IOL haptic design.*** Haptic designs may also influence the axial position of the lens, thus influencing the effective power of the lens optic. The effect of angulation and haptic design is taken care of while calculating A-constant of the IOL.

5. ***Lens transmission characteristics.*** There are many transmission characteristics of the lens material which need to be considered with the optical aspects of IOL. A few of them are as follows:

- *UV absorption.* The human crystalline lens partially absorbs near-UV and short-wavelength visible radiation (320–450 nm). As the lens ages, this absorption increases as a result of chromophore formation and lens yellowing. Ordinary PMMA IOLs absorb very little UV light. Evidence suggests that the increased amount of UV light reaching the pseudophakic retina has the potential to cause retinal damage. Keeping this in view, some manufacturers have added chromophores to create UV-absorbing IOLs. The two classes of chromophores generally used are the hydroxybenzophenones and the hydroxyphenylbenzotriazoles. It is as yet unclear whether UV-absorbing IOLs actually make any difference in the incidence of clinical retinal disorders. Otherwise, UV-absorbing lenses appear to be chemically safe for intraocular implantation, but they are at higher risk for chipping during YAG-laser posterior capsulotomy.
- *Chromatic aberration.* It has been reported that the plastic IOLs that allow transmission of wavelengths as short as 300 nm produce almost a doubling of chromatic

aberration of the image reaching the retina compared with the chromatic aberration in the phakic eye. This effect of IOLs may be responsible for the complaints of increased glare sensitivity noted by the pseudophakic patients.

- *Colour vision perceptions.* It has been observed that in terms of total colour balance, the pseudophakic eyes receive more red and less blue than the phakic eyes.
- *Light scattering.* It has been suggested that the plastic IOLs scatter about two to three times more light than the normal crystalline lens. Because of this, for a fixed increase in glare luminance, the decrease in visual acuity is more marked in pseudophakic eyes than in phakic eyes.
- *Contrast sensitivity function.* Contrast sensitivity is decreased in pseudophakes as compared to the normal phakes. But it has been reported that contrast sensitivity function is much better in pseudophakes as compared to the spectacle-corrected aphakes.

OPTICAL GOALS IN IOL IMPLANTATION

The IOL implantation is preferred over spectacle correction of aphakia because of its obvious optical advantages. The crucial requirement for comfortable and useful binocular vision following cataract surgery is minimization of aniseikonia. Therefore, the optical goal in IOL implantation should be to produce such a refractive condition that will minimize the aniseikonia. The optical strategic goals in selecting the desired IOL power are as follows:

1. ***Pseudophakic emmetropia.*** Usually it is aimed to make the pseudophakic eye emmetropic. However, some surgeons prefer to aim for slight residual myopia because of two reasons: (i) to compensate for possible error in the final results and (ii) to partially mask the lack of accommodation.

The question often arises whether a patient who has a unilateral cataract should be made emmetropic. The patient should be made emmetropic when the following conditions prevail:

- Binocularity is present.
- Cataract surgery in the other eye is imminent.
- The refractive state of the fellow eye is between emmetropia and 2.5 D of hyperopia.

2. ***Pseudophakic ametropia***. Because of optical reasons, the pseudophakic eye may be made ametropic under following situations.

   i. *In unilateral cataracts* (other eye having no cataract at all), the IOL power chosen should be such that it matches the refractive error of the other eye to minimize aniseikonia. Unfortunately, when the second eye will undergo cataract surgery, it will be necessary to make that eye ametropic as well; and the patient will continue to require significant additional spectacle correction. Therefore, alternatively, if possible, the ametropia of the second eye may be corrected by contact lenses and the cataractous eye may be made emmetropic.

   ii. *Monovision.* After discussion, a few patients opt to use their one eye for distance vision and the other for near vision. In such cases, the IOL power selected should make one eye myopic by 2–3 D for a comfortable near vision.

IOLS AND NEAR VISION

The conventional IOL is a single-focus device, restricting the practitioner to only a single power to select for a particular patient. A number of solutions that have been put forward which will allow the patient who has an intraocular implant to see clearly the distance as well as near, are as follows:

1. ***Implantation of an emmetropic IOL*** with use of *reading glasses* or bifocals/progressive as per situation.
2. ***A small amount of myopic astigmatism*** (i.e. refractive error of about –0.75 to –1.25 DC 180 degrees) would allow uncorrected visual acuity of about 20/40 for distance and near.
3. ***Monovision approach***, i.e. one eye to be emmetropic (for distance vision) and second eye

purposely made myopic by 2.5–3.0 D (for near vision). Such an approach has a patient satisfaction rating of greater than 50%.

4. ***Implantation of multifocal IOLs*** is being considered in an attempt to provide both near and distance visions without the need for spectacle correction.

5. ***Accommodative IOLs,*** used to provide best uncorrected distance and near visions, are losing popularity.

6. ***Extended range of vision IOLs,*** e.g. TECNIS Symfony IOL, which provide uncorrected distance and near visions due to its elongated focus, are gaining popularity nowadays.

7. ***Trifocal IOLs***. These are newer lenses which allow distant vision, intermediate vison and near vision. Examples include Alcon PanOptix trifocal IOLs, Zeiss AT LISA Tri.

MULTIFOCAL IOLs

At present, two general styles of multifocal IOLs are in vogue. Both rely on the eye's ability to select one clear image from two or many unfocused images. This inherent limitation will exist until there is a novel method for actually altering the power of an implanted lens according to the user's immediate need. The currently available multifocal IOLs using either refractive or diffractive principles are as follows.

1. Refractive Optics Multifocal IOLs

These IOLs, also termed as *bull's-eye* design lenses, have concentric rings of different powers. These lenses, using concentric zone philosophy, are available in two styles:

i. ***Two-zone lenses.*** These have a central near-vision segment surrounded by a distance-vision segment (Fig. 9.2) and so also may be called a bifocal IOL. Since the pupil constricts during near focus, the central section is about 2 mm in diameter. Optimally when the pupil dilates during distance viewing, the peripheral distance segment is exposed. This design has a disadvantage in bright sunlight, since the constricted pupil blocks the distant segment of the lens. It is thus poorly tolerated by patients who enjoy outdoor sports in which clear vision is required.

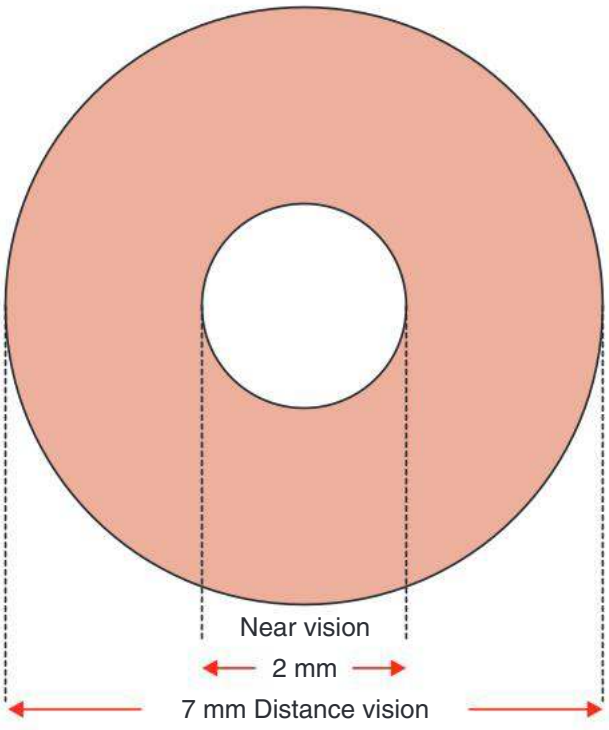


Fig. 9.2 *Two-zone type of bifocal intraocular lens.*

ii. ***Annulus type or bull's-eye lens.*** The pupils constrict not only during near task but also for distance visual tasks in bright light. Therefore, it becomes imperative that the central zone must function for both distance and near. Thus, in annulus design multifocal IOLs, the central portion of the optics contains the distance-vision refraction and there is a near-vision ring outside it, which is in turn surrounded by another distance-vision ring (Fig. 9.3). With this lens style, even marked pupillary constriction allows distance vision and mild constriction allows distance and near visions, and all the three lens segments are exposed when the pupil is dilated. However, excessive constriction during reading in bright light blocks the add portion of the lens, thus preventing clear near vision.

2. Diffractive Optics Multifocal IOLs

In these lenses, the near and distance correction is put in each of the concentric rings, using diffraction optics. The diffractive optics utilizes the principle of wavefront optics of light. The diffraction optics lens combines a standard

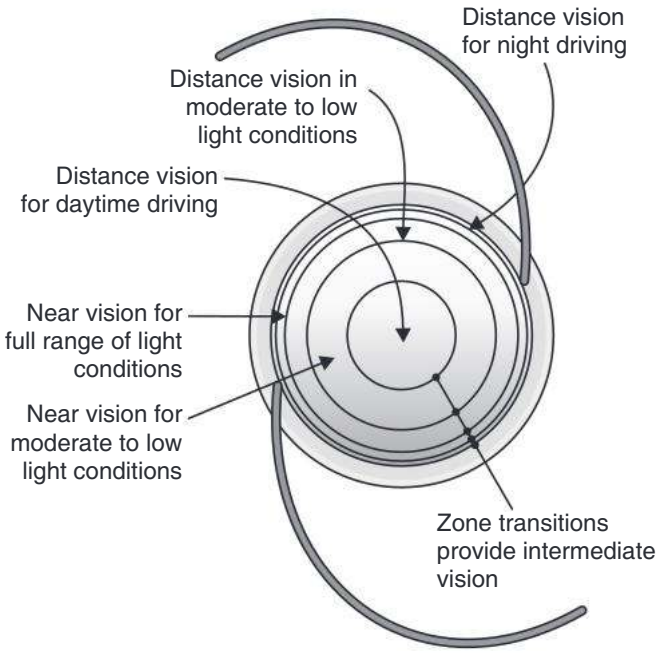


Fig. 9.3 *Annulus type of multifocal intraocular lens.*

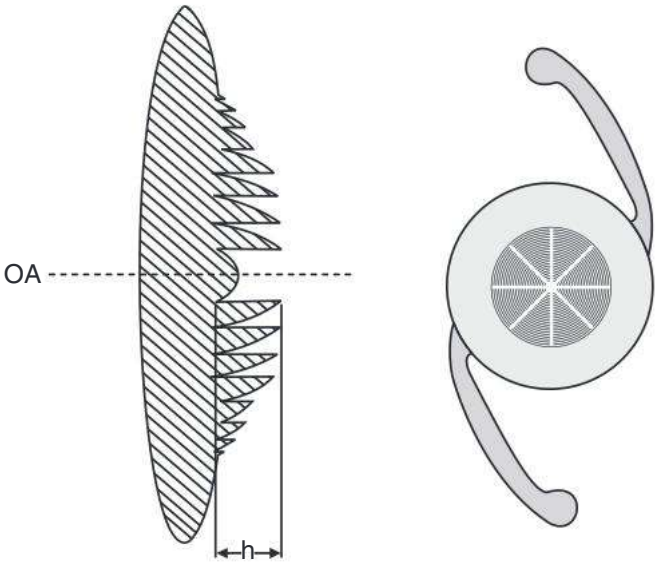


Fig. 9.4 *Diffractive optics multifocal intraocular lens.*

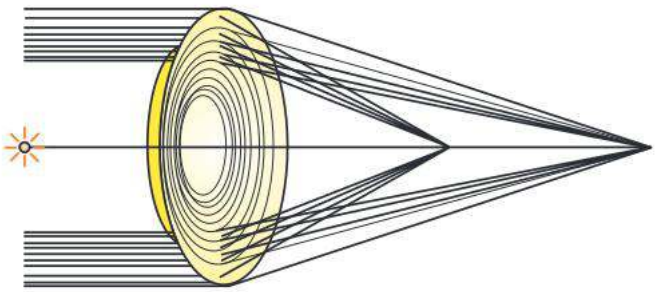


Fig. 9.5 *Optics of diffractive type of multifocal intraocular lens.*

convex curvature placed on the front surface with approximately 25 concentric annular zones cut on the posterior surface with microscopic steps between coterminous annuli (Fig. 9.4). The step height is in the range of the wavelength of light. Such a lens design produces two diffractive orders in which the incoming waves of light will be in phase, resulting in discrete optical foci of equal intensity. Actually, 82% of the light is found in two major foci (approximately 41% of the light is in phase and focused for near vision and about another 41% is in phase and focused for distance vision) and the remaining 18% is lost (Fig. 9.5). This diffractive optical effect is present at all points (or more precisely, at all sufficiently large areas) of the lens. Thus, even if the lens is decentred or pupil is eccentric or deformed, the portion of the lens within the pupil will supply power for distance and near visions.

Drawbacks of diffractive *IOLs* include the following:

The intermediate vision in these lenses has been typically compromised.

Another problem is the problem of glare and halos caused by the randomly diffracted rays of light.

Furthermore, the contrast and scotopic vision are compromised because at any given focal point only a portion of total light intensity is utilized for creating an image. Most of the lenses split light in the ration of 60:40 (distance:near – light distribution).

Innovative changes attempted to correct these problems include the following:

- *Height and spacing of the diffractive rings are reduced* from the centre to the periphery. This reduces the scatter from the periphery hence reducing glare.
- *Rings are also made with smooth rounded edges* in lens to reduce glare e.g. Acri. LISA (Zeiss Germany).
- *Partial optic diffractive lenses* are also available, where the diffractive rings only occupy central 3 mm of the lens the peripheral lens

is clear giving a better night time driving vision, e.g. ReSTOR (Alcon Labs Inc., Fort Worth, Texas).
- *Full optic diffractive lenses* are also available which provide near and far visions, e.g. TECNIS from AMO.

Apodization. Along with the above-mentioned changes in the diffractive rings from the centre to the periphery IOLs are available in which the diffractive rings are also progressively sloped greater from the centre to the periphery. This changes the angle of diffraction of light affording good intermediate vision. This is called *concept of apodization*, e.g. the iDIFF Plus and AcriDIFF (trifocal). The iDIFF Plus lens is a hydrophilic lens, while the AcriDIFF (trifocal) lens is hydrophobic lens.

Disadvantages of Multifocal IOLs

1. ***Reduced light intensity.*** The light intensity entering the eye is halved. Thus, the greatest optical disadvantage of multifocal IOLs, in general, is that even in the ideal situation not all the light entering the eye reaches the retina in focus for either near or distance vision, as:

i. *In bull's-eye lenses*, the amount of light transmitted for each of the focal lengths varies with pupil size (i.e. the area of the IOL exposed). Therefore, distant and near objects may be of different intensities.

ii. *In diffractive optics IOLs*, image intensity is equal for near and distance visions, but even in the ideal situation, only one-half of the light entering the eye is in focus.

2. ***Reduced contrast sensitivity.*** Contrast sensitivity is decreased in multifocal IOLs as compared to conventional IOLs, obviously because of decreased intensity of the light focused. Moreover, even more light may be lost due to scattering, further decreasing retinal image contrast. The patients fitted with a multifocal IOL may, therefore, need somewhat brighter light to read well, and generally function less well in dim light.

3. ***Off-axis aberrations*** in decentred IOLs create more problems in multifocal IOLs as compared to conventional IOLs. Although both *bull's-eye* and diffractive IOLs require excellent centration, it is more critical with diffractive lenses since they suffer stronger off-axis aberration.

4. ***Perception of rings*** around point sources of light is another problem faced with use of multifocal IOLs.

Present Status of Multifocal IOLs

The advantage of the multifocal IOL is that it provides near and distance visions without additional refractive correction. However, this return must be weighed against the superior optical performance of conventional IOLs with the bifocal spectacles.

Nevertheless, an advance generation of multifocal IOLs (e.g. Alcon ReSTOR lens and AMO ReZoom lens) have been designed in a fashion that reduces the halo, the colour distortion and contrast sensitivity loss that occur with multifocal IOLs.

TRIFOCAL IOLs

These are newer lenses which allow distant vision, intermediate vison and near vision. Examples include Alcon PanOptix trifocal IOLs, Zeiss AT LISA Tri. Recently many other companies have come up with trifocal IOLs.

AcrySof IQ PanOptix IOL

AcrySof IQ PanOptix IOL (Alcon) FDA approved in 2019, uses ENLIGHTEN Optical Technology, a proprietary design that optimizes intermediate vision without compromising near and distance visions available in spherical (Fig. 9.6) and toric designs.

Features include the following:
- Hydrophobic acrylate/methacrylate copolymer
- Optic 6 mm, overall diameter 13 mm
- Non-apodized new trifocal design
- Redirects light from the third step height to distance
- Intermediate +2.17 D add
- Near +3.25 D add
- Spherical range: 6 to +34.0 D

Fig. 9.6 *AcrySof IQ PanOptix Trifocal Spherical IOL.*

- Light distribution less dependent on pupil size.

Potential side effects. These are due to the design of multifocal IOL (AcrySof IQ PanOptix Trifocal IOL) models. These may be worse than with a monofocal IOL, including visual disturbances such as glare, rings around lights, starbursts (rays around light sources) and reduced contrast sensitivity (especially in dim lighting). These side effects may make it more difficult to see while driving at night or completing tasks in low lighting conditions such as at night or in fog, or in a dimly lit room after surgery as compared to before surgery.

AT LISA Tri and AT LISA Tri Toric From ZEISS

Features. Introduced in 2012, features of these IOLs (Fig. 9.7A and B) are as follows:

- Hydrophilic acrylate with hydrophobic surface properties
- Optic 6 mm, overall diameter 11 mm
- Trifocal over 4.34 mm, bifocal from 4.34–6 mm
- Diffractive profile using 'smooth steps'
- Intermediate +1.66 D add
- Near +3.33 D add
- Spherical range: 0.0 to +32.0 D
- Maximized pupil-independent design
- Performs well at distance and near visions.

Potential side effects. Trifocal IOLs come with certain photopic phenomena like glare and halos as well as a reduced contrast sensitivity, but most patients after a certain adjustment period tolerate these well.

EXTENDED DEPTH-OF-FOCUS IOL

Until now, IOL correction for presbyopia was achieved through IOLs with different designs (bifocals, near segment sector-shaped, trifocals, etc.) that split the light in several focal areas or accommodative IOLs that change their shape and dioptric power when the ciliary muscles contract. Recently, a new optical technology for

A B

Fig. 9.7 *(A) Zeiss AT LISA tri 839MP; (B) Zeiss AT LISA tri toric 939 M/MP.*

providing extended range of vision has been developed, i.e. *TECNIS Symfony EDOF IOL ZXR00,* which is different than the one used by current multifocal IOLs, for offering an extended range of vision.

Technology of EDOF IOL. Instead of several focus areas, Symfony IOL get one elongated focus area by implementing two technologies:

- Proprietary diffractive optic design that extends the length of focus and
- Achromatic technology that corrects chromatic aberration.

Because it tackles this chromatic aberration, this IOL is known as the EDOF IOL.

Features of EDOF IOL *(Symfony IOL).* It is made of UV blocking hydrophobic acrylic material with a biconvex, wavefront-designed anterior aspheric surface and a posterior achromatic diffractive surface with 6 mm optic diameter. It has a proTEC frosted, continuous 360-degree posterior square edge design of optic with C-loop haptics. The overall diameter of IOL is 13 mm with power varying from +5 to +34 D in 0.5 D increments.

Commonly available EDOF IOls are described below briefly.

1. TECNIS Symfony

The TECNIS Symfony IOL (Johnson & Johnson Vision) was the first EDOF IOL approved by the FDA for the treatment of presbyopia (Fig. 9.8).

Features of TECNIS Symfony Extended Range of Vision IOLs are as follows:

- The biconvex optic incorporates a proprietary wavefront-designed aspheric or toric-aspheric anterior optic, designed to compensate for corneal SA.
- The posterior optic has a proprietary achromatic diffractive surface designed to correct chromatic aberration and a unique echelette feature to extend the range of vision including far, intermediate, and near, while maintaining the corneal SA compensation.

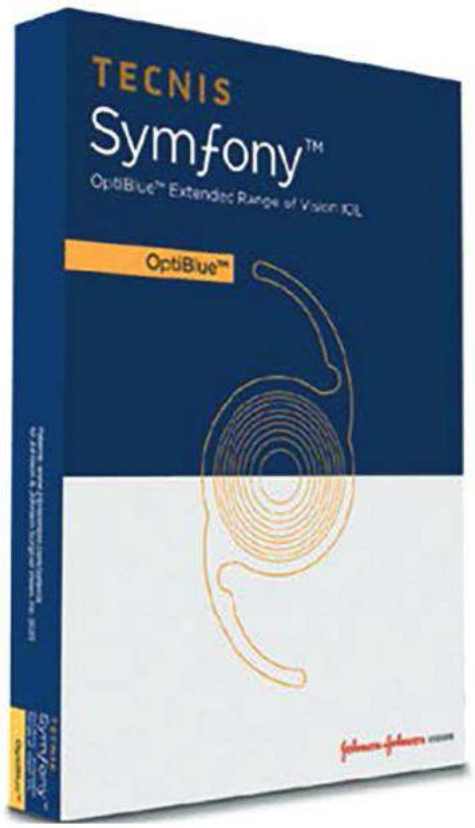


Fig. 9.8 *TECNIS Symfony IOL (Johnson & Johnson Vision).*

- TECNIS Symfony IOLs are designed to have pupil-independent lens performance in any lighting condition.
- They correct spherical and chromatic aberration vision quality comparable to that of monofocal IOL. Compared to an aspheric monofocal IOL, the lens provides improved intermediate and near visual acuity, while maintaining comparable distance visual acuity.
- Has lower level of dysphotopsias than multifocal IOLs.
- However, its new improvements, a violet light filter (OptiBlue) was added to lessen the severity of halos while still allowing the transmission of blue light, for scotopic vision and circadian rhythm entrainment. New design also has reduced light scatter to improve contrast and to reduce starburst symptoms with improvement in dysphotopsia symptoms.

2. AcrySof IQ Vivity

It is (Fig. 9.9) a non-diffractive EDOF lens. It has two transition zones that reshape the wavefront into a stretched wavefront (X-Wave technology). There is a 1 µm plateau located on the central 2.2-mm optic creates a transition that shapes and stretches the wavefront. Shifting the wavefront anterior to the retina provides intermediate vision at 66 cm and near vision at 44 cm. It provides good vision in both bright and dim environments because the X-Wave technology is not dependent on pupil size. The non-diffractive design is said to reduce the visual disturbances (dysphotopsias) compared to diffractive designs. This IOL is a good option for individuals who wish to be less dependent on glasses after cataract surgery but who are not good candidates for a multifocal lens because of mild glaucoma, higher-order aberrations after refractive surgery, or ocular surface disease; and those who may be bothered by dysphotopsias and have concerns about their quality of vision when driving at night. However, they may require glasses to read, very fine print.

3. TECNIS Synergy IOLs

*T*ECNIS Synergy is a hybrid design that features both the echelette EDOF technology from the TECNIS Sym*f*ony IOL and combines it with diffractive multifocal (trifocal) optics for near vision (Fig. 9.10). It received FDA approval in April 2021. Both the non-toric, TECNIS Synergy (Johnson & Johnson Vision) IOLs and the toric, TECNIS Synergy Toric II (Johnson & Johnson Vision) IOLs are available.

The lens is designed to deliver a full range of vision with a peak at distance and with fewer so-called gaps in vision than trifocal lenses. The vision provided by this lens is less dependent on the pupil size than the case with trifocal IOLs.

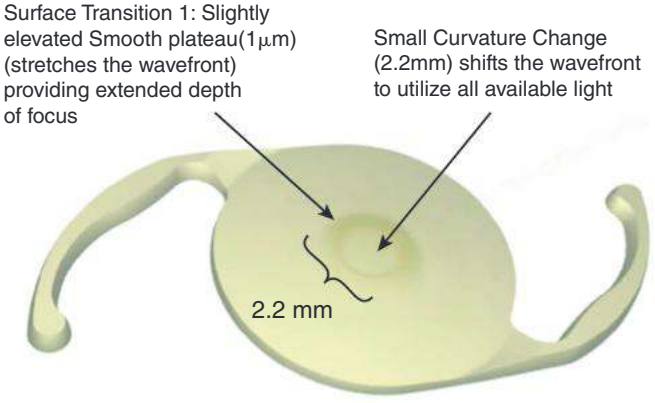


Fig. 9.9 *AcrySof IQ Vivity IOL.*

IC-8, SMALL-APERTURE IOL

Small-aperture or pinhole optics increases the depth of focus and depth of field. Other EDOF IOL technologies use optical aberrations to flatten the depth of focus, but the IC-8 lens incorporates a pinhole to collimate light rays of light passing through an aberrated cornea to reach the retina through the central aperture. The small-aperture design blocks the peripheral defocused (and often aberrated) rays from disrupting the image and flattens the defocus curve on both the myopic and hyperopic sides, providing EDOF in both slightly hyperopic and slightly myopic patients.

Therefore, such an IOL may benefit patients who have atypical corneas such as those with keratoconus, a history of radial keratotomy or corneal scarring.

IC-8 IOL (AcuFocus) is a one-piece, aspheric, hydrophobic acrylic, monofocal lens with an embedded mask (Fig. 9.11). The IOL has a large landing zone for achieving an emmetropia result, and it eliminates much of the noise in the visual system from higher-order aberrations. The lens' wavefront-filtering design eliminates unfocused peripheral rays, so that only central rays focus on the retina. Its small aperture provides an EDOF that makes the implant more tolerant of residual sphero-cylindrical refractive error than a multifocal IOL. IC-8 lens is implanted in the non-dominant eye of patients, and a standard monofocal lens is typically implanted in the dominant eye.

Swiss Advanced IOLs: Lucidis, Eden and Harmonis

All these three are EDOF lenses with their patented **Instant Focus Technology**.

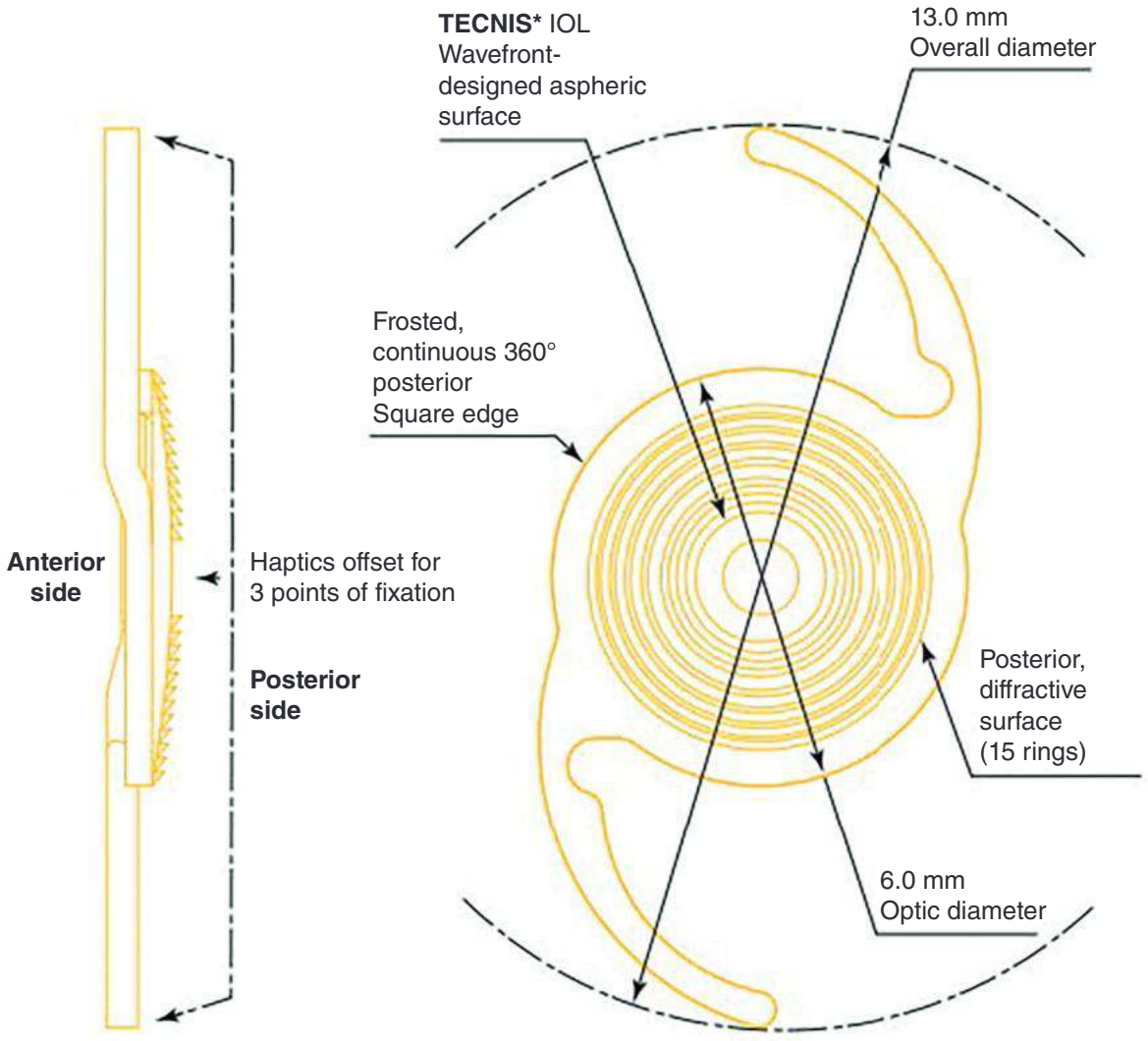


Fig. 9.10 *Non-toric, TECNIS Synergy (Johnson & Johnson Vision) IOL.*

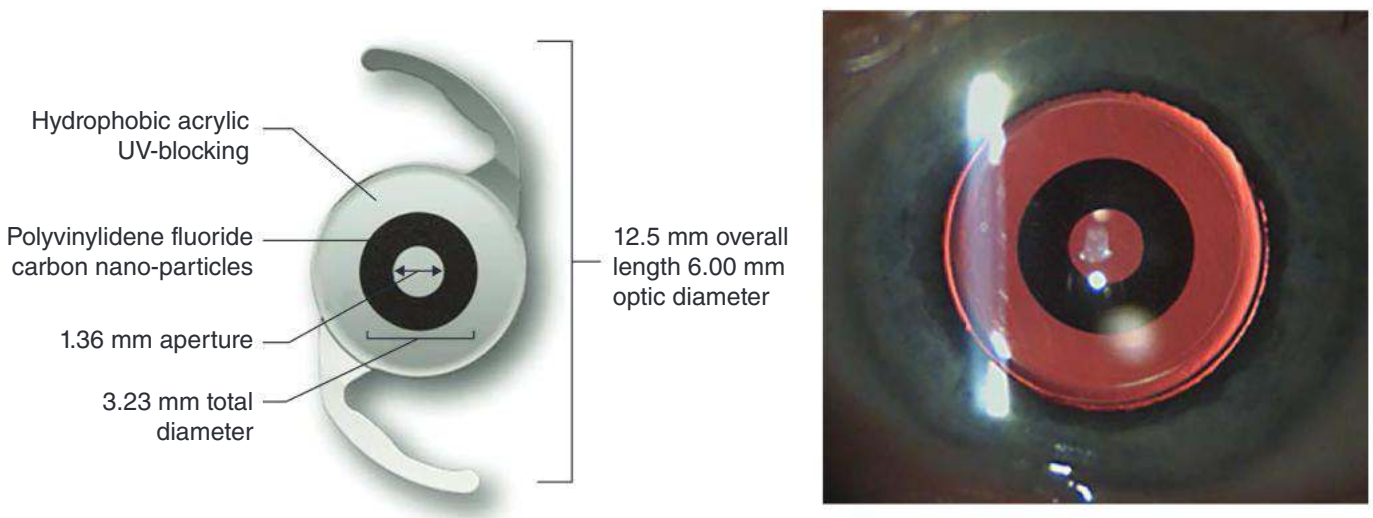


Fig. 9.11 *IC-8 small-aperture IOL.*

The aspheric surface of the centre of the lens generates a peak of light through constructive light wave interference. The resulting beam of light is called pseudo-nondiffracting beam (PNDB) which enables to extend the depth of focus (Fig. 9.12):

- Lucidis integrates the EDOF technology **Instant Focus** built into its aspheric optical centre surrounded by its refractive outer surface.
- *Eden* integrates the EDOF technology **Instant Focus** built into its aspheric optical centre surrounded by its refractive–diffractive outer surface.
- *Harmonis* is a high-end customizable EDOF IOL. It offers patients the possibility to personalize the lens using a dedicated online configurator. It integrates the EDOF technology **Instant Focus** built into its aspheric optical centre surrounded by its refractive–diffractive outer surface.

All three are available in power range of +5.0 to +30.0 D lens with 0.5 D increments. Lucidis and Eden offer an add/EDOF of +3.0 D and they are also in toric. Harmonis comes with add of +2.5 D to +3.5 D (by 0.25 D steps) and EDOF of 1.0 to 2.0 D (by 0.5 D steps).

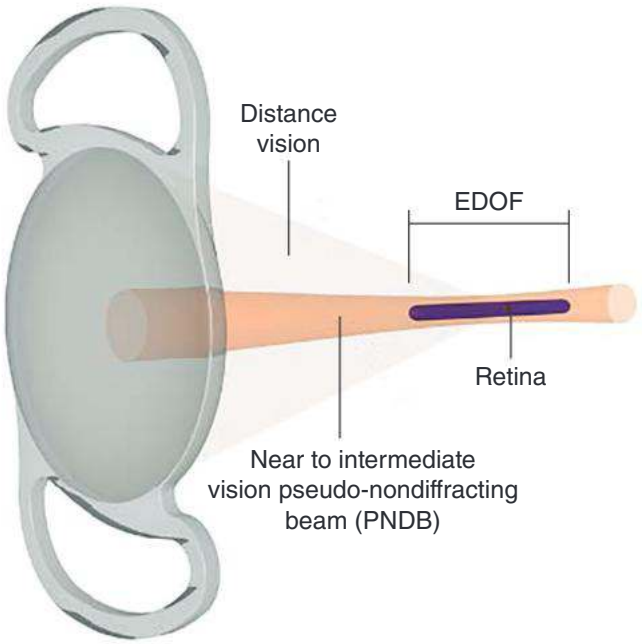


Fig. 9.12 *Swiss Advanced IOL.*

NEW-GENERATION MONOFOCAL IOLs WITH INTERMEDIATE VISION

TECNIS Eyhance

TECNIS Eyhance and Eyhance Toric II IOLs (Fig. 9.13) (Johnson & Johnson Vision) were FDA approved in February 2021. The Eyhance is the first in a new class of monofocal IOLs that provides additional depth of focus without sacrificing the modulation transfer function or inducing dysphotopsias that are associated with multifocal and EDOF IOLs. The new lens is distinguished by a critical difference in design – namely, a continuous change in power from the periphery to the centre of the lens, creating a unique anterior surface that improves intermediate vision, maintains distance image quality comparable to aspheric monofocal IOLs.

RayOne EMV

The RayOne EMV (model 200E, Rayner) (Fig. 9.14) is a UV light–absorbing one-piece IOL intended for placement in the capsular bag using the RayOne injection system (Rayner). Antivaulting haptic technology allows the IOL to be implanted through a sub–2.2-mm corneal incision and promotes rapid centration and fixation in the capsular bag. The IOL is available in powers from 10.00 to 30.00 D in 0.50 D increments. The RayOne EMV is unique because it has positive SA at the centre of its optic and a blended edge region to maintain visual acuity and contrast sensitivity designed the IOL for patients who can tolerate defocus in the second eye or monovision. With a monovision strategy, elongated optical performance in the hyperopic direction allows the lens to maintain

Fig. 9.13 *The Eyhance Toric II IOL.*

Fig. 9.14 *RayOne EMV IOL.*

some distance vision in the patient's non-dominant eye.

ISOPURE PhysIOL

The PhysIOL ISOPURE Lens ISOPURE is a non-diffractive aspherical lens based on a polynomial technology. ISOPURE is designed to provide cataract patients high far vision quality, combined with functional intermediate vision by accentuating the EDOF effect without inducing photic phenomena. It has a larger depth of focus compared to a monofocal lens, low incidence of halos, glares or starbursts and comparable to a monofocal lens. Features include the following:

- Glistening-free hydrophobic acrylic IOL.
- 10 to 24.5 D: Overall diameter: 11 mm and optic diameter: 6 mm
- 25 to 30 D: 10.75 mm, optic diameter
- - 25D to 30 D: 5.75 mm optic polynomial surface design haptic design micro (four-closed loops) and posterior angulated haptic (Fig. 9.15)

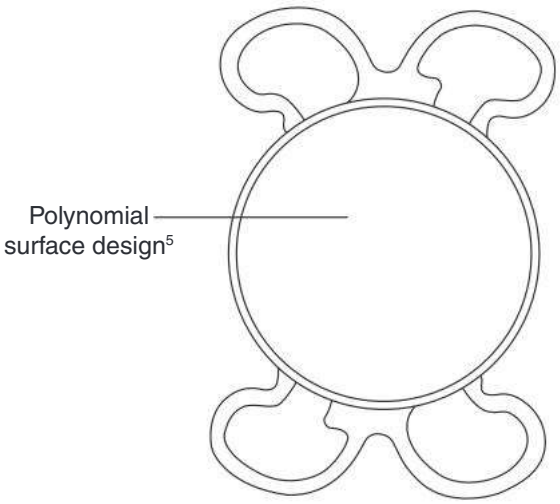


Fig. 9.15 *ISOPURE PhysIOL, four closed loops lens.*

■ ACCOMMODATIVE IOLs

Current commercially available accommodative IOLs are based on Helmholtz's theory of accommodation. These are IOLs which afford both distant and reasonable near visions as well with the help of haptics which can flex and also with the help of materials that expand and contract within the capsule bag along with the ciliary body contraction and the to and fro piston like motion of the anterior vitreous.

Accommodative IOLs are designed in such a way that they exhibit anterior movement of the optic to improve near vision. As a result of anterior movement, these lenses give about 0.5–1.0 D of accommodative amplitude more than a standard monofocal IOL. With such lenses, about 90% of the patients achieve 6/9–6/12 and J_3 vision, which is adequate for driving and reading newspaper without correction. Furthermore, with accommodative lenses, the patients get same quality of distance vision that they get with monofocal lenses cf. multifocal lenses with which quality of distance vision is poor. In other words, with accommodative lenses, there is no loss of contrast sensitivity, no colour distortion and there are no halos at night. Because of these advantages, the implantation of accommodative lenses does make a sense.

A *blended vision concept* with accommodative IOLs is providing wonderful results. With

blended vision, i.e. one eye slightly myopic and the other emmetropic, the patients are achieving good distance, intermediate (computer distance) and near vision, as well as good stereopsis at all distances, and no night vision syndrome.

Type of Accommodative IOLs

The available models of accommodative lenses are divided into two main groups:

i. Single Optic Accommodative IOLs

These are designed to translate anteriorly with accommodative effort. This forward movement increases the effective lens power at the spectacle plane. The mechanism of action varies between the various single optic accommodative IOLs, and is dependent on ciliary muscle contraction either producing an increase in vitreous fluidic pressure (pushing the lens forward) or releasing the zonule tension and allowing the elastic capsular bag to press upon the IOL haptics. The accommodative amplitude of these IOLs is limited by the power of the IOL and can be reduced further with capsular opacification, as this reduces capsular bag elasticity. Roughly, the IOL movement of 0.6 mm causes 1 D of accommodation at the spectacle plane. The lenses based on the above mechanism are as follows:

- Crystalens,
- Medennium smart IOL and
- Kelman tetraflex IOL.

The Crystalens HD (Bausch & Lomb) is the most popular FDA-approved accommodative lens in use today. It is a 4.5 mm aspheric optic IOL with long hinged plate designed haptics with polyimide loops at their ends. This hinged accommodative lens is designed to vault posteriorly against the capsular. This movement is dependent on positive vitreous pressure to shift the lens forward. These IOLs provide a 1.5 D add for near vision too. Being an aspheric monofocal optic, it provides clear distant vision without the associated halos and ghost images or loss of contrast sensitivity unlike the multifocal IOLs. The function of the accommodative IOL would greatly depend on the strength of ciliary muscle contraction, which may be waning off with age, so a few patients might still need reading glasses.

The Medennium smart IOL, (Medennium, Inc., Irvine, CA) may overcome many of the aforementioned obstacles. The lens is composed of a hydrophobic acrylic material with unique thermoplastic properties that permit a temperature-induced change in its shape. Chemically, bonding wax to the acrylic polymer creates a 'smart' material, which remains in a solid state at room temperature. Since the wax component melts at body temperature, adjusting the percentage of wax content produces a semisoft gelatinous polymer once the lens is in the eye.

The Kelman tetraflex IOL features a square-edge design with a 5.75-mm optic, which may be inserted through a 2-mm incision. The lens is composed of PolyHEMA (hydroxyethyl methacrylate), a highly biocompatible material consisting of 26% water. The structural configuration of the tetraflex is entirely different from that of Crystalens. The tetraflex has no hinges and it is angulated forward (i.e. away from the capsular bag) and therefore, has a unique mechanism of accommodation independent of positive vitreous pressure. The haptic configuration of the tetraflex allows the lens to move with the entire capsular bag. Unlike with the Crystalens, no atropinization is necessary with the tetraflex IOL.

ii. Dual Optics Accommodative IOLs

In this type of lens, the optic consists of two lenses; a high plus anterior lens and a minus posterior lens, which are separated by spring-like haptics.

- *In the non-accommodative phase*, the tension in the capsular bag and zonules keeps the two optics in close proximity, whereas spring haptics are collapsed and exhibit potential energy.
- *With accommodative effort*, the zonules relax, the capsular bag expands and the springs exhibit kinetic energy. This change allows the

optics to separate and the anterior plus lens moves forward, thus producing a higher optical power that yields accommodation. The lenses based on this principle include:

- Synchrony dual optics IOL and
- Sarfarazi elliptical accommodative IOL.

Visiogen Synchrony IOL (Visiogen, Inc., Irvine, CA) is the first dual-optic accommodating IOL to undergo clinical trials. It is designed to utilize the natural mechanism of accommodation according to the Helmholtz's theory. Made of the latest generation of silicone, the single-piece design is sized so as to distend and fill the capsular bag. With a relaxed ciliary muscle, the zonules become tense, and the taut capsular bag compresses two optics together. As the ciliary muscle contracts, the zonules and capsular bag relax. This relaxation permits the +34.00 D anterior optic to move forward. A small-diameter, 4.5-mm capsulorrhexis needed to confine the moving anterior optic (5 mm diameter) to the capsular bag. An injector system has been developed to deliver the lens through a 3.5-mm incision.

Note. Accommodative lenses that are currently available and those under investigation are effective in managing presbyopia. The available lenses are providing between 0.5 and 1.25 D of accommodation. The quality of retinal image provided by these lenses is superior to multifocal lenses. These favourable results open the door for more use of these lenses in future for presbyopia.

FUTURE IOL DESIGNS

Injectable Gel IOLs

Femtosecond laser cataract surgery can create a controlled capsulorrhexis and can break up the lens into many pieces which means they can be removed through a small incision. The next step would be to introduce a lens into the eye through this small opening. This may be made possible using *injectable gel IOLs*, which are being researched in a project called Phaco-Ersatz which began in 1986 at the Bascom Palmer Eye Institute. Human trials will include a thorough antiposterior capsule opacification programme. Similar to an accommodating IOL, this lens implantation will not be possible in case of posterior capsular rupture because of risk of extrusion into the vitreous cavity. *Phaco-Ersatz* is a very exciting and highly anticipated project. Injectable gel IOLs have the main advantage of restoring accommodation; but so far, this technology is not available commercially.

Electro-Optic Diffractive IOL

This lens which is under development has the following components:

- A static monofocal IOL,
- A central aspheric modification for far and intermediate visions,
- A smart electroactive diffractive liquid crystal lens for near,
- Microsensors to detect physiological triggers for accommodation and
- On-board processors and algorithms to control the power sequence.

Research in this IOL is being made by Elenza. While accommodation would induce an increase in power of 2–2.5 D, microsensors would sense a change in illumination with miosis and alter power using integrated circuits accordingly.

Light-Adjustable IOL

Light-adjusted lenses (LALs) consist of a silicone matrix into which smaller, photosensitive molecules are embedded. Two to four weeks after implantation of the lens, when the eye is healed, the refraction is measured and a low intensity beam of UV light is used to correct any residual error. This polymerizes the photosensitive molecules, which creates a concentration gradient between the irradiated region and the rest of the optic. Over a 12-h period, the photosensitive molecules migrate from untreated areas, down the concentration gradient, and into the irradiated region until there is no concentration gradient. This movement causes the irradiated region to swell and thereby increases the lens power, if centre of the lens is irradiated, and vice versa, if the periphery is

irradiated. Even astigmatic errors and high-order aberrations can be corrected, if irradiation is done in a particular meridian. After verification of the new refraction, the surgeon 'locks in' the power by irradiating the entire lens optic, thereby achieving a stable power of the IOL. During the interval between the lens implantation and the light adjustment, patients need to wear sunglasses with UV absorbers while performing outside activities. This is necessary to avoid unwanted, non-controlled polymerization of the silicone macromers with unpredictable results regarding change in IOL power.

FUTURE ACCOMMODATING IOLs

All of the IOLs discussed here are currently under investigation.

FluidVision

Design. The FluidVision lens (Alcon) is made of a flexible hydrophobic acrylic shell filled with index-matched silicone oil. The latest bench tests demonstrated that the IOL can be injected through a 3.2-mm incision with a new version of the PowerJect injection system (Alcon). A fluid-driven change in the shape of the IOL mimics the natural accommodation of the eye, creating a continuously variable monofocal lens. During accommodation, the capsular bag squeezes the fluid from the haptics into the centre, inflating the lens. In the unaccommodated state, the fluid moves the other way, deflating the lens (Fig. 9.16).

Juvene

Design. Juvene (LensGen) is a modular accommodating silicone IOL that is composed of two components—a base lens and a fluid lens (Fig. 9.17). The base lens is inserted first and fixated in the capsular bag. The fluid lens is then inserted and attached to the base lens. The dioptric power of the fluid lens changes in response to compressive forces from the capsular bag on the base lens.

Atia Vision

Design. The Atia Vision accommodating IOL (Atia Vision) is a modular system with two optical components (Fig. 9.18). The accommodating portion – the base – is in direct contact

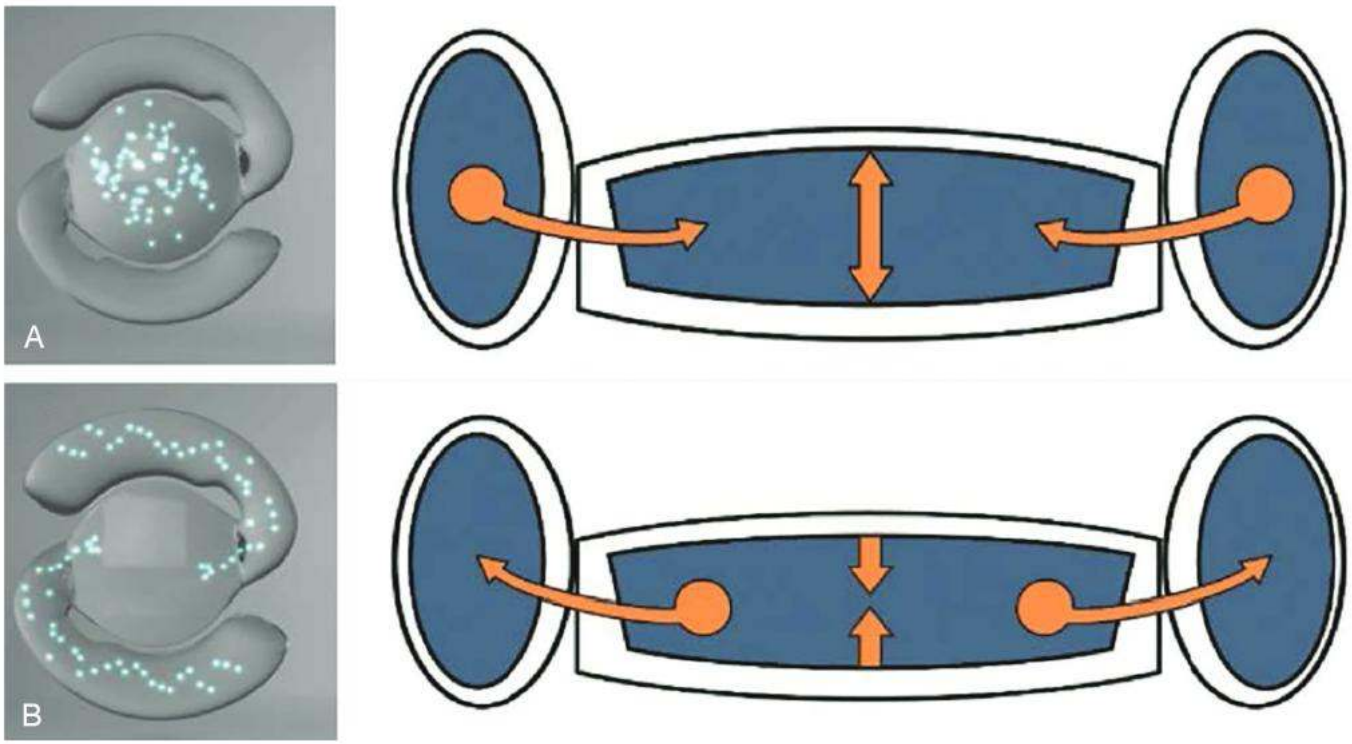


Fig. 9.16 *The FluidVision accommodating IOL in the accommodated (A) and unaccommodated (B) states.*

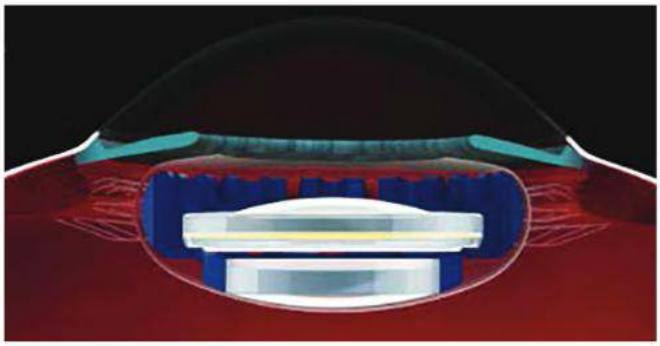


Fig. 9.17 *The Juvene accommodating IOL in the accommodated state.*

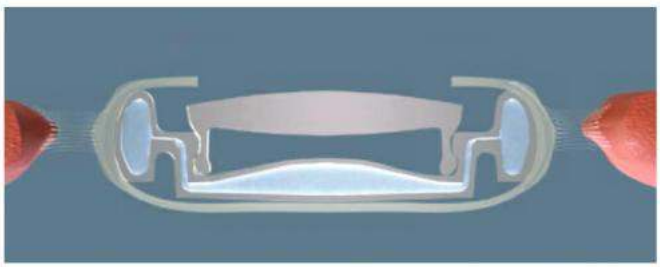


Fig. 9.18 *Schematic drawing showing the Atia Vision accommodating IOL in the accommodated state.*

with the open capsular bag for efficient energy transfer from the ciliary muscle to its optic. The exchangeable front lens is a static optic that controls the final refractive power of the IOL. There is no energy transfer between the base and the front lens. Upon accommodation, the fluid moves from the periphery of the base to its centre, changing the shape and increasing the power of the optic.

Lumina

Design. The Lumina (AkkoLens) is a hydrophilic acrylic lens designed for positioning at the sulcus plane (Fig. 9.19). The lens consists of two optical elements that each have an elastic omega-shaped loop with a spring function and non-elastic connections to the main body of the lens. When the lens is positioned at the sulcus plane, the ciliary muscle contacts the body of the lens and drives accommodation directly.

In the unaccommodated state, the omega-shaped springs of the Lumina are relaxed, the

Fig. 9.19 *Schematic drawing of the Lumina accommodating IOL showing the overall design of the lens.*

optical elements overlap. When the eye accommodates, the ciliary muscle contracts and compresses the Lumina, resulting in a mutual shift of the optical elements. The optical power increases linearly with the shift, and the eye focuses at closer distances. The size of the Lumina is customized to each eye based on the measured sulcus-to-sulcus diameter.

Opira

Design. Opira (ForSight Vision6) is a dynamic, shape-changing lens made of silicone that is designed for placement in the sulcus plane (Fig. 9.20). This lens allows direct ciliary body engagement without zonular or capsular bag intermediaries. The haptics are fixated within the capsulorrhexis (Fig. 9.20A). The lens spans from the ciliary body on one side to the ciliary body on the other side. Contraction of the ciliary muscle compresses the peripheral aspect of the lens, which leads to a dynamic change in the shape of the anterior surface, thus changing the power of the IOL (Fig. 9.20B). The static posterior lens aspect could be used to correct regular astigmatism or for postoperative refractive adjustment.

SAV-IOL (Swiss Advanced Vision) – R-TASC

Real-Time Autofocus Servo Control (R-TASC) (Fig. 9.21) is an active IOL with real time autofocus and wireless connectivity system that detects the distance of objects.

The signals thus received trigger micropumps to move a liquid in and out of the optic, which causes the curvature of the optic to change, resulting in modification of the power

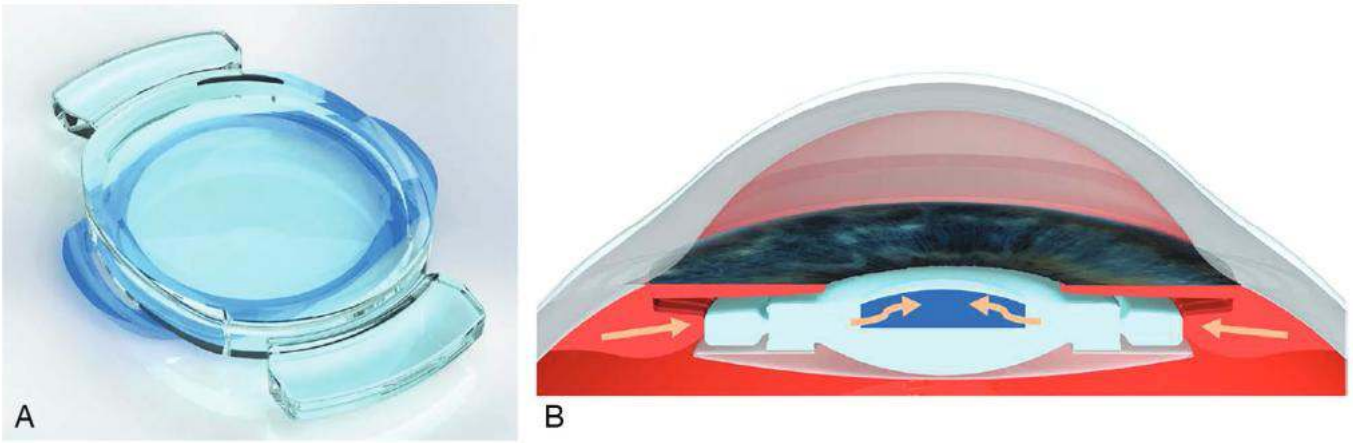


Fig. 9.20 *Overall design of the Opira accommodating IOL (A). Schematic drawing showing its site of fixation and mechanism of accommodation (B). Contraction of the ciliary muscle compresses the peripheral aspect of the lens, leading to a dynamic shape change of the anterior surface. (Courtesy: ForSight Vision6.)*

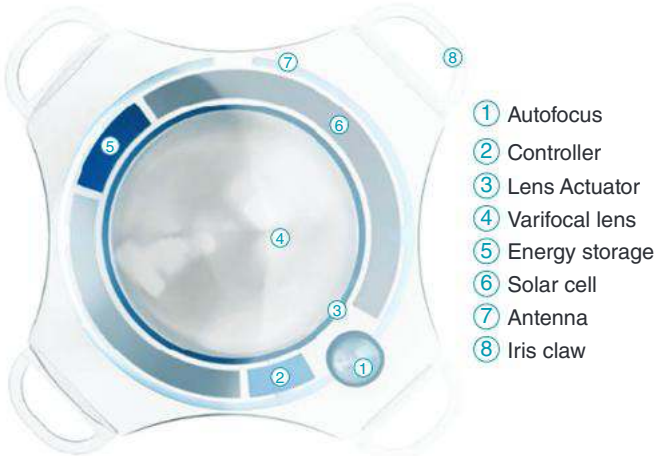


Fig. 9.21 *SAV-IOL (Swiss Advanced Vision) – R-TASC.*

of the lens in real time. The speed of this process is 0.2 s, equivalent to that of a healthy eye. Additionally, the lens is powered by solar energy in conjunction with induction.

R-TASC will be fitted alongside a monofocal lens (for distant vision) or added on patients who already have a monofocal lens but want to restore their visual accommodation. It will enable patients to retrieve a full and continuous visual accommodation range without any visual disturbances or loss of light. There is option of remote calibration of lens by the patient or surgeon for optimal vision at all times. The R-TASC platform is future proofed to incorporate interactive features such as augmented reality.

OPTICAL ASPECTS OF IOL–SPECTACLE COMBINATIONS

Most patients with IOL require supplementary spectacle correction to obtain the best possible visual acuity. This is owing to two reasons: First, despite the fairly close approximation that can be made to IOL power, some spherical ametropia is not uncommon and second, a varying degree of astigmatic error is induced after cataract surgery. The IOL–spectacle combination, however, has an additional effect on the net image magnification, owing to the Galilean telescope principle, as follows:

1. ***If the pseudophakic eye is hyperopic***, it has been calculated that each dioptre of spectacle correction required results in a further magnification of the retinal image by approximately 2%.
2. ***If the pseudophakic eye is myopic***, for every dioptre of residual myopia, the magnification of retinal image is decreased by approximately 2%.

Application of IOL–Spectacle Combinations

1. ***Principle of Galilean telescope*** to modify image magnification in IOL–spectacle combination to tackle the problem of aniseikonia can

be utilized. Such systems have been proposed using individual eikonometric measurements of aniseikonia in each case. Nomograms that are available apply equally well to either contact lens or IOL lens minimization of aniseikonia. The residual ametropia is then corrected by the supplementary spectacle lens.

2. *Unilateral pseudophake may be made iseikonic for distance vision*, but a problem may arise with near vision. As the patient looks through the near reading add with the pseudophakic eye, there occurs image magnification in this eye. Little or no magnification occurs, however, in the phakic eye as the patient accommodates for near vision. This results in an increased aniseikonia for near work. This problem can be eliminated by simply prescribing a reading add for the phakic eye as well, regardless of that eye's accommodative capabilities.

OPTICAL RESULTS OF IOL IMPLANTATION

By all means, results of IOL implantation are optically superior to the correction of aphakia with spectacles and even with contact lenses. Some aspects of the optical results of IOL implantation, which need some discussion, are as follows.

1. Residual Refractive Error after IOL Implantation

Some residual refractive error after IOL implantation is of universal occurrence. It is discussed in detail in the section on optics-related complications of IOLs. The main problem is significant residual corneal astigmatism left after the surgery. However, with recent microincision cataract surgery and meticulous biometry, the problem of astigmatism and residual refractive error has reduced. Furthermore, toric IOLs are now available to correct the astigmatism.

2. IOLs and Aniseikonia

Aniseikonia varying between 4% minification and 6% magnification in the operated eye has been reported in a large series of monocularly pseudophakic patients. The normal tolerance for aniseikonia has been measured by different methods as being between 5% and 8%. However, the ability to fuse images when there is considerable change in size ultimately depends upon the width of Panum's area. If this sensory fusion width falls below physiological values, lesser degrees of aniseikonia may induce a disturbing effect, possibly even an aniseikonia of 2% or less. Apparently, a larger aniseikonia can be tolerated, if exposure to it is continuous and unvarying.

3. IOLs and Stereopsis

Pseudophakic patients have significantly less aniseikonia as compared to aphakics corrected with spectacles and with contact lenses. A significant correlation has been found between increasing aniseikonia and decreasing stereopsis. In a study, no stereopsis was demonstrated with aniseikonia of greater than 19%.

In another study, visual functions in 30 monocularly aphakic patients whose vision was corrected with contact lenses were compared with 30 patients who had received IOL implants. The average vision of both groups was comparable when patients with IOLs were wearing supplementary spectacle correction. The aniseikonia of the two groups was 6.99% and 1.92%, respectively. The average stereopsis of 46% in the former group and 82% in the latter was probably related to the aniseikonia.

4. Optical Results in Children With IOL Implantation

Management of childhood cataract is a very complex and controversial topic. The optical outcome of paediatric aphakia is also not very satisfactory.

Factors that affect the optical outcome in childhood IOL implantations are as follows:

- Unilateral versus bilateral cataract,
- Time of surgery,
- Problem of preventing/treating amblyopia,
- Difficulties in IOL power calculation,
- Significant change in refractive status with growth and
- High incidence of PCO, secondary membrane formation and other IOL-related complications.

Recommendations for childhood cataract at present are as follows:

i. ***Surgery should be done at an early date*** to avoid irreversible amblyopia. In unilateral cataracts, it should be planned as early as possible, preferably within 6 weeks of birth.

ii. ***Surgery of choice*** is to perform lens aspiration with primary posterior capsulorrhexis with or without anterior vitrectomy.

iii. ***Correction of paediatric aphakia*** is still an unsolved query. Presently, common views are as follows:

- *Children above the age of 2 years* can be corrected by implantation of PCIOL during surgery.
- *Children below the age of 2 years* should preferably be treated by extended wear contact lens. Spectacles can be prescribed in bilateral cases. Later on, secondary IOL implantation may be considered. Present trend is to do primary implantation at the earliest possible especially in unilateral cataract, i.e. in all cases because most surgeons have reported negative experience in the compliance with glasses and contact lenses.

iv. ***Paediatric IOL: size, design and power.*** The main concerns regarding the use of IOL in children are the growth of the eye, IOL power considerations, increased uveal reaction and long-term safety. Present recommendations are as follows:

- *Size of IOL* above the age of 2 years may be standard 12–12.75 mm diameter for in the bag implantation.
- *Design of IOL*, presently, most surgeons are preferring foldable IOLs made of hydrophobic acrylic material (e.g. Acrys of IOL manufactured by Alcon Labs).
- *Power of IOL.* Most surgeons follow the following protocol:
  - In older children (>8 years), emmetropia is the target.
  - In children between 2 and 8 years of age, 10% undercorrection from the calculated biometric power is recommended to counter the myopic shift.
  - In children below 2 years, an undercorrection by 20% is recommended from the biometric readings.

Note. *Most surgeons follow Dahan et al.'s simplified approach* based on the AL only, which is as follows:

Axial length	*IOL power*
17 mm	28 D
18 mm	27 D
19 mm	26 D
20 mm	24 D
21 mm	24 D
22 mm	23 D
23 mm	23 D
>24 mm	Axial length –1 D

Similarly, Vasavada *et al* have suggested the following approach:

Age	*Undercorrection*
0–3 months	35%
3–6 months	30%
6–12 months	25%
1–2 years	20%
2–4 years	15%
4–6 years	10%
>6 years	5%

v. ***Amblyopia is must to be prevented/treated***. The appropriate schedule and its importance must be stressed upon the parents.

5. Optical Results of IOL Implantation in Macular Degeneration

IOLs definitely provide better optical results in patients with macular degeneration. It has been suggested that for patients with macular degeneration, neither spectacles nor contact lenses provide the optimum optical correction for aphakia. In addition to constricting field of vision, the aphakic spectacles magnify the apparent central scotoma in such patients. Use of contact lenses is practically not possible in aphakic patients with severe bilateral macular degeneration. IOLs have been implanted in patients with dense macular scotoma with an improvement in their satisfaction and mobility.

OPTICS-RELATED COMPLICATIONS OF IOLS

1. *Post-operative refractive error.* It is not an uncommon complication despite appropriate implant power selection. Obviously, an overpowered IOL leads to post-operative myopia and an underpowered lens results in hypermetropia. Occurrence of post-operative hypermetropia is a much more unpleasant situation for the patient than the myopia. In fact, a small degree of myopia (up to 1 D) is rather welcomed by some patients, for it is comfortable for day-to-day near work.

Some of the factors responsible for occurrence of post-operative refractive errors are as follows:

- Errors in biometry due to either errors in AL or keratometry or both.
- Defects in the manufacture and packaging of the lens.
- Lens power determination may differ for different manufacturers, thus leading to effective power differences of up to 1.0 D or more among companies.
- Mislabelling of lenses is also a theoretical possibility, but this is rare.
- Surgeon factor may also be responsible for this complication.

2. *Implant tilt and astigmatism.* Some tilting of the posterior chamber implant is common. Post-operative tilting of the IOL leads to changes in the actual refractive power of the lens and induces aberrational astigmatism. An average of about 4- to 5-degree tilt is reported in some studies. A 10-degree tilt in an IOL of 20 D induces about 0.5 D of astigmatism. Thus, one may conclude that the incidence of lens tilt is high, but the visual effect is small. However, rarely, large degrees of IOL tilt may also be found.

3. *Implant decentration and malposition.* Optical changes occur due to decentration and malpositioning of the IOLs, which are not uncommon post-operative findings.

- *A decentred lens may induce prismatic effect.* Applying Prentice's rule, a lens decentred by 3 mm with a power of 20 D would induce a prism of $20 \times 0.3 = 6$ PD $= 6\ \Delta$D. Patients with mild decentrations are usually asymptomatic. When significant decentrations occur, the patients usually complain of glare and only rarely of double vision or decreased visual acuity. If the induced prism is in the vertical meridian for which the patient has poor fusional reserves, it may be poorly tolerated and may cause frank vertical diplopia.
- *Spherical errors in refraction* may be induced by axial malposition of a lens from the predicted postoperative position.

4. *The edge effect.* The edge of an ACIOL can often produce a semicircular flare. Light from the side is refracted by the IOL much as a fibre-optic and is transmitted to the opposite edge from which it can be redirected to the retina. When the edge of a PCIOL is within the pupillary aperture, because of either decentration of the lens or post-operative asymmetry of the pupil, significant clinical symptoms, especially glare and monocular multiopia, can result.

5. *Positioning holes effect.* Positioning holes of the lens can also be present in the pupillary aperture due to either decentration of the lens or asymmetry of the pupil. Light striking a positioning hole degrades retinal image in two ways. First, the opening in the hole allows light to pass through without being focused. Thus, it is akin to allowing a narrow beam of light from a flashlight to fall over a portion of the retinal image. Second, the edges of the hole effectively spread out the beam, because of diffraction, splashing it over part of the retinal image.

6. *Loop effects.* The clear haptics of the one-piece IOL, if decentred into the pupil or positioned across an iridectomy, can also degrade the retinal image. Such patients usually complain of an annoying glare when in bright sunlight.

7. *Reflections from the IOL.* Since the front of IOL faces aqueous, its high IR, compared with that of the crystalline lens, reflects light more strongly. However, this causes little annoying symptoms to the patient, since the IR of the

cornea is similar to the aqueous and very little light is actually reflected from the cornea.

Dysphotopsia refers to abnormal light reflexes perceived by the patient. In pseudophakic eye, such a sensation may be produced due to following phenomena (described above):

- Edge glare,
- Surface reflections,
- Positioning hole's effect and
- Loop effect.

CALCULATION OF IOL POWER

Calculation of accurate IOL power is an important step in modern cataract surgery. It is an important step in successful IOL implantation. The refractive power of the pseudophakes is final, and the patient must live with any mistake committed or be subjected to repeat operation, i.e. the removal/replacement of the IOL with all the potential risks. Later correction, in other words, can only be achieved with lens exchange or extraocular aids like glasses or contact lenses, or corneal refractive surgery.

To ensure that our patients will have the optimal correction, the power of the lens to be implanted must be determined individually in every case. The development of modern ultrasonography units has made it possible to conveniently and accurately measure the AL of the eye. In the absence of ultrasonography in the past, IOL power was determined using an intelligent guesswork approach. However, now various formulae have been developed to calculate the IOL power on the basis of various measurements (biometry).

CRUDE METHODS OF IOL POWER CALCULATION USED IN THE PAST

In the 1980s, IOL power was a guesswork based on the patient's previous refractive status. However, ethically as well as legally 'guesswork' approach for calculating IOL power should not be employed presently, since it is a far less accurate method and its widespread use rapidly revealed that there were occasional unexpected and unsatisfactory results, deviating very widely from the targeted final refraction.

The use of 'guesswork' approach for determining IOL power in the past led to the development of following concepts:

- IDEM lenses,
- Standard lens and
- Emmetropia lens.

Note. These concepts have no place in the present day practice. However, they are described here as historical events.

IDEM LENSES

These lenses are so named since the pre- and post-operative refraction with them is the same. Therefore, IDEM lenses were recommended for the patients who were emmetropic before the onset of cataract. Gernet and Zorkendorfer (1982) have shown that the refractive power of the natural lens is 23.70 D. The cardinal plane of this lens is approximately 6 mm behind the corneal apex. The distance for the cardinal plane of the posterior chamber lens is less; i.e. it is further removed from the retina. In order to focus parallel rays of light on the retina, it must be weaker than the natural lens. Therefore, a 20 D artificial lens in the posterior chamber will restore the preoperative refractive error. Similarly, IDEM lenses can be calculated for other sites of implantation as shown in Table 9.2.

Here, it is must to mention an important limitation. An IDEM artificial lens will restore the preoperative refractive error, only if the natural lens indeed had about 23.70 D refractive power. This, however, is not always the case. The refractive power of an eye is the result of the combination of different factors, such as the corneal curvature, the distance of lens from the cornea (the depth of anterior chamber), the dioptric power of the lens and the length of the eye. Each of these values can deviate and still an eye can be emmetropic as the different components compensate for each other. Therefore, deviations of 2 D are common and of more than 3 D are rare with the concept of IDEM lens.

Table 9.2 *Power of different IDEM lenses*

Description of lens	Abbreviation of lens	Power (D)
Angle-supported lenses	AACL	+17.0
Iris clip lenses	ACL	+18.0
Iris plane lenses		+19.0
Posterior chamber lens (convexity of optic: anterior)	PCL	+20.0
Posterior chamber lens (nodal point closer to retina than with PCL)	PPCL	+21.0
Posterior chamber lens (convexity of optic: posterior)	PPPCL	+22.0

STANDARD LENS

The standard lens is one that is approximately 2 D stronger than the IDEM lens, thereby rendering the pseudophakic eye about 1.5 D myopic as compared to preoperative emmetropic refraction. Since 80% of eyes are less than 1 D near-sighted or farsighted, this will be a correct, or at least not an incorrect, result for the majority of patients. Furthermore, in emmetropic patients, these were useful in keeping a balance between the distance and near visions. Since these lenses were the most commonly used implants, they were called standard lenses.

- The standard PCIOL had a refractive power of +22.0 D.
- The standard ACIOL had a refractive power of +20 D.

One has to know, however, that the standard lens is good only for a majority of, but by no means for all, eyes.

EMMETROPIA LENS

The emmetropia lens was used with the intention of restoring emmetropic status in previous ammetropic patients. The power of an 'emmetropia lens' was calculated by multiplying primary refractive error by 1.25 and then adding (for hypermetropia) or subtracting (for myopia) this number from the IDEM lens power. Thus,

- *Power of emmetropia lens in hypermetropic patients* = Power of IDEM lens + (Preoperative refractive error × 1.25).
- *Power of emmetropia lens in myopic patients* = Power of IDEM lens – (Preoperative refractive error × 1.25).

For this, a careful history has to be taken, including the kind of glasses the patient wore comfortably in the past. Old refractive values should be accepted, only if they come from reliable records or unequivocal history, or if they match our clinical findings. However, as mentioned in 'IDEM lens' description, deviation of 2–3 D is not rare; therefore, using primary refraction as the basis to determine the power of IOL to be implanted also entails the possibility of significant errors.

IOL POWER CALCULATION WITH BIOMETRY

With the advent of miniscience of biometry, now it is possible to calculate the power of IOL fairly accurately.

Major aspects of IOL power calculation are as follows:

- Biometry,
- Formulae for calculating IOL power,
- Clinical variables, i.e. IOL power calculation in special situations and
- Optimization of IOL power.

BIOMETRY

Biometry essentially includes:

- Measurement of AL,
- Keratometry (K-reading), i.e. measurement of corneal power and
- Effective IOL position.

I. MEASUREMENT OF AXIAL LENGTH AND ESSENTIALS OF BIOMETERS

AL is the most important factor in biometric calculations. A 1 mm error in AL measurement results in a refractive error of approximately

2.35 D in a 23.5 mm eye, the error with wrong AL assessment being less in case of longer eyes as compared to shorter eyes.

Methods of Measurement of Axial Length

1. ***Ultrasonic measurement*** of AL can be made by applanation method or immersion technique, the latter being more accurate. A-scans measure the time required for a sound pulse to travel from the cornea to retina. In eyes more than 25 mm, staphyloma should be suspected especially when multiple disparate readings are obtained. To measure these eyes and to obtain the true measurement to the fovea, a B-scan technique must be used.
2. ***Optical measurement of AL*** uses partial coherence laser. The IOLMaster measures time required for infrared light to travel to the retina. This technique does not require contact with the globe, so corneal compression artefacts are eliminated.

Essentials of A-Scan Biometry

Settings of the Biometer

Calibration check. The calibration of the biometer using the model eye provided with it should be checked from time to time to ensure accuracy. Instructions for the calibration check are specific and are provided with each instrument by the manufacturer.

Gain or sensitivity setting. Gain refers to the electronic amplification of the sound waves received by the transducer. The amplification factor is called a decibel (dB).

- Normal setting of gain is 70% in most of the biometers.
- Increase in gain may be required when the height of echoes achieved is inadequate as in very dense cataracts, other ocular opacities and high myopia. Increase in the gain produces taller echoes.
- Decrease in the gain is done when artefacts are seen near the retinal echoes, e.g. in silicone-filled eyes and pseudophakic eyes.

Sound velocity setting should be done appropriately according to the type of eye, i.e.

- Normal,
- Cataractous (mild, moderate or dense),
- Aphakic and
- Pseudophakic (silicone or acrylic).

Note. Change in the sound velocity due to materials like silicone oil in the eye can produce an error of 3–4 D.

Operative Instructions

Operative instructions to be kept in mind while performing the A-scan for measuring AL are as follows:

Placing of probe on the anaesthetized cornea should be such that

- It points towards macula, this is especially important in myopes, who may have a staphyloma.
- There is no fluid bridge between the probe and the cornea.
- Cornea should not be depressed, otherwise it will result in inadvertent shortening of AL.

Mode settings may be manual or automatic, depending on the operator's preference:

- Manual mode setting allows the examiner to choose the best echo pattern produced by the eye. However, there may be delay in pressing the foot pedal, and one may miss the right reading.
- Automatic mode is operated by a software algorithm inside the instrument, which controls the interpretation of echo pattern. Most of the surgeons use this mode. It is particularly useful in uncooperative patients.

Note. (1) It is always better to have an observer who should decide whether the best echo pattern has been selected by the automatic mode or not. In this way, one can have advantage of manual dynamic biometry as well as that of static graph of automatic biometry. (2) AL of both eyes should be measured for comparison.

Characteristics of a Good Scan

A-scan produces one-dimensional images in which echo strengths are displayed as vertical deflections or spikes of varying heights, on a

display screen. Characteristics of a good scan are as follows:

- Corneal echo is seen as a tall single peak.
- Aqueous chamber does not produce any echo.
- Anterior and posterior lens capsules produce tall echoes.
- Vitreous cavity produces few to no echoes.
- Retina produces tall, sharply rising echoes with no staircase at the origin.
- Orbital fat produces medium to low echoes.

Selection of the Scan

The scan with the maximum AL, within the range obtained, should be selected.

II. MEASUREMENT OF REFRACTING POWER OF CORNEA

The central corneal power is the second most important factor in the calculation formulae, with a 1.0 D error in corneal power resulting in 1.0 D post-operative refractive error. Central corneal power can be measured by the following:

- *Keratometry or corneal topography*, neither of which measures the corneal power directly.
- *Pentacam* is relatively new imaging system that uses a single Scheimpflug camera to measure the radius of curvature of the anterior and posterior corneal surfaces, as well as corneal thickness, for the calculation of corneal power.
- *Galilei*, a device which measures corneal power in a similar fashion similar to pentacam.

Keratometry

It is the most frequently used method to measure the refractive power of cornea. ***Important points to be considered for keratometry*** are summarized here:

- While performing keratometry, the patient should be instructed to look into the keratometer. Majority of the patients with immature cataracts can fixate the reflection of their own eye, so they should be instructed to fixate into the centre of this reflection. Patients with mature cataract can be instructed to fixate the pin with the other eye.
- Mires should be focused in the centre of the eye to take care of the refractive error of the observer.
- Both the minus signs and the vertical component of the plus signs should be superimposed completely. If there is any angle between them, rotate the keratometer till they can be completely superimposed.
- Keratometry may be difficult or impossible in conditions with irregular or distorted corneal surface. In such cases, keratometric readings of opposite eye may be used or K-reading may be calculated from the corneal topography map.

III. EFFECTIVE IOL POSITION

Effective IOL position is influenced by several factors:

1. ***Anatomical factors*** include AL, the steepness of cornea, limbal white-to-white measurement, preoperative ACD and lens thickness (LT). Holladay showed in a study that the depth of anterior chamber had a positive and partial relationship to the limbal white-to-white measurement.
2. ***IOL-related factors*** include shape, length, flexibility, anterior angulation (if any) and the material of the haptic of IOL.
3. ***Surgeon-related factors.*** Surgeon's individual surgical technique can also influence the effective lens position (ELPo).
4. ***Bag to sulcus shift.*** In situations like posterior capsule rent or loss of anterior capsule integrity, the IOL needs to be placed in ciliary sulcus instead of the normal 'in the bag' position. This requires deduction from the calculated IOL power in order to compensate for increase in effective IOL power, depending upon the base power of IOL, empirically taken 0.50–0.75 D less by most surgeons.

OPTICAL BIOMETERS

The introduction of optical biometry has significantly improved the accuracy of AL measurement from 0.12 mm in immersion ultrasound to 0.02 mm in optical methods. The fact that the retinal pigment epithelium is the

end-point of an optical measurement (refractive AL), whereas the interface between the vitreous and the neuroretina is the end-point of an ultrasonic measurement (anatomical AL), makes measurements by optical methods longer than those taken with ultrasound. In general, optical biometers are reported to give accurate measurement of IOL power as compared to conventional A-scan biometry. However, in eye with dense cataract and posterior staphyloma the AL measurement is more accurate with immersion A/B-scan (Holladay or Shamma's method) than with optical biometer. Commercially available optical biometer include:

- IOLMaster and
- LensStar.

IOL MASTER

IOL Master 500 (Zeiss Humphrey System) is a combined biometric instrument that measures quickly and precisely parameters of human eye needed for IOL power calculation by a non-contact technique. It also incorporates the software to calculate IOL power from various formulae.

Working Principle

It is a non-contact optical device that measures the various parameters based on the following principles:

1. ***AL measurement*** is based on a patented interference optical method known as 'partial coherence interferometry (PCI)'. This technique relies on a laser Doppler technique to measure the echo delay and intensity of infrared light reflected back from the tissue interfaces – cornea and retinal pigment epithelium. The instrument is calibrated against the ultrahigh resolution 40 MHz Grieshaber Biometric System. An internal algorithm approximates the distance to the vitreoretinal interphase for the equipment of an immersion A-scan ultrasonic AL.
2. ***Corneal curvature (K)*** is determined by measuring the distance between the reflected light images as in conventional keratometry (principle of reflection).
3. ***ACD*** is determined as the distance between the optical sections of the crystalline lens and the cornea produced by lateral slit illumination.
4. **White-to-white** is determined from the image of the iris.
5. **Calculation of IOL power** by the software incorporating internationally accepted calculation formulae.

Advantages of the IOLMaster

Operative advantages

1. ***Patient comfort***, as the technique involves non-contact measurements.
2. ***User-friendly***, as the operator can learn the technique very quickly.
3. ***Single instrument*** for measuring AL, corneal curvature (K) and ACD.
4. ***Cross-infection*** risk is not there, as the technique is non-contact.

Technical advantages

1. ***Liquid crystal display (LCD)*** functions both for monitoring patient's eye alignment and displaying the results of calculation of IOL power.
2. ***Safety features*** are extensively integrated.
3. ***More accurate AL measurement*** as compared to A-scan (five times) of the eyes, with AL ranging between 14 and 40 mm.
4. ***Especially useful in certain ocular conditions*** where conventional methods are not so accurate, which include:
   - Small corneal scars,
   - Anterior cortical spokes,
   - Posterior subcapsular plaques,
   - Other localized media capacities and
   - High to extreme myopia with a type 1, peripapillary posterior staphyloma (ability to measure to the fovea in such a condition is an enormous advantage over conventional A-scan ultrasonography).
5. ***Incorporates five IOL power calculating formulae*** in an integrated manner. These include Haigis, Hoffer ϕ, Holladay, SRK-II and SRK/T formulae.
6. ***Individual optimization of formulae*** is possible for every user. Data of the desired lenses need to be entered in the database. On

the basis of post-operative refraction results, the lens constants that are entered in the calculation formulae may be personalized (i.e. individually optimized).

7. ***Biometry in patients undergone corneal refractive surgery*** is possible by use of the following:

- Refractive history or contact lens method and
- Haigis-L formula for calculation of IOL power following myopic laser-assisted in situ keratomileusis (LASIK) or photorefractive keratometry (PRK).

Procedure

The procedure and operational details of the instrument are beyond the scope. The interested readers may consult the company's manual.

IOL MASTER 700

IOLMaster 700 (Fig. 9.22) is a biometry device based on swept-source OCT (SS-OCT) technology that enables full-eye length tomography, providing good fixation control. It uses high frequency 1,055 nm tuneable laser source for AL, LT, ACD and central corneal thickness (CCT) measurements. Light is projected onto the cornea at three zones (1.5, 2.5 and 3.5 mm). PS and WTW are obtained using an LED light source.

Advantages of IOL Master 700

- It provides 1mm horizontal scan of the retina to ensure that the measurements are on the visual axis by using the presence of foveal pit.

Fig. 9.22 *IOLMaster 700.*

- Keratometry measurements are distance dependent.
- The measurement speed of IOLMaster 700 is faster than IOLMaster 500.
- IOLMaster 700 high repeatability and reproducibility.
- IOLMaster 700 penetrates the opaque media better and measure the AL with fewer drop-outs compared with the LenStar and IOLMaster 500 even in dense cataracts.

LENS STAR

LenStar LS900 (Haag-Streit diagnostics) provides highly accurate laser optic measurements for every section of the eye and is the first optical biometer that can measure the thickness of the crystalline lens. With its integrated Olsen formula and the optional Toric Planner featuring the Barrett toric calculator, the LenStar provides the user with latest technology in IOL prediction for any patient.

Working Principle

It is a non-contact optical device which measures multiple parameters based on the following characteristics:

1. ***CCT***. As for every other LenStar axial measurement, optical coherence biometry is used to measure CCT with stunning reproducibility of ±2 μm. CCT is a key parameter in glaucoma diagnosis, and is also used for laser refractive surgery and/or to differentiate prior myopic or hyperopic LASIK procedures when there is no patient history.

2. ***Keratometry/topography***. LenStar's unique dual zone keratometry, featuring 32 marker points, provides perfect spherical equivalent, magnitude of astigmatism and axis position, making it the biometer of choice for toric IOLs. With the optional T-Cone topography add-on, LenStar provides full topography maps of the central 6 mm optical zone that are crucial for cataract planning.

3. ***White-to-white***. Based on high-resolution colour photography of the eye, every white-to-white measurement can be reviewed and adjusted by the user, if necessary. As such, it is fully

reliable for use with anterior chamber and sulcus-fixated phakic IOLs. It can also be used to determine advanced IOL calculation formulae.

4. ***Pupillometry***. Measurement of the pupil diameter in ambient light conditions can be used as an indicator for the patient's suitability for apodized premium IOLs, as well as for laser refractive procedures.

5. ***LT***. Accurate measurement of the LT is key to optimal IOL prediction accuracy when using the latest IOL calculation formulae, Olsen or Holladay II. Measuring the LT with LenStar significantly improves the IOL prediction accuracy of Holladay II and leads to a different IOL power selection in 30% of cases.

6. ***ACD***. Like all axial dimensions captured by the LenStar, ACD is measured by optical coherence biometry, providing more precision and reproducibility. This allows ACD to be measured on phakic as well as on pseudophakic eyes. Additionally, the LenStar is able to display the anatomical ACD (endothelium to anterior lens surface).

7. ***AL.*** It uses a superluminescent diode as the laser source which enables measurement of the AL of the patient's eye, precisely on the patient's visual axis and in the presence of dense media. The user can review and move all of the measuring gate positions on the A-scan, if necessary.

8. ***Special eye conditions.*** All of the described measurements are available for use on the regular eye, as well as for aphakic, pseudoaphakic and silicone oil-filled eyes. In case of error, users may even change the selected eye condition after completion of the measurement procedure.

Advantages

In addition to all the advantages provided by IOLMaster, LenStar also allow the user to calculate power for toric IOL implantation using Barrett toric calculator, which is incorporated in its software.

LenStar LS900

An easy-to-use manual selection of the retinal peaks in the A-scan enables the user to measure RT (distance between the ILM and the RPE) and to calculate IOL based on the individual RT. A typical value for the RT is automatically displayed and employed for IOL calculation. LenStar delivers results comparable to existing ultrasound and optical biometers.

Upgrades to LenStar LS900

Automated positioning system (APS) kit added onto the LenStar LS900 for automated dynamic eye tracking.

Easier mechanical tracking minimizes user delay and error, full measurement with single click, quicker measurement with single click, quicker measurement for improved tear stability and support T-Cone measurement through the latest through the latest EyeSuite.

The T-Cone toric platform complements LenStar's comprehensive measurement palette with true 11-ring Placido topography of the central 6 mm of the anterior cornea, and highly accurate K-readings of the 2.3 and 1.65 mm rings. This offers reassurance of axis location and determines regularity and symmetry of the astigmatism.

With the integrated Barrett toric calculator taking cornea front and back surface into account, you achieve excellent toric IOL calculation. And, the software enables you to plan the surgery on high-resolution images of the eye that can be transferred to the surgery room via EyeSuite for improved outcomes

EyeSuite IOL software offers latest generation IOL calculations such as the Hill-RBF method and Barrett and Olsen for standard IOL, enabling improved results with any patient. It further includes a comprehensive set of premium post-refractive formulae, including Barrett's True-K and the Masket formula, which are regarded as best in class. For torics, it optionally offers a complete planning suite to calculate the implant, considering the front and back of the cornea and create intuitive surgery sketches, enabling excellent transfer of the plan to surgery.

IOL MASTER VERSUS LENSTAR

The LenStar LS900 device enables to perform accurate and repetitive biometric measurements and implant power calculations. Implant calculation results obtained using the LenStar LS900 device are comparable to those achieved using the IOLMaster V.5 device, which has been commonly accepted as standard for over a decade.

- IOLMaster 500 is based on the principle of PCI with 780 nm infrared diode as the source, which emits a dual beam and a short coherence length of 160 μm. LenStar is based on the principle of low coherence reflectometry with 820 nm super luminescent diode as the light source and a 3 dB fibre coupler.
- The use of both devices is limited by significant lens opacification, posterior capsule calcification and in presence of posterior staphyloma. In such cases, additional ultrasound biometry should be performed.
- Keratometry results obtained using both devices should not be used alternatively because of the different measurement methods and different refraction indices.
- The LenStar takes two sets of keratometric readings: one at 1.65 mm and one at 2.3 mm, with 16 points each which is more accurate than IOLMaster which takes a single set at 2.5 mm with six points each.
- The LenStar LS900 device comparing to the IOLMaster additionally enables pachymetry, macular retinal thickness, lens thickens and pupil diameter measurement.
- Newer IOL power calculation formulae like the Barrett universal II formula, Olsen formula and Hill-RBF are available in LenStar LS900 but not in IOLMaster V.5.
- LenStar can also calculate power for toric IOL implantation using Barrett toric calculator, which is not possible in the case of IOLMaster.
- LenStar software runs on an external PC, which allows direct communication with electronic medical record programs; the software can automatically fill in data fields in a chosen formula.

AL-SCAN (Nidek) 2012

AL-Scan (Nidek) 2012 uses an 830 nm infrared laser diode for AL measurement with PCI. With AL-Scan in 10 s, six values for cataract surgery are measured:

- AL
- Corneal curvature radius
- ACD
- CCT
- White-to-white distance
- Pupil size.

The AL-Scan incorporates a 3D auto tracking and auto shot. The 3D auto tracking follows eye movements along the X–Y–Z directions to ensure accurate alignment of the eye. Once correct alignment is completed, the auto shot immediately captures the image and data.

Anterior segment observation with Scheimpflug imaging and double mire ring keratometry. The AL-Scan provides sectional lens image, pupil image and reflected image of double mire rings projected onto the cornea. It measures keratometry (K) at 36 measurement points in two circles with diameters of 2.4 and 3.3 mm, reflected from the corneal surface.

WTW and PS are obtained by analysing the image of the iris and fitting the best circle with the lowest error square to the detected edge. ACD and CCT are measured with an incorporated Scheimpflug camera with a 470 nm monochromatic light, the light source used for WTW measurements is green (wavelength 525 nm). The sectional lens image assists in the evaluation of the severity of the cataract. The pupil image assists in the assessment for multifocal IOL. The reflected image of mire rings assists in detecting an irregular corneal surface.

In cases where the optical biometer cannot measure an eye with an extremely dense cataract, the AL-Scan provides an optional built-in ultrasound biometer, allowing measurement of virtually any cataractous eye with a combined model. The AL-Scan requires no connection with an external ultrasound unit.

IOL power calculation formula on AL-Scan SRK, SRK II, SRK/T, Binkhorst, Hoffer Q, Holladay 1, Formula/H, Camellin-Calossi, Shammas-PL with additional Barrett formulae available for the NAVIS-EX AL-Scan Viewer Barrett Universal II, Barrett True-K and Barrett toric calculator.

NAVIS-EX is the image filing software that enables data from the NIDEK diagnostic devices to be centralized in the NAVIS-EX database.

The Pentacam AXL Wave (OCULUS)

The Pentacam AXL Wave (Fig. 9.23) device consists of a Scheimpflug camera which rotates around the eye and a PCI-based optical biometer. It was introduced in autumn 2015. In addition to anterior segment tomography, ACD, CCT and WTW measurements, corneal topography, anterior and posterior corneal surface and SAs, it also has integrated AL measurement. Calculation of toric IOLs is based on the total corneal refractive power and it takes into account the influence of the posterior corneal surface. The latest model, the Pentacam AXL Wave, includes a Hartmann-Shack wavefront sensor to measure total eye aberrations and objective refraction, as well as retroillumination for preoperative assessment of crystalline lens opacities in the non-dilated pupil and postoperative control of IOL position and inclination. In all, this one device performs five major functions in one measurement routine on the same measuring axis and using the same alignment navigation: objective refraction, total eye wavefront, retroillumination, optical biometry and anterior segment tomography.

Aladdin/Aladdin LT (Topcon)

Aladdin/Aladdin LT (Fig. 9.24) is an optical biometer based on *optical low-coherence interferometry* (OLCR) with an 830 nm super luminescent diode and Placido topography system. It allows to perform eight measurements in one acquisition: AL, keratometry, corneal topography, ACD, pupillometry, WTW, CCT and LT, although the last two parameters (measured by OLCR) are available only on the Aladdin LT. Pupillometry can be measured in three modes: dynamic, photopic and mesopic. Corneal topography is based on the reflection of 24 Placido disc rings with a diameter of 8 mm. Topography-based keratometry is obtained by analysing approximately 1,024 data points of four dedicated Placido rings whose diameters range between 2.4 and 3.4 mm. Aladdin provides also Zernike analysis and keratoconus screening.

OA-2000 (Tomey)

OA-2000 (Fig. 9.25) combines Placido-disc topography and OLCR biometry. It measures AL, CCT, LT and ACD using the OLCR technique. Corneal curvature is measured by Placido-disc

Fig. 9.23 *The Pentacam AXL Wave (OCULUS).*

Fig. 9.24 *Aladdin/Aladdin LT.*

Fig. 9.25 *OA-2000.*

Fig. 9.26 *Galilei G6 ColorZ.*

topography with nine rings each 256 points in a 5.5 mm zone projected onto the cornea. It also measures WTW and PS.

Galilei G6 ColorZ (Ziemer)

Galilei G6 ColorZ (Fig. 9.26) combines OLCR optical biometry, dual-Scheimpflug imaging and Placido-disc topography measures AL, LT, ACD, CCT, corneal topography, PS and WTW. In addition to biometry, Galilei G6 provides high-definition pachymetry, total corneal wavefront, curvature and astigmatism data of the

Fig. 9.27 *Argos biometer.*

anterior and posterior cornea– complete data required to plan cataract or refractive surgery. ColorZ has high-contrast top view image in vibrant colours for more intuitive and advanced diagnostics so as to give enhanced visualization of a range of details such as blood vessels, iris pattern and pupil. Color Eye Metrics Report with improved overlays measurement in high resolution. It has new biometry software adding customized, biometry peak detection for AL measurement. Toric IOL calculator for premium IOL selection. Addition of state-of-the-art IOL calculation formulas (i.e. Barrett Universal II, Barrett Toric, Holladay II export, PANACEA export).

Argos biometer (Movu)

Argos biometer (Fig. 9.27) uses a 1,060 nm wavelength and 20 nm bandwidth swept-source technology to collect two-dimensional OCT data of the full eye (SS-OCT). It measures AL, LT, ACD and CCT with SS-OCT. Keratometry values are generated by illumination from a ring of 16 infrared LEDs. In addition, the device measures PS by analysing the two-dimensional OCT image

ANTERION (Heidelberg Engineering)

ANTERION (Fig. 9.28) utilizes the power of high-resolution SS- OCT images to provide the most important anterior segment examinations and measurements in one modular, upgradeable platform. The single workflow-efficient solution brings together corneal topography and tomography, anterior segment metrics, AL measurement and IOL calculation to transform the day-to-day routine of busy practices and clinics.

SS-OCT that uses a 1300 nm wavelength with a scanning rate of 50000 scans/s, 14 mm scan depth and 10 μm of axial resolution. Anterior and posterior corneal curvature is measured using 65 B-scans on 8 mm considering an RI of 1.3375 and 1.376, respectively. It measures the horizontal WTW distance using an 820 to 890 nm LED light source.

Applications

1. Cornea applications. Generate high-resolution images and detailed maps, including camera image, OCT image, anterior and posterior axial curvature maps, tangential maps, elevation maps, total corneal power map, corneal wavefront maps and pachymetry map.

2. Cataract applications. The data obtained in the cornea analysis combined with the ACD and width, LT and AL determines the parameters for IOL calculations. View the camera image and OCT image to confirm your measurements.

3. Metric applications: Measure ACD, volume and angle, spur-to-spur, white-to-white and angle opening distances, trabecular iris space area (TISA) and LT parameters all in one application.

4. Imaging applications: Visualize anterior segment pathologies and signs of surgical interventions, e.g. keratoplasty, LASIK, implanted IOLs and phakic lenses using the versatile anterior segment imaging application.

Fig. 9.28 *ANTERION (Heidelberg Engineering).*

FORMULAE FOR CALCULATING IOL POWER

Depending upon the basis of their deviation, the various formulae for calculating IOL power have been grouped into theoretical formulae and regression formulae.

- *Theoretical formulae*. These are based on mathematical principles revolving around the 'schematic eye'.
- *Regression formulae.* These were arrived at by looking at post-operative outcomes retrospectively.

Taking into consideration the time when they were evolved and the corrections incorporated into them with newer developments, the IOL power calculating formulae have been grouped into various generations, i.e.:

- First-generation formulae,
- Second-generation formulae,
- Third-generation formulae,
- Fourth-generation formulae and
- Fifth-generation formulae.

A. FIRST-GENERATION FORMULAE

The earliest formulae used for IOL power calculation were the first-generation theoretical and regression formulae.

I. Theoretical Formulae

Various theoretical formulae derived from the geometric optics as applied to the schematic eyes, using theoretical constants, had been developed to calculate the power of IOL required for post-operative emmetropia. These formulae were based on three variables:

- The AL of eyeball,
- K-reading and
- The estimated post-operative ACD.

A few of the first-generation theoretical formulae include the following.

1. Binkhorst Formula

$$P = \frac{1336\ (4r-a)}{(a-d)(4r-d)}$$

where

P is the IOL power in dioptres.
r is the corneal radius in millimetres (average).
a is the AL in millimetres.
d is the assumed post-operative ACD plus corneal thickness.

2. Colenbrander–Hoffer Formula

$$P = \frac{1336}{a-d-0.05} - \frac{1336}{\frac{1336}{K} - d - 0.05}$$

where K is the average keratometry in dioptres.

3. Gill's Formula

$$\begin{aligned} P &= 129.40 + (+108 \times K) \\ &= +(-2.79 - L\ eye) \\ &\quad + (0.26 \times LCL) \\ &\quad + (-\ 0.38 \times Ref) \end{aligned}$$

where
P is the desired IOL power.
K is refractive power of cornea in dioptres.
L eye is the AL in millimetres.
LCL is the distance of apex of anterior corneal surface to apex of IOL in millimetres.
Ref is the desired post-operative refraction.

4. Clayman's Formula

Assume
Emmetropizing IOL = 18 D
Emmetropic AL = 24 mm
Emmetropic average keratometer reading = 42.0 D
1 mm in AL = 3 D of IOL power
1 D in keratometry = 1 D of IOL power
If IOL power >21 D, deduct 0.25 for every dioptre >18.0 D.
For example: AL = 22 mm; K = 43.0 D.
It leads to 6 D hyperopia in length; 1.0 D myopia in keratometry.
Hence, IOL power = 18 + 6 – 1 = 23.0 D – (23 – 18) × 0.25 D = 21.75 D.

5. Fyodorov's Formula

$$P = \frac{1336 - LK}{(L-C) - \frac{CK}{1336}}$$

where

P is the implant power for emmetropia.
L is the AL in millimetres.
K is the corneal curvature in dioptres.
C is the estimated post-operative ACD.

Algebraic Transformation of Theoretical Formulae

These apparently different formulae are in fact identical except for the correction factors. They can all be algebraically transformed into

$$P = \frac{N}{L-C} = \frac{NK}{N-KC}$$

where

P is the implant power for emmetropia.
N is the aqueous and vitreous RI.
C is the estimated post-operative ACD in millimetres.
L is the AL in millimetres.
K is the corneal curvature in dioptres.

Drawbacks of Theoretical Formulae

Although the theoretical formulae in practice generally are reliable for eyes with AL

between 22 and 24.5 mm, they have following drawbacks:

1. They tend to predict too large an emmetropic value in short eyes (less than 22 mm) and too small a value in long eyes (more than 24.5 mm).
2. They are too cumbersome to apply without the assistance of a calculator or a computer.
3. They still require a guess about the ACD, and the ultimate result depends on the accuracy of that guess.
4. Most of these formulae were developed and iris-supported lenses were commonly used. So, the estimate for the distance between the cornea and the implant (post-operative ACD) are different for the presently used PCIOLs.
5. These formulae are based on theoretical simplistic assumption about the optics of the eye.

II. Regression Formulae

In view of the drawbacks of theoretical formulae, there had been a tendency to use the simpler empirical formulae in clinical practice. The empirical formulae are based on regression analysis of the actual post-operative results of implant power as a function of the variables of corneal power and AL. In other words, a 'best-fit' line or curve is plotted from the known ALs and K-readings and is subsequently used to predict the implant power needed for future patients.

A number of regression formulae are available. The commonly used are the SRK formula and its modifications.

SRK-I Formula

It was introduced by Sanders, Retzlaff and Kraff (SRK), based on the regression analysis, taking into account the retrospective computer analysis of a large number of post-operative refractions. The post-operative ACD was not included but was replaced with A-constant which is unique to each different type of IOL and is determined by the manufacture depending upon its material, position of the eye and optic and haptic design angulation, etc. The SRK formula is as follows:

$$P = A - 2.5\ L - 0.9\ K$$

where

P is the IOL power.
A is the constant specific for each lens.
L is the AL in millimetres.
K is the average keratometry in dioptres.

This formula has become the most widely used formula for IOL power calculation. However, like theoretical formulae, it also performs well for eyes with AL between 22 and 24.5 mm. In converse to theoretical formulae, the regression formula tends to predict too small a value in short eyes and too large a value in long eyes. To address this problem, SRK-I formula has been modified twice.

B. SECOND-GENERATION FORMULAE

I. Theoretical Formulae

Modified Binkhorst Formulae

Binkhorst in 1981 improved the prediction of effective lens position (ELP) by using a single variable predictor, the AL, as a scaling factor for ELP and presented a formula to better predict ACD.

II. Regression Formulae

SRK-II Formula

The basic equation of the formula is same, i.e.

$P = A - 2.5\ L - 0.9\ K$, but the A-constant is modified on the basis of the AL as follows:

- If L is <20 mm: A + 3.0
- If L is 20–20.99 mm: A + 2.0
- If L is 21–21.99 mm: A + 1.0
- If L is 22–24.5 mm: A
- If L is >24.5 mm: A – 0.5

Modified SRK-II Formula

In this formula, based on the AL, A-constant is modified as given:

- If L is <20 mm: A + 1.5
- If L is 20–21 mm: A + 1.0
- If L is 21–22 mm: A + 0.5
- If L is 22–24.5 mm: A
- If L is 24.5–26 mm: A – 1.0
- If L is >26 mm: A – 1.5

C. THIRD-GENERATION FORMULAE

Most of the third-generation formulae are a hybrid of both theoretical and regression (empirical) formulae.

Holladay I Formula

In 1988, Holladay proved that the use of a two-variable predictor (AL and keratometry) could significantly improve the predictor of ELP, particularly in unusual eyes. He proposed the formulae based on geometric relationship of the anterior segment (third-generation theoretical formula). However, soon this formula was modified and now the Holladay I formula, though theoretical, also uses an empirically derived constant, which is then added to the ACD estimate.

Hoffer's ϕ Formula

Hoffer's ϕ formula is a third-generation theoretical formula, optimized with regression techniques for ACD. This formula performs best for short eyes.

SRK/T Formula

It is a non-linear theoretical optical formula, empirically optimized for post-operative ACD, retinal thickness and corneal RI. It thus combines the advantages of both the theoretical and empirical analyses. This formula seems to be significantly more accurate for extremely long eyes (>28 mm).

D FOURTH-GENERATION FORMULAE

Holladay II Formula

It is being considered more accurate because of its enhanced ability to predict the position of the implants. Software programs are available in the modern biometers to use the Holladay formulae. Otherwise, the Holladay formulae are very exhaustive. The various constants and equations used in this formula are as follows:

Measured Values

K = average K-reading (dioptres)
R = average corneal radius (millimetres) = 337.5/K
AL = measured ultrasonic axial length (millimetres)

Recommended Constants

C = RI of cornea = 4/3
A = RI of aqueous = 1.336
RT = retinal thickness factor = 0.200 mm

Chosen Values

V = vertex distance of pseudophakic spectacles (millimetres); default = 12 mm
Ref = desired post-operative spherical equivalent refraction (SER) (dioptres)
SF = 'surgeon factor' = distance (millimetres) from aphakic anterior iris plane to optical plane of IOL. It is analogous to A-constant of SRK formula

Definitions of Other Variables

AG = anterior chamber diameter from angle to angle (millimetres)
ACD = anatomic ACD (millimetres), distance from corneal vertex to anterior iris plane
Alm = modified AL (millimetres) = AL + retinal thickness factor (RT)
I = power of IOL (dioptres)
A Ref = actual post-operative spherical equivalent refraction (SER) (dioptres)

Holladay Consultant IOL Program

It uses Holladay II formula with seven variables.

Refractive Formula

It is a theoretical formula described by Holladay to calculate IOL power for aphakic, ametropic, pseudophakic and PRLs. According to this formula, AL measurement is not required. This formula calculates IOL power from the following parameters:

- Preoperative refractive power,
- Corneal power,
- Desired post-operative refraction and
- Vertex distance.

However, this formula was not found to be very good for aphakic eyes, as it is difficult to measure the vertex distance accurately, and this may result in high errors.

Haigis Formula

Haigis introduced his formula in 1999. The formula is built on the same theoretical base as all others, and differs only in the way the ELP is calculated. Haigis proposed using three different constants to better define the ELP. These

constants are called the a0, the a1 and the a2 constants. The three constants can be used as standard, optimized or triple optimized. In the standard form, none of the constants is optimized. The first constant, a0, is derived from the A-constant using a standard equation (a0 = 0.62467 × A-constant – 72.434). The a1 and a2 constants are set at default values, a1 = 0.4 and a2 = 0.1. Single or triple optimization of the Haigis constants can improve prediction accuracy, but requires a large number of cases.

Wang-Koch Adjustment

A Wang-Koch (WK) adjustment can be applied to some third- and fourth-generation IOL formulae to optimize the calculation for AL >25 mm.

- *For the Holladay II formula*, adding AL adjustment can improve the accuracy of the lens calculation.
- *When applied to other IOL formulae*, the WK adjustment has yielded differing results, improving the accuracy of some formulae while worsening the error in others. The adjustment seems to improve Holladay I, and shifts the hyperopic errors at longer ALs to more myopic errors.

Overall, the effect of the WK adjustment is to shift refractive outcomes in long eyes from hyperopic to myopic, and can be considered as an adjunct to the use of the Holladay I, Hoffer Q, SRK/T, and Haigis formulae in long eyes. However, the Barrett is still the more accurate formula.

E. FIFTH-GENERATION FORMULAE

Hoffer H-5 Formula

The Hoffer H-5 formula is the first fifth-generation IOL power formula introduced in 2013, which uses the structure of the Holladay II formula and takes into account the demographic specifics of the individual patient based on race and gender. Fourth-generation formulae use arbitrary average biometric values. These values are completely different in males and females and in different races. The gender/race-specific average is used for a specific patient rather than the overall human average.

NEWER IOL POWER CALCULATION FORMULAE

1. Barrett Suite

It is a combination of five formulae.

i. ***Barrett Universal II Formula:*** Barrett universal II formula determines lens position via anatomical depth, utilizes a lens factor related to the physical position of the principal planes of the IOL and calculates the change in principal planes for positive and negative IOLs. It is termed as 'universal formula' because it is designed for use with multiple lens styles and with short, medium and long ALs. The Barrett universal II for non-toric IOL calculation with keratometry (K) values. It is available in LenStar optical biometer.

ii. *Barrett toric for toric IOL calculation* with keratometry (K) values.

iii. *Barrett true K for non-toric IOL calculation* for post-Laser Vision Correction cases (LASIK, LASEK, PRK) and RK with keratometry (K) values. Better results with this formula are seen if pre-refractive surgery refraction and post-refractive surgery refraction is known.

iv. *Barrett TK toric for toric calculation* with total keratometry (TK) values.

v. *Barrett treatment for IOL exchange and piggyback selection* after surgical surprises.

Figure 9.29 is the display of Barrett formula.

Fig. 9.29 *Display of Barrett Suite.*

2. Olsen Formula

The Olsen formula uses exact ray tracing which allows better prediction ELP as a function of LT and ACD to account for the true physical dimensions of an eye's optical system. It uses the same technology employed by physicists to design telescopes and camera lenses.

A key feature of the Olsen formula is accurate estimation of the IOL's physical position using a newly developed concept, the C-constant (Fig. 9.30). The C-constant can be thought of as a ratio by which the empty capsular bag will encapsulate and fixate an IOL following in-the-bag implantation. This approach predicts the IOL position as a function of preoperative ACD and LT. It is also available in LenStar optical biometer.

3. Hill-RBF Formula

The new Hill-RBF method is a pure data-driven IOL calculation approach and, therefore, it is free of the limitation of lens-position estimation. RBF stands for *Radial Basis activation Function*. It is driven by an advanced, self-validating method using pattern recognition based on artificial intelligence and sophisticated data interpolation.

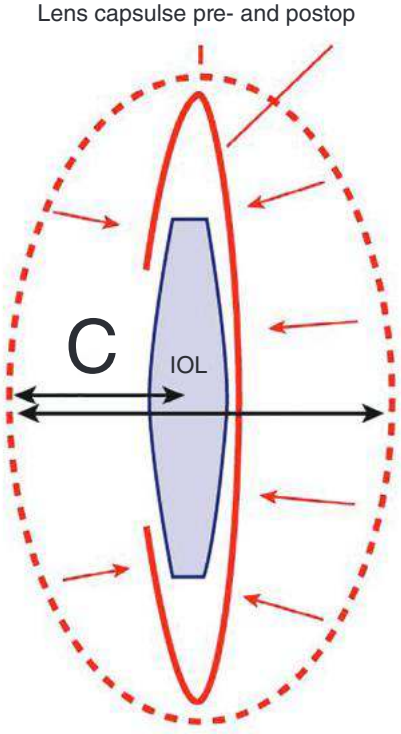


Fig. 9.30 *Concept of C-constant in Olsen formula.*

Starting with a large number of cases where the biometry and the outcomes are known, RBF is capable to find distinct patterns in the apparently random cloud of data points.

The current algorithm is based on outcome data of more than 3400 eyes, with LenStar biometry data and the Alcon SN60WL IOL implanted. It works best with this combination of biometry device and IOL but works also very good with biometry data from other optical biometry devices and with other biconvex IOLs from +6 to +30 D.

Reliable calculation results are labelled with 'in bounds', results that deserve more attention of the surgeon, since the prediction algorithm was not able to determine the desired level of reliability, are labelled 'out of bounds'. An out of bounds labelled result does not need to be inaccurate, but the Hill-RBF method informs the surgeon that the respective pattern of biometric measurements is not well studied by the algorithm and it is recommended to use the Olsen and the Barrett formula to confirm the proposed IOL.

Hill-RBF 2.0 was derived from a large data set with expanded 'in bounds' biometry ranges. Version 2.0 is based on more than 12,000 eyes and, opposite of the original version, can calculate IOL power for a target different than zero. Required inputs are AL, K and ACD (LT, CCT and CD are optional).

Hill-RBF 3.0 was trained on an even more enlarged and refined data set compared to previous versions and provides more reliable predictions in extreme cases, i.e. long and short eyes, than ever before.

New patient parameters, i.e. LT, white-to-white corneal diameter, CCT and the patient's gender refine the spherical and toric IOL power calculations even further.

4. Kane Formula

Based on the theoretical optics and incorporates regression and artificial intelligence (AI) to further refine its predictions.

Uses AL, K, ACD and patient gender along with LT and CCT to predict refractive outcome.

Focus of formula is to decrease the errors in eyes with extreme dimensions. It maintains its accuracy at extreme AL, resulting in 25.1% reduction in absolute error in long eyes (≥26 mm), compared to SRK/T; and 25.5% reduction in absolute error in short eyes (≤22 mm), compared with Hoffer Q.

Figure 9.31 is the display of Kane formula.

5. EVO 2.0 Formula: Developed by Dr Tun Kuan Yeo

EVO stands for emmetropia verifying optical, is a new thick lens formula that is based on the theory of emmetropization and generates an 'emmetropia factor' for each eye. It uses AL, keratometry and ACD with optional variables for LT and white-to-white distance.

The **EVO toric formula** is a toric IOL formula based on the EVO formula. It combines theoretical posterior cornea astigmatism prediction, thick lens modelling for different types of toric IOLs, and a dynamically interconnected prediction of IOL power and toricity.

Figure 9.32 is the display of EVO formula.

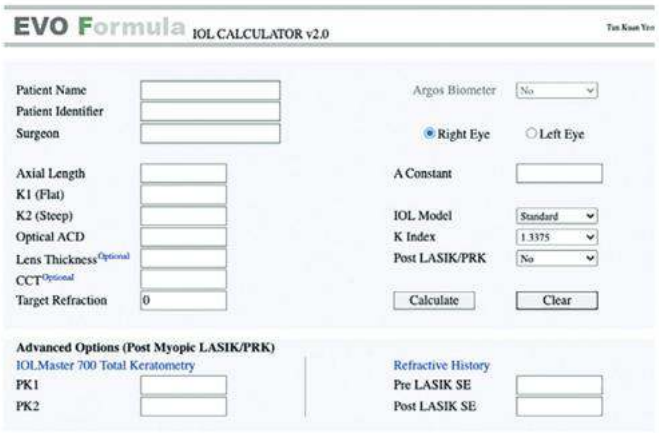


Fig. 9.32 *Display of EVO formula, IOL calculator v2.0.*

The Postoperative spherical Equivalent Prediction using ARtificial Intelligence and Linear algorithms (PEARL) project aims to assess the potential of AI techniques in the IOL calculation field, to determine the optimal architecture of those formulae, and to encourage open research in this field by publishing the experiments and the related code under an open-source license. *Calculator is not designed for meniscus IOL calculations. This calculator works best with PhysIOL FineVision IOLs.*

6. PEARL-DGS Formula: Developed Using Optical and Machine Learning Modelling

PEARL stands for Prediction Enhanced by Artificial Intelligence and output Linearization. *DGS* named after the formula developers: Debellemanière, Gatinel, and Saad.

The PEARL formula is based on thick lens equations and uses machine learning models to predict the posterior corneal radius and the *theoretical internal lens position* (TILP).

7. Ladas Formula

As different IOL formulae perform more accurately for certain eye dimensions. The Ladas formula works by combining the most accurate portions of the IOL formulae to make a 'super formula'.

Depending on the AL or corneal power of the patient, this super formula will choose, among the available formulae, the most ideal one to

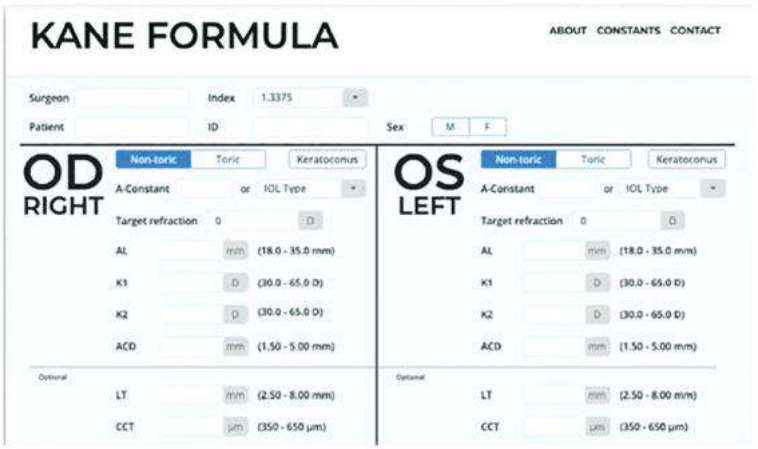


Fig. 9.31 *Display of Kane formula.*

use. The formulae incorporated into the Ladas are SRK/T, Hoffer Q, Holladay I, Holladay with WK adjustment and the Haigis. For AL <21.49 mm, the Hoffer Q was used. For AL >25 mm, Holladay I with WK adjustment was used, and for all other eyes, Holladay I was applied. The formula has evolved to be a more accurate with the help of complex deep learning techniques and AI. One published study has compared the Ladas formula with the newer IOL formulae. Ladas was less accurate than the Barrett universal II (except in the short AL group) and Holladay I, but was more accurate than Hill-RBF V1.0. Since the Ladas formula only helps select the optimal formula to use for a particular eye, it still needs a lens constant, which can be optimized as per the surgeon.

9. Naeser 2 Formula

This is a thick-lens formula developed by Kristian Naeser, MD. The original Naeser 1 formula was based on the manufacturer's cutting-card for the IOL anterior and posterior curvatures. The Naeser 2 uses calculated data for the architecture of the IOL. AL measurements are optimized so that the refractive outcomes are equally good in short, medium and long eyes. The results reported by the author were as good as those obtained with the BUII formula.

USES OF DIFFERENT FORMULAE

Most of the IOL calculation formulae work well for eyes with ALs between 22 and 24.5 mm. However, in case of longer and shorter ALs, their inaccuracy needs to be compensated by optimization.

Optimization is the process of increasing the accuracy of a formula by altering and refining the manufacturer's lens constant. It is worked out by analysing post-operative outcomes with respect to targeted refraction for a particular surgical technique, in a specified IOL design and for a given range of ALs (see page 366).

Albeit controversial, some guidelines have been developed for which formulae to use under specific circumstances. Although earlier widely used, the SRK-II and older ones now obsolete. Appropriate calibration of settings and adjustments of constants is a must before IOL power prediction. No single formula has been found to be useful in all circumstances. So depending upon the circumstances, possible recommendation is as follows:

Circumstance	*Choice of formulae*
AL - <20 mm	Holladay II/Hoffer Q
-20–22 mm	Hoffer Q
-22–24.5 mm	SRK/T; Hoffer Q; Holladay
-24.5–26 mm	Holladay I
>26 mm	SRK/T
Myopic LASIK	Haigis L
Piggyback	Holladay's refractive formula

The newer formulae Barrett universal II formula; Olsen's formula, Hill-RBF formula and Hoffer H-5 formula are still not widely available in the biometry software. Due to the absence of compelling comparative evidence of the superiority of these formulae over each other, it is justifiable to continue using an appropriate combination (according to AL) of the two variable–single constant formulae.

Note. Ultimately, the choice of formula is up to the surgeon, but whatever the method, every effort should be made to ensure the highest possible accuracy.

ERRORS IN IOL POWER CALCULATION

Even with the recent advances like IOLMaster and Orbscan, which have greatly improved the accuracy of ocular biometry, errors in the prediction of IOL power still exist in almost all the methods. These could be subjective or intrinsic in nature.

Most of the existing methods of IOL power calculation are based on the *mean zero error (MZE)* concept, where the empirically fit parameters (such as ELPo) are defined by regression formulae with one-constant optimization. The current MZE methods have personalized the following factors for improved accuracy:

1. ***AL.*** The factor with maximum contribution to error. Sources of error in AL include:
   - Corneal indentation,
   - Improper calibration,
   - Anatomical thickness of retina and

- Failure to recognize appropriate echo patterns on A-scan ultrasound.

2. ***Corneal power errors.*** These can arise due to inaccuracies in keratometric evaluation.

3. ***Estimated lens position,*** also known as effective ACD, this can result in an error of 0.5–2.5 D for every 1 mm error in calculating ELPo. This parameter takes into account both placement of the IOL during surgery and thickness of the lens to be implanted.

4. ***Errors from formula used.*** As discussed above, certain formulae have more accuracy in the setting of long and short ALs. Selecting inappropriate formula can produce an error of 0.50–2.5 D in the final IOL power.

5. ***Manufacturer labelling error.*** The higher the IOL power, the higher will be the error.

BIOMETRY IN SPECIAL CONDITIONS

1. BIOMETRY FOR TORIC IOLs

For toric IOL power calculation, commonly used calculators are (Fig. 9.33):

- ASSORT calculator,
- Holladay IOL Consultant toric planner and
- Barrett toric calculator

The ASSORT calculator has a unique feature of calculating the most effective implant available and to compare IOLs based on the target postoperative refraction. The software also includes optimized lens constants for commonly used formulae, such as Hoffer, Haigis, Holladay and SRK/T, to obtain the ELP. The astigmatic effect of the phaco incision can be dynamically

Fig. 9.33 *A, The Alcon toric IOL calculator. B, The Barrett toric calculator. C, The Holladay IOL consultant toric IOL calculator.*

adjusted based on the incision placement. The new parameter of corneal topographic astigmatism (CorT Total) can be employed to include an accurate measure of corneal astigmatism with inclusion of the posterior cornea. So, it displays all pre- and post-operative toric implant requirements.

The Holladay IOL consultant software features both a ToricPreOp planner for forward calculation and a ToricPostOp Back Calculator for back calculation. The ToricPreOp planner allows the user to determine the ideal toricity and axis of placement for a toric IOL using K-readings and the expected SIA from the cataract incision. It does not use a constant ratio of 1.46 to determine the ideal toricity of the IOL from the corneal astigmatism, which is used by some other calculators that can result in errors with low- and high-powered IOLs. Before using the planner, the surgeon should confirm that the K-readings and the axes for the flat and steep Ks are correct. The ToricPostOp Back Calculator allows the surgeon to determine the exact amount that the toric IOL should be rotated to produce the smallest residual astigmatism.

2. BIOMETRY IN APHAKIC EYES

It is required for secondary IOL implantation. In an aphakic eye, sound travels at the speed of 1532 m/s. The two lens spikes are absent in these cases or may be replaced by a single spike obtained by the anterior vitreous face and posterior lens capsule. Therefore, if available, immersion technique of biometry is the method of choice for aphakes rather than the contact technique. In modern biometers, options are available for aphakic mode as well.

3. BIOMETRY IN PSEUDOPHAKIC EYES

It is required in those cases, needing an IOL exchange. Such eyes have an extremely high spike at the lens followed by artificial chain of reduplication of echoes, which can be misinterpreted as spikes from the retina. This can be avoided by lowering the gain, which eliminates the artificial spikes and increases the retinal spikes. In cataractous eye, the velocity of sound speed is about 1550 m/s, but this is not so in pseudophakic eye. In such an eye, sound speed depends on the sound transmission characteristics and the centre thickness of the IOL in that particular eye. In modern biometers, options are available for phakic, pseudophakic or aphakic mode. This should be rechecked while measuring routine cataract cases to avoid miscalculation of IOL power.

Apparent axial length (AAL) and true axial length (TAL). When AL is measured in apseudophakic eye with an ultrasonic probe with a velocity setting of 1550 m/s, which is the standard setting for the normal cataractous eye, the result obtained is labelled as AAL. This is not TAL because unlike the cataractous eye, the average sound speed in the pseudophakic eye is not 1550 m/s. Sound speed in pseudophakic eye depends both on the 'sound transmission characteristic' and the 'centre thickness' of the IOL in that particular eye.

Holladay formula for pseudophakic biometry:

$$TAL = (0.988\ AAL) + T\ [1 - (1532/V)]$$

where TAL is true axial length, AAL is apparent axial length measured at 1550 m/s, T is the thickness of IOL and V is the velocity of sound in the IOL.

Secondary piggyback IOL for pseudophakia

It has been suggested that in patients who have a significant residual refractive error following the primary IOL implantation, it is often easier surgically and more predictable optically to leave the primary implant in place and calculate the secondary piggyback IOL power to achieve the desired refraction; rather than doing the IOL exchange. The formulae to calculate IOL power in such cases include:

- *Holladay's refractive formula.* This method does not require knowledge of the primary implantor, the AL. This formula works for plus as well as minus lenses.
- Gill's nomogram for secondary piggyback IOL.

Apart from Holladay's refractive formula, Gill's nomogram can also be used to calculate power for secondary piggyback IOL. It requires AL and spectacle spherical equivalent (SE) to calculate the required power. Gill's nomogram

for residual hypermetropia and residual myopia is as follows:

For residual hyperopia

Axial length (mm)	*IOL power (P)*
<22	1.5 × SE + 1
22–25	1.4 × SE + 1
≥25	1.3 × SE + 1

For residual myopia

Axial length (mm)	*IOL power (P)*
≤22	1.5 × SE – 1
22–25	1.4 × SE – 1
≥25	1.3 × SE – 1

4. BIOMETRY IN VITRECTOMIZED EYES

Measuring the AL of eyes in which the vitreous has been replaced with silicone oil is difficult because sound attenuation within the liquid silicone causes the retinal spike to be small and confusing to identify. The difficulty can be overcome simply by increasing the 'system gain'. The result obtained is the AAL, which must be converted to TAL.

Formula suggested by Professor John Shammus:

Velocity of sound wave in silicone oil medium is 990 m/s in an average eye.

TAL = 1133/1550 AAL

For example, a cataractous eye containing silicone oil

AAL = 30.00 mm

TAL = 1133/1550 AAL
= 1133/1550 × 30
= 21.93 mm

As the silicone oil alters the optics of the eye due to its IR, further adjustment is required after calculation of IOL power using the TAL. Usually these eyes require an IOL which is 2–3 D stronger than indicated by standard power calculation.

5. PAEDIATRIC BIOMETRY AND IOL POWER CALCULATION

See page 342.

6. BIOMETRY AND CALCULATION OF IOL POWER AFTER KERATOREFRACTIVE SURGERY

Routine IOL power calculation based on the AL and the keratometry is often inaccurate in eyes that have undergone previous keratorefractive surgery and often leads to an unacceptable hyperopic error, which inconveniences the patient for both near and distance visions. In fact, the corneal refractive surgeries alter the basic assumptions on which the biometry for IOL calculations is based – namely the perfectly spherical nature of cornea. The refractive surgeries mainly affect the central cornea, as well as alter the posterior corneal curvature, which is not routinely measured. The errors occur due to instruments, IR and formulae used. This incorrect IOL power alteration occurs due to three errors: instrument error, IR error and formulae error.

1. ***Instrument error.*** Keratometers and corneal topographers used to calculate corneal power cannot obtain accurate measurements in eyes that have undergone corneal refractive surgery. The major cause of error is that the most keratometers measure at the 3.2 mm zone of central cornea, which often misses the central flatter zone of effective corneal power; the flatter the cornea, the larger the zone of measurement.
2. ***IR error.*** The assumed IR of normal cornea is based on the relationship between the anterior and posterior corneal curvatures. This relationship is changed in PRK, LASIK and LASEK eyes, but not in RK eyes where alteration in curvature occurs but the relation between anterior and posterior corneal curvatures is maintained. The manual keratometers measure only the front surface curvature leading to error in calculation. This overestimates the corneal power by 1 D for every 7 D of correction of refractive error.
3. ***Formula errors.*** All modern formulae except the Haigis formula use AL and K reading to predict position of IOL post-operatively (ELP). In post-corneal refractive surgery, eyes flatter K causes error in calculation.

Note: Because of the above errors, special methods need to be adopted to measure the actual corneal power after any keratorefractive procedure.

Special Methods to Calculate IOL Power After Keratorefractive Surgery

There are more than 20 methods proposed over the years to calculate true corneal power or adjust the calculated IOL power to account for the errors caused. Methods to measure IOL power post-refractive surgery can be divided as 'indirect' or 'direct' based on the measurement of the corneal power after surgery. Direct involves actual measurement, while indirect makes assumptions based on historical data or theoretical analysis (Table 9.3).

Indirect Methods

1. ***Clinical history/calculation method***. This is the most accurate method, but requires that the keratometry and refraction prior to the keratorefractive procedure be known, in addition to the stabilized post-operative refraction. In this method, the change in refraction at the corneal plane is subtracted from the original K-reading prior to the procedure, to obtain a calculated post-operative K-reading. Although this is the most accurate method, the preoperative parameters may not be available, since there is usually a long time interval between the refractive surgery and the cataract extraction. In addition, one must be careful to measure the post-operative refraction before any myopic shift occurs due to nuclear sclerosis.

$$\text{K postReSx} = \text{K preReSx} - \text{Difference in spherical Equivalent}$$

where,

ReSx = refractive surgery.

- Convert the pre- and post-operative refractions into spherical equivalent refraction (SER) [sphere 0.5 (cylinder)].
- Now convert these SERs at the spectacle plane (SEQS) with a given vertex distance (V) (in millimetres) into SER at the corneal plane (SEQC)

$$\text{SEQC} = 1000/[(1000/\text{SEQS}) - \text{V}]$$

Therefore, the change in refraction at the corneal plane = Preoperative SEQC – Post-operative SEQC.

- Now subtract this from the mean preoperative K-reading to get the mean post-operative K-value. This is to be used for IOL power calculation.

It is most accurate as the preoperative values are precise up to ±0.25 mm (30).

2. ***Contact lens over refraction method.*** In this method, the SER is determined by normal refraction and then repeated with a hard contact lens in place. If the SER does not change with the contact lens, then the K-reading of the cornea must be equal to the base curve of the plano contact lens. If the patient has a myopic shift in refraction with the contact lens, then the base curve of the contact lens is greater than that of the cornea by a magnitude equal to the amount of the shift. If there is a hyperopic shift in refraction with the contact lens, then the base curve of the contact lens is less than that for the cornea by the amount of the shift.

Formulae for corrected K-value needs four parameters:

- Base curve wioptres (BC),
- Power of contact lens (P),

Table 9.3 *Direct and indirect methods to measure IOL power in patients with status post-refractive surgery*

Indirect methods	Direct methods
Clinical history method or calculation method	Modern theoretical formulae with modifications (Haigis, Holladay), Gaussian optics and regression formulae
Contact lens (CL) over-refraction	Aramberri 'double-K'
Vertexed IOL power	Topographical methods
Intraoperative autorefraction measurement	Camellin and Calossi method
DBR method	Rosa method
	Direct measurements

- Refraction without contact lens (R_{base}) and
- Refraction with contact lens (R_{CL}).

The formula is as follows:

$$K\ postReSx = BC + P + (R_{CL} - R_{base}).$$

Limitation of this formula is the reliability of refraction in the patient with cataract.

For example: A patient with current base SER (R_{base}) = +0.5 sphere.

SER with plano contact lens (R_{CL}) = –2.0 D (myopic shift).

Suppose base curve (BC) of contact lens used is 35 D. Then,

$$\begin{aligned} K\ postReSx &= 35 + 0 + [-2.0\ D - (+0.5\ D)] \\ &= 35 + (-2.5) \\ &= 32.5D \end{aligned}$$

Use this K for IOL power calculation.

This is also an accurate method for determining the K-value, but the main limitation is that the cataract itself may prevent an accurate refraction.

3. ***Vertexed IOL method***. Based on theoretical studies by Feiz, Latkany and their colleagues, various nomograms were developed after calculating IOL power post-LASIK with SRK/T and three other formulae. The change in the spherical equivalent after LASIK was used to modify the IOL power. Its main limitation is the theoretical nature of the study and the lack of large published data with regard to its accuracy.

4. ***Intraoperative retinoscopy/autorefraction method.*** In this technique, retinoscopy or autorefraction by handheld autorefractometer is performed intraoperatively in the aphakic eye after completion of the cataract extraction. The IOL power is then calculated from the aphakic refraction.

Advantage. Theoretically, it seems to be a simple method.

Disadvantages. Asepsis during surgery may be jeopardized and inaccuracy is possible in retinoscopy especially in the eyes which had refractive surgery for hyperopia.

5. ***DBR method.*** In this method, like calculation method, preoperative patient data are essential. For it, the refractive surgeons need to measure AL along with refraction and keratometry during refractive surgery and keep a record of the IOL power calculated for emmetropia. The record of residual refractive error after stabilization of the post-surgery refraction is also needed. The calculation is explained with an imaginary example:

Prerefractive surgery data

- Refraction: –5.25 D
- Keratometry: 46.20 D
- AL: 25 mm
- IOL power for emmetropia (A-constant 118.0): 16.80 D

Post-refractive surgery data

- Refraction: Plane

Calculation

- 0.7 D change at spectacle plane (known fact) = 1.0 D change at IOL planeRI

Therefore, 5.25 D change at spectacle plane = 5.25/0.7 = 7.5 D change at IOL plane

Thus, IOL power for emmetropia = 16.8 + 7.5 = 24.3 D

Direct Methods

So named as one actually measure the corneal power post-operatively to calculate the effective keratometric dioptres. Although most modern devices do not directly measure the posterior corneal curvature, they use alternative algorithms to approximately assume the RI change induced or simply use different variables to predict ELP.

1. ***Gaussian optics and linear regression.*** The Gaussian formula uses anterior and posterior radii of curvatures, RI of air (1.0), of anterior K (1.376) and of aqueous humour (1.336), and corneal thickness to calculate the effective refractive power (EffRP). The posterior corneal curvature is not directly measured but predicted from the data of Olsen *et al*. EffRP was then used to predict ELP, along with the application of linear regression analysis. Errors of nearly 0.5 D are still noted.

2. ***Corneal topography/keratometry method.*** These systems are based on the assumption that the posterior radius of curvature of the cornea averages 1.2 mm less than the anterior surface and use an index of refraction of 1.33. This assumption is no longer true in corneas subjected to keratorefractive surgery and it leads to an overestimation of the keratometry by 14% of the change induced by the refractive surgery, i.e. after LASIK, if there is a 7 D change in the refraction at the corneal plane with a preoperative K = 44 D, the actual power of the cornea is 37 D, but the topography/keratometric system reads 38 D. Hence, there is a 1 D overestimation for a change of 7 D, and a 2 D overestimation for a change of 14 D. Therefore, whatever the change in post-operative K-reading, undercorrect it by 14% to get an accurate post-operative K-reading. If this correction is not made, then the end result will be a hyperopic refractive error due to an underestimation of the IOL power.

3. ***Aramberri double-K method.*** It is one of the most important methods. It uses pre-LASIK corneal power (or 43.5 if unknown) for the calculation of ELP and post-LASIK corneal power for the calculation of the IOL power. This can be done automatically in the Hoffer programmes (for the Hoffer —Ñ, Holladay I, SRK/T formulae) and in the Holladay IOL consultant programme (for the Holladay II).

4. ***Camellin and Calossi method.*** They reported a formula which uses induced refractive change as well as anterior and posterior curvatures of cornea to predict IOL power.

5. ***Rosa method.*** This uses a correction factor (R factor) for corneal radius which was derived from a regression formula and then compared with the calculation method and double-K method. In their study of 19 eyes, R factor was found to be superior when applied to the SRK/T and Holladay I. The actual formula for IOL power is derived from manual measurements of corneal power (K) and AL.

$$K = (0.0276 \times AL + 0.3635) \text{ manual } K$$

6. ***Direct measurements of anterior and posterior corneal power.*** With the invention of these newer instruments, direct measurement of the posterior corneal power is also possible, which then gives more accurate results for IOL calculation after refractive surgery. The Orbscan and the Pentacam both have been used to measure posterior corneal power, with the Pentacam having slight advantage. But these need more study and data.

7. ***Role of Barrett true K non-toric in post-refractive surgery IOL power calculation***

Barrett True K Non-toric IOL calculation formula (a part of Barrett Suite), is useful in post-laser vision correction cases (LASIK, LASEK, PRK) and RK. Better results with this formula are seen if prerefractive surgery refraction and post-refractive surgery refraction are known. Presently this formula is being considered first choice for calculation of IOL power in post-refractory surgery cases.

Conclusion

For accurate calculation of IOL power in patients who have undergone keratorefractive surgery, an access to pre- and post-operative patient data is essential. Therefore, it becomes mandatory for the refractive surgeons to maintain detailed records. It may also be prudent to provide all the patients undergoing refractive surgery with a copy of the relevant data, in case they approach another ophthalmologist for cataract surgery. This endeavour will definitely result in more accurate refractive outcomes following cataract surgery and IOL implantation, in patients who had undergone keratorefractive surgery.

Note 1. Always use more than one modern third-generation and fourth-generation formulae (SRK/T, Hoffer ϕ, Holladay II, Haigis) to calculate IOL power in such patients and choose the highest value. Never use a regression formula (SRK-I or SRK-II).

Note 2. Presently recommended formula is Barrett True K for non-toric IOL calculation.

IOL POWER CALCULATION IN PATIENTS WITH CORNEAL TRANSPLANTS

It is extremely difficult to accurately predict corneal power in transplant patients. If a triple

procedure is planned, it is suggested that K-readings of other eye be used. An alternative option is to use the average K-readings from a series of previous transplants. If there is a corneal scar, but no graft is planned, other eye readings can be used or even the power calculated using AL and refractive error of affected eye.

OPTIMIZATION OF IOL POWER

Optimization of IOL constants is the process by which a constant is refined for a particular surgical technique, lens, formula, surgeon or measurement device based on previous outcomes. This has been shown to improve outcomes significantly and can be done with any formula, lens or specific situation. The need for optimization of IOL power is felt due to the fact that with the exception of the Haigis formula, all other currently popular IOL formulae utilize a single 'lens-constant' for the completion of the calculation, the rest of the terms of the formula being derived from measurable data. These constants are named differently for different formulae. For example:

- *SRK group* of formulae uses the term A-constant, while
- *Holladay employs* a different constant called the Surgeon's factor (SF) and
- *Hoffer-Q formula* is characterized by the pACD or the personalized ACD.

Since each of these formulae is constructed differently, the constants are also different and cannot be used interchangeably between formulae.

Optimization is the process of finding the specific value of a lens constant, which when used for that particular IOL type, will result in the most accurate IOL power calculations. For a group of patients for whom a particular type of IOL has been implanted, optimization is performed by calculating the lens constant in such a manner that the formula produces the exact refractive error that was actually encountered in that eye. Such a value of the lens constant would make that formula 'perfect' for that specific case.

SOME OBSERVATIONS ABOUT IOL POWER OPTIMIZATION

- *Surgeons optimize their IOL constant* using data from a sample of operated eyes.
- *The IOLMaster manual* recommends the use of 200 eyes with deviations in post-operative refractions within two standard deviations (SDs) of the mean.
- *Aristodemou et al. evaluated optimization of IOL constant.* They assessed the benefits of IOL-constant optimization for IOLMaster biometry on refractive outcomes after cataract surgery for all surgeons and individual surgeons. Optimization of IOL constants reduced the mean absolute errors from 0.66 and 0.52 D to 0.40 and 0.42 D for the SofPort AO IOL and Akreos Fit IOL, respectively. The percentage of eyes within G0.25, G0.50 and G1.00 D of target refraction improved from for both IOL models.
- *Bonfadini et al have also described optimization of IOL constant for Descemet's striping automated endothelial keratoplasty (DSAEK) triple surgery cases*. In this study, prediction errors were calculated retrospectively for consecutive DSAEK triple procedures. These prediction errors then were used to determine an IOL constant for this cohort of patients. The new optimized IOL constant subsequently was compared with the manufacturer's IOL constant, allowing evaluation and quantification of refractive benefits of optimization. This showed significantly improved accuracy of predicted post-operative refraction compared with the manufacturer's IOL constant, which may help to improve the post-operative refractive outcomes in patients undergoing the DSAEK triple procedure.

OPTIMIZATION VERSUS PERSONALIZATION

The process of optimization can be taken further, by only considering data from a specific pool. For instance, one such pool might consist of eyes that have been operated upon by surgeon Dr X, using biometry device B, keratometry device C and the measurements having been performed by Mr D. Such narrow focussing is called personalization, and it refines

optimization. Personalization allows the incorporation of systematic errors of the measurement devices, as well as individual bias of the surgeon or technician. This further improves IOL power prediction accuracy to an extent.

DYNAMIC IOL OPTIMIZATION*

One of the more recent strategies for IOL power optimization is called dynamic IOL optimization. This is a powerful personalized analysis system that bypasses the conventional optimization of the lens constants, and instead focuses on the relative performance of the formulae as a whole. Conceptually, it can compare an infinite number of IOL power calculation algorithms.

The software has a user-friendly interface that runs on the MS Excel platform. The user is required to fill in the IOL model names, the surgeons' names, etc., as a one-time exercise, with an option for later additions. Following this, the database is created, wherein the user enters case details including biometry, IOL details and post-operative refraction. A minimum of 11 complete entries are required before the program can generate optimized IOL powers. This is a safeguard to ensure statistical robustness.

When IOL power calculation is required, the user enters the case-specific biometry details and chosen IOL model. The program then automatically scans the database and chooses a niche cohort.

This cohort comprises of eyes that have a structural configuration that is similar to the test eye. The parameters for this selection are AL and keratometry. This ensures that when optimizing the IOL power for an unusual eye, e.g. a myope, only the matching portion of the database that contains similarly myopic eyes will be evaluated.

Once the niche cohort is chosen, the program then automatically evaluates the relative performance of different IOL formulae in that cohort. Outliers are automatically excluded. This information is then prospectively applied to the test case, yielding a single, usable IOL power.

Advantages of dynamic IOL optimization:

- First and foremost, it is easy to use.
- There is no need for additional equipment purchase, as it works to make the most of the existing data. The user need not choose a formula as per the ocular configuration. Instead, there is a smooth surface of prediction based on the surgeon's own clinical outcomes.
- Since lens constants are bypassed, there is no need to consider separate values for the contact, immersion or optical methods of measuring AL.
- The program works continuously. As new data are added, the optimization protocol recalculates everything. New information is thus constantly incorporated into the system. This is better than optimizing the lens constants every now and then, doing it for different formulae and for different AL ranges.
- Since cohort selection is continuous rather than discrete, there is zero data wastage. The entire process of DIO is facilitated by a very simple user interface.

IMPORTANT CONSIDERATIONS AND FINAL SELECTION OF IOL POWER

BIOMETRY: IMPORTANT CONSIDERATIONS

- The surgeon should prefer to do biometry himself or herself, or should have a reliable technician.
- Take care to select the correct mode/velocity.
- Data input should be done very carefully.
- Selection of the appropriate formula is very important.
- Always check and compare the ALs of both eyes.
- To minimize errors in IOL power calculation, recheck the preoperative measurement under following circumstances:
  - AL <22 mm or >25 mm.

**From: Saurabh Sawhney, Ashima Aggarwal, DOS times, September–October 2016.*

  - Average corneal power <40 D or >47 D.
  - Calculated emmetropic implant power is >3 D from the average for the specific style used.
  - The difference in corneal power >1 D, AL >0.5 mm and emmetropic implant power >1 D is found between two eyes.
- IOL power chosen should be compatible with history.
- Always choose a power that is suitable for patient (age, profession and needs).
- Surgeon factor should always be estimated.
- Optimization of IOL power should also be done.

FINAL SELECTION OF IMPLANT POWER

After the measurements have been obtained, and the implant power formula chosen has been applied, the surgeon armed with the calculated emmetropizing and ametropizing values for the patient must make the final decision as to what strength implant to place in the patient's eye. The following factors should be considered:

1. ***Fellow-eye refraction and cataract***, if any. If the refractive error of opposite eye lies between –2.0 and +2.0 D, then emmetropia should be aimed for. These patients can usually tolerate an anisometropia of 2.0 D. If the refractive error is more than ±2.0 D and both eyes have got cataract, then stepwise reduction can be done by choosing suitable implant powers; e.g. –4.0 D preoperative refraction can be reduced by aiming for 2.0 D undercorrection in one eye and then emmetropia in the other.
2. ***Lifestyle of patient.*** Active patients are best served by near emmetropia; sedentary patients may prefer myopia.
3. ***Hedging.*** It has been found that the actual post-operative refraction varies by more than 1 D from the calculated refraction in over 10% of the cases, and so it is preferable to hedge towards myopia.

RECOMMENDATIONS FOR SELECTION OF IOL IN THE OPERATING ROOM

1. The surgeon and a responsible assistant should personally select the primary and backup implants from stock.
2. IOL power and style to be used should be mentioned in the OT list against each patient's name and fixed on the operating room wall.
3. OT staff should be made aware of the importance of proper IOL power.
4. Avoid using varieties of IOL styles.
5. Corresponding ACIOL power should also be calculated preoperatively for use in case of need.
6. Before IOL implantation, the assistant and the operating surgeon must recheck the IOL power.

10 Low Vision Management

Chapter Outline

LOW VISION

The term low vision is variously used. From the viewpoint of patient management with low vision aids (LVAs), the low vision essentially refers to 'A level of vision that prevents a person from performing customary vision activities with standard or conventional optical correction'. Such patients on many occasions can benefit for day-to-day activities by exploitation of the significant usable residual vision with the help of LVAs.

DEFINITION OF LOW VISION

Terminologies for Visual Function and Dysfunction

Visual function. It is defined simply as the ability to perform important tasks that require vision. Visual acuity is only one measure of visual function. Other measures include visual field, contrast sensitivity, preferred retinal locus ability, glare sensitivity, colour vision, stereopsis and binocularity.

To improve visual performance, an organized approach to patient assessment and treatment is required.

Visual dysfunction. Certain terminologies in relation to visual dysfunction are as follows:

- *Visual disorder* refers to a deviation from normal visual structure by disease, injury or anomaly affecting vision.
- *Visual impairment* refers to reduction of visual function, i.e. visual acuity, visual field and/or contrast sensitivity.

- *Visual disability* refers to reduced ability to perform a certain task, e.g. to read, to write, orientation and mobility.
- *Visual handicap* refers to non-performance of the tasks related to individual and societal expectations because of visual disability.

VISION IMPAIRMENT

Categories as per WHO, Eleventh Revision of International Classification of Diseases (ICD). The International Classification of Diseases 11 (May 2019) classifies vision impairment into two groups, distance and near presenting vision impairment.

Distance Vision Impairment

The distance vision impairment, maximum presenting distance visual acuity (PVA) 6/12 or less in the better eye, has been divided into four categories (Table 10.1):

- *Mild visual impairment:* visual acuity worse than 6/12 to 6/18
- *Moderate visual impairment*: visual acuity worse than 6/18 to 6/60
- *Severe visual impairment:* visual acuity worse than 6/60 to 3/60
- *Blindness:* visual acuity worse than 3/60.

Near Vision Impairment

- Near visual acuity worse than N6 or M.08 at 40 cm.

Table 10.1 *Categories of vision impairment (WHO, 2019)*

Category of visual impairment	Level of visual acuity (Snellen)
Normal vision: 0	6/6 to 6/12
Mild vision impairment: 1	6/12 to 6/18
Moderate vision impairment: 2	Less than 6/18 to 6/60
Severe vision impairment: 3	Less than 6/60 to 3/60
Blindness: 4	Less than 3/60 (FC at 3 m) or visual field <10 degrees

CAUSES OF LOW VISION

In general, irreversible damage to ocular media or visual pathway due to any disease entity may result in low vision. The conditions that are more frequently encountered are as follows:

In children, albinism, optic neuropathy, trauma, infections, paediatric glaucoma, amblyopia, nystagmus, retinopathy of prematurity and retinal and optic nerve abnormalities account for the majority of patients visiting LVA clinics.

In young adults, occurrence of low vision is less likely. They may present with late-onset congenital retinal disorders, ocular injuries, glaucoma, alcohol neuropathy, toxic retinopathy, leukaemic retinopathy, myopia, amblyopia, etc.

In old age, permanent progressive visual loss occurs in the increasing population. While percentages vary, the most common conditions are age-related macular degeneration (AMD), diabetic maculopathies, other macular and retinal degenerations, glaucoma and myopic degeneration.

Essential Components of Vision and Diseases Affecting Them

- *Central vision.* This is the detailed vision we use when we look directly at something. AMD affects central vision. Diabetic retinopathy can affect central or peripheral vision.
- *Peripheral vision.* This is the less detailed vision which is used to see everything around the edges. Glaucoma affects peripheral vision first. Strokes can affect one side of the peripheral vision.
- *Contrast sensitivity.* This is the ability to distinguish between objects of similar tones like milk in a white cup or to distinguish facial features. All ocular problems can decrease contrast sensitivity.
- *Depth perception.* This is the ability to judge the position of objects. New vision loss in one eye can affect depth perception, such as the height of a step.
- *Visual processing.* The lens in our eye focuses light rays onto our retina. The retina converts

these light rays into signals that are sent through the optic nerve to our brain, where they are interpreted as the images we see. A problem with any of these processes affects our vision in various ways.

MAGNITUDE OF GLOBAL VISION IMPAIRMENT AND BLINDNESS: SOME FACTS

The number of blinds across the globe is not within the exact realms of counts. However, from time to time, the World Health Organization (WHO) provides the estimates:

Statistics of global blindness. According to WHO estimates (2020) is as follows:

- Number of blinds world over: 43.28 million
- Number of people with moderate to severe distance vision impairment (MSVI): 295 million
- Total number of people with vision impairment (blinds plus MSVI): 338.28 million
- Of the total 338.28 million with visual impairment (blinds plus MSVI): 157.49 million have uncorrected refractive errors and 83.48 million have cataract.
- Over 80% of all vision impairment (blindness plus and MSVI) is avoidable.
- Number of people with distance-vision impairment are 526 million and with near-vision impairment are 510 million.
- About 90% of vision impaired people live in low- and middle-income countries (LMICs).
- About 55% of moderate or severe vision impaired people are women.
- About 80% of people who are blind or have moderate or severe vision impairment are aged 50 years and above.

MANAGEMENT OF A PATIENT WITH LOW VISION

Visual impairment can be either central or peripheral vision loss. The type of rehabilitation varies depending on visual acuity, age, type of visual disability and individual expectations. The approach to a patient who has central vision loss is different from one who has tunnel vision. Low vision rehabilitation aims for patients to live independent and productive lives by using their residual vision efficiently. It not only includes recommending LVAs but also training for using these devices and the rehabilitation process. Rehabilitation is a collaborative effort of vocational therapists, social workers and psychologists, led by an ophthalmologist.

Management of a patient with low vision is not only tricky but also a challenging situation. It requires a combined use of the knowledge of science and art of practicing medicine. It comprises three important components:

1. ***Low vision aids.*** Knowledge about the optical principle, details of working, indications, advantages and disadvantages of the available LVAs are mandatory before taking up the task of managing a patient with low vision. Therefore, LVAs will be discussed first.
2. ***Evaluation of a patient with low vision*** critically is the key to successful prescription of an LVA. This component will be taken up next.
3. ***Prescription of an LVA.*** The job of prescribing an LVA is an uphill task. However, if the prescriber is well versed with the functioning of various available LVAs and has mastered the art of critically evaluating the patients with low vision, the difficult job becomes simplified. At this juncture, the work remaining to be done is to match a particular patient with the most-suited LVA(s).

LOW VISION AIDS

A *patient with a low vision* is a person who because of an irreversible disorder of the visual system cannot perform customary visual activities without the special vision-enhancing devices. An *LVA* conventionally refers to an *optical device* that improves or enhances residual vision by magnifying the image of the object at the retinal level. In addition, there are some *non-optical aids* that may help in enhancing the

visual performance. So LVAs can be divided into two groups:

- Optical LVAs and
- Non-optical LVAs.

OPTICAL LVAs

BASIC PRINCIPLE

The optical LVAs are based on the fact that with sufficient magnification, the normal retina surrounding the damaged central retina can be used for central vision. Though the non-foveal retina cannot interpret details of objects with the clarity of fovea and parafoveal region, a functionally useful image can be perceived. The measure of visual acuity varies with the extent of involvement of central retina. The visual acuity is maximum at the fovea, where there are a maximum number of cones, and decreases rapidly towards the periphery (Fig. 10.1).

The patient's visual acuity determines how close the working distance should be brought during near work to obtain an image large enough to be appreciated. The closer the working distance, the higher is the lens add required, assuming that the accommodation is negligible.

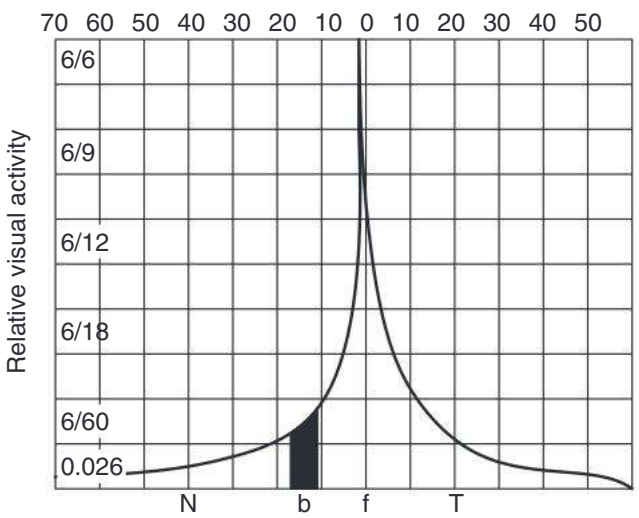


Fig. 10.1 *Regional variations of the visual acuity in the retina. N, nasal retina; b, blind spot; f, fovea; T, temporal retina.*

BASIC FEATURES OF OPTICAL LVAs

These may vary depending upon the patient's visual status and daily needs and are as follows:

- *Power*, in dioptres, is variable.
- *Focus* may be fixed or variable.
- *Illumination* – the LVA may be self-illuminated or non-illuminated.
- It may be *monocular* or *binocular* LVA.
- It may be unified, bifocal or trifocal LVA.

TYPES OF OPTICAL LVAs

I. Optical LVAs for near
   - Magnifying spectacles
   - Hand magnifiers
   - Stand magnifiers
   - Telescope system for near (telemicroscope)

II. Optical LVAs for intermediate

III. Optical LVAs for distance
   - Telescopes
   - Intraocular LVAs (IO-LVAs)

MAGNIFYING SPECTACLES

Magnifying spectacles are the most commonly prescribed LVAs and many patients achieve a high degree of success with their use. These are especially suited for near and intermediate distance.

Optical principle. Magnification by a convex lens is obtained by bringing the object within its focal distance. An erect, virtual and magnified image is produced (Fig. 10.2).

Types and designs. When no distance prescription is required, *half eye glasses* are preferable because they reduce the weight, thickness and size. High-add bifocals or high-add trifocals can be used to read large print at a

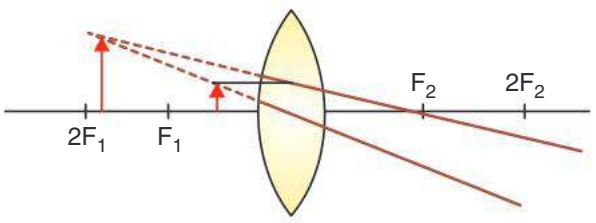


Fig. 10.2 *Image formed by a convex lens when the object lies between its focal point and optical centre.*

great distance. Both uniocular and binocular spectacles are prescribed depending upon the situation (Fig. 10.3).

- *Binocular spectacles* prescribed usually vary in power from +4 D with 6Δ base-in to +12 D with 14Δ base-in.
- *Monocular spectacles* consist of standard aspheric lenses from +4 D to +20 D in 2 D increments and specially designed microscopic and double lenses from +24 D (6×) to 60 D (15×).

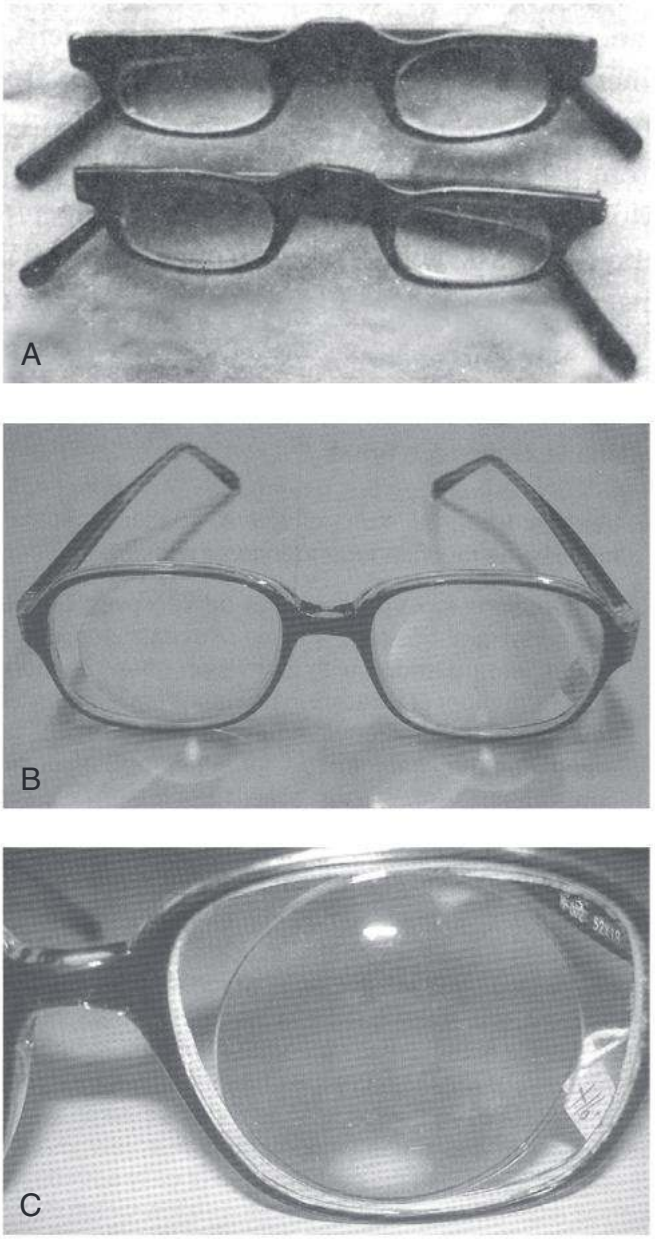


Fig. 10.3 *Magnifying spectacles: A, binocular half eye frame spectacles having convex lenses with base-in prism; B, binocular full frame spectacles having aspheric lenses; C, magnified view of B.*

Instructions for use. The patient should be instructed to hold the material very close and then move it out and scan the lines one by one. Light must be properly adjusted. The patients should be advised to have patience and learn the reading skills since the speed is reduced to word-by-word pace and the reading distance is always closer. Writing with spectacle aids requires special instruction. The visual task of writing is not as demanding as reading and hence may require reduced power lens.

Advantages. (1) Cosmetically acceptable, (2) more comfortable and easy to use, (3) both hands are free to hold reading material, (4) field of vision is large, (5) simultaneous vision for near and distance is possible, (6) less expensive.

Disadvantages. (1) Spherical aberrations are created with high plus lenses, unless aspherical lenses are used; (2) due to short focal length of high plus lenses, the patient has to hold the print close to the eye, thereby illumination on the reading matter is reduced.

HAND-HELD MAGNIFIERS

These often help patients with near vision problem. These can be used along with distance and reading spectacles or with a bifocal reading addition. The patient does not require accommodation to see the image and mostly patients prefer to use these with the spectacle correction for distance vision.

Indications. They are primarily indicated for spot or short-time tasks in patients with field of vision reduced to 10 degrees or more. They are also used by patients with low vision as an auxiliary lens for finer jobs.

Type and design (Fig. 10.4). These are available from +4 to +40 D and even of more power. Most patients accept 8, 12, 16 or 20 D depending upon the task and degree of impairment. Their magnification is variable since the power varies with the distance between the object and the focal point of magnifier. The hand-held magnifiers should preferably have a wide field,

Fig. 10.4 *Hand-held magnifiers (HHMs): A, standard HHMs; B, foldable (pocket) HHM; C, self-illuminated HHM.*

should be lightweight and should have self-contained illumination.

Visolett magnifiers are special types of hand-held magnifiers that almost double the spectacle magnification or approach the magnification achieved by reading without correction, diffusely increase illumination and provide binocular vision. They have a constant magnification of approximately 1.8×. These are useful as LVAs in high myopes.

Visolett when combined with a spectacle magnifier almost doubles the magnification effect. This must be used with reading glasses or at the near point of an uncorrected myopia because the image is about 5 cm from the magnifier.

Instructions for use. The patient should be shown how to put the magnifier flat on the reading surface to begin with and raise it until the image is clear and undistorted.

Advantages. (1) Working distance is more as compared to spectacle lenses; (2) accommodation is not required for reading; (3) easy to manipulate for viewing eccentrically.

Disadvantages. (1) Hand is not free; (2) it may be inconvenient and tiring to use a hand magnifier because the hand has to be kept moving to cover the reading material; (3) not useful in the absence of manual dexterity; (4) reduced field of view as compared to spectacles; (5) need to be held at the correct distance to obtain maximum power.

STAND-MOUNTED MAGNIFIERS

Optical principle. The stand-mounted magnifiers form a virtual image a short distance behind the lens.

Types and designs (Fig. 10.5). These are available in two forms: pre-focused and focusable. These range in power from +4 to +60 D. The self-illuminated designs have advantage of providing non-glare light source. The image produced by these magnifiers usually requires some accommodative effort. Many patients prefer to use stand magnifiers to see items of specific interest such as stock market page and bills.

Instructions for use. The patient should be taught to place the stand-mounted magnifier flat on the reading material and to look at the image through reading glasses or bifocals to converge the divergent rays coming from the magnifier lens. Because of the reduced aperture of these magnifiers, the eye must be closer to the lens surface to obtain the full width of the reading field.

Indications for use are similar to those for hand magnifiers.

Advantages. (1) These are technically simple for a patient to use because they are pre-focused

Fig. 10.5 *Stand-mounted magnifiers.*

and rest on a rigid mount; (2) these aids are of choice for patients with hand tremors.

Disadvantages. (1) Small field of vision; (2) difficult to use, if the surface is not flat.

TELESCOPES

The telescopic system or telescope is an optical instrument that improves the resolution of an object by increasing the size of the image projected on the retina, making it closer. It is available for far, near and middle distances.

Telescope enables greater participation in daily and social activities such as watching television and reading white boards, street signs, house and building numbers, billboards and menu boards. On the other hand, restriction of visual field and illumination, difficulty in locating and focusing on objects quickly and limited focus depth are disadvantages of the telescopes. Telescopes are not universally accepted due to expense, difficulty in using the devices and aesthetic considerations. Good coordination and training are essential.

Optical system. Telescopes are the optical aids used to magnify distant objects, i.e. those lying beyond 4.5 m.

There are two basic types of telescopic systems: the Galilean telescope and the astronomical or Kepler's telescope.

1. *Galilean telescope* consists of a convex objective lens and a concave ocular lens separated by the difference of their focal lengths. This type of system produces an upright magnified virtual image (Fig. 10.6).

2. *The astronomical (Kepler's) telescope* (Fig. 10.7) consists of two convex lenses separated by the sum of their focal lengths. This system produces a magnified inverted image. Prisms or mirrors are needed to invert the image, so it will be in the same position as the object when the telescope is used. The application of this system in low vision is limited because of the size and weight of the elements involved.

Types and designs (Fig. 10.8). Uniocular as well as binocular telescopes are available. These can be either hand-held or spectacle-mounted. The

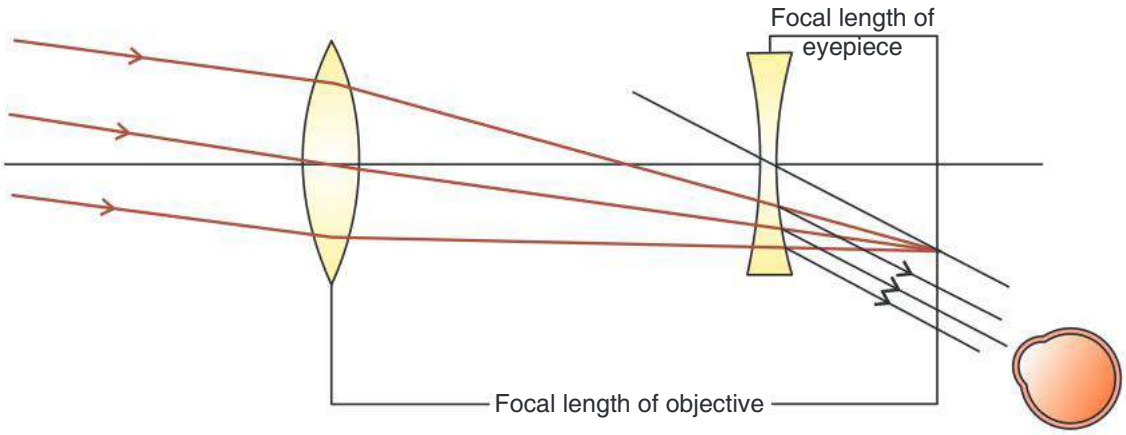


Fig. 10.6 *Optics of Galilean telescope.*

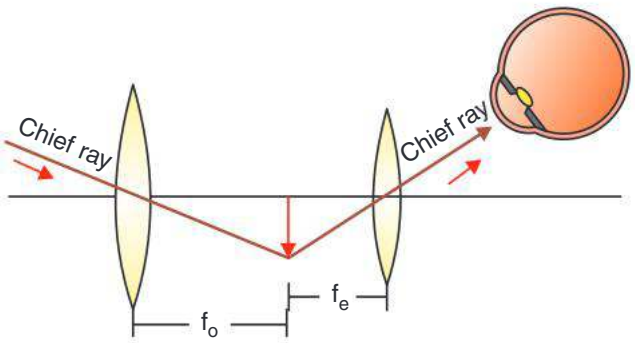


Fig. 10.7 *Optics of Kepler's telescope.*

poorer the vision, the stronger is the power of the telescope required. The maximum useful power for the hand-held telescope is 8× and for the spectacle type is 4×.

- *Monocular telescopes* are easy to carry and use. They have a small but important place in low vision.
- *Binocular telescopes* give binocular vision. They allow for a good grip but are cumbersome to carry. Moreover, if one eye is worse than the other, then a binocular telescope offers no improvement in viewing quality.

Indications for use are as follows:

1. *Telescopic spectacle systems* are used by a limited number of patients on an intermittent basis for *sedentary distance viewing*. Telescopic systems are used when it is not possible to obtain the magnification by moving closer.
2. *Hand-held and ring-style telescopes* are suitable for distance spotting, such as street and bus signs, blackboards and wall menus.
3. *For near and intermediate tasks*, one can focus the telescope for near viewing by (a) adding plus lenses behind the optics of the telescope, (b) adding plus lenses in front of the objective lens or (c) increasing the tube length of the telescope. Such types are called *telemicroscopes*. These are useful for tasks that prohibit close working distances and require the hands to be free, such as viewing computer monitors, drafting, artwork and typing. These can also be offered to patients as an alternative to reading or writing when the patient is unable to maintain a close working distance because of health, postural problems or tremors.

Limitations. In using a telescopic spectacle system, problems encountered are a reduction in field of view, ring scotomata, parallax and a decrease in depth of focus. There is also a loss of light transmission as light passes through each lens surface in the system. So these are not useful for ordinary distance viewing. Telescopic systems are also considered controversial for driving because of the constricted fields.

Telescopic Contact Lenses

A telescopic contact lens is a high-powered minus lens, which when used along with a high-powered convex lens spectacle provides a

Fig. 10.8 *Telescopes: A, monocular; B, monocular hand-held; C and D, binocular.*

magnification of up to two times and an enlarged visual field. It is cosmetically more acceptable than a spectacle-mounted telescope. For an upright image, the Galilean design is incorporated in the telescopic contact lens. Since the magnification is limited, these are suitable for patients with mild to moderate visual impairment.

Tremblay et al in 2013 designed a telescopic contact lens that allowed shift from normal to magnified vision using 3D glasses and electrical polarization. It was a 1.6 mm-thick scleral contact lense with poor corneal oxygenation making it difficult for long-term use. Another such type of scleral telescopic contact lens in which shift between normal and magnified vision is achieved by blinking uses battery-operated LCD glasses.

INTRAOCULAR LOW VISION AIDS

Telescopic Intraocular Lenses

Telescopic intraocular lenses (IOLs) are used in patients with AMD to provide magnification via surgical methods. Till now, seven types of such IOLs have been used in AMD but only short-term results are available, and none of them have proven to be ideal. These include the implantable miniature telescope (IMT) (VisionCare Inc., Saratoga, CA, USA) (Fig. 10.9A), IOL-VIP system (Soleko, Pontecorvo, Italy), Lipshitz macular implant (LMI) (Optolight Vision Technology, Herzlia, Israel), sulcus-implanted Lipshitz macular implant (LMI-SI) (OriLens; Optolight

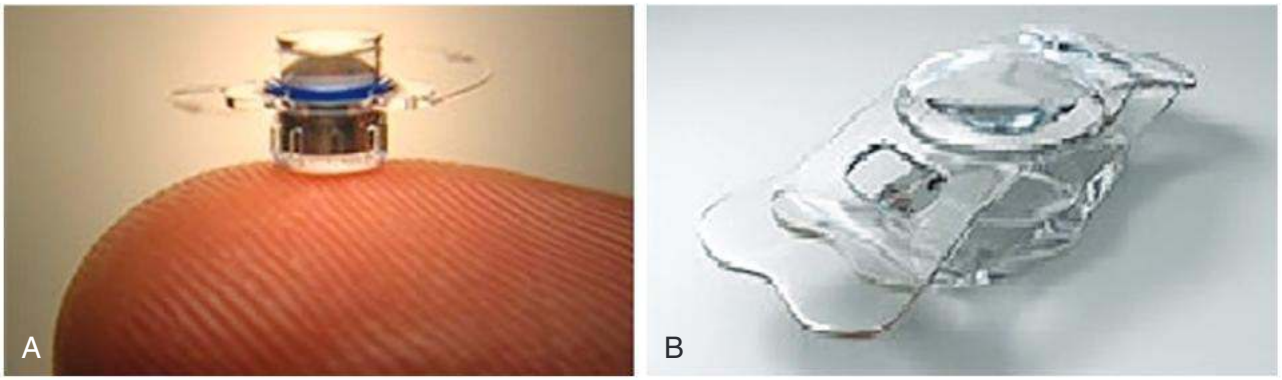


Fig. 10.9 *Telescopic intraocular lenses (IOLs) (A). Implantable miniature telescope (B).*

Vision Technology), Scharioth macula lens (Medicontur Ltd., Zsámbék, Hungary), iolAMD (London Eye Hospital Pharma, London, UK) (Fig. 10.9B) and Fresnel prism intraocular lens (P-Flex; Rayner Intraocular Lenses Ltd., Worthing, UK). The magnification power of the lenses are as follows: 2.5× with the IMT, 2.5× with the LMI, 1.2× with the iolAMD lens, 1.3× with the IOL-VIP system and 1× in the Fresnel prism intraocular lens.

Retinal Prosthesis

Retinal prostheses are implantable electronic devices that stimulate visual sensation within the eyes of individuals with retinal diseases such as AMD and RP, where the optic nerve is normal. Due to its accessibility and neuronal architecture, the retina is the easiest target for treating outer retinal disease. Retinal prostheses are categorized based on electrical impulse delivery mechanism and where in the eye the device is to be placed, which can be subretinal or epiretinal. The advantage of epiretinal device is that it can be easily implanted with minimal risk but subretinal devices have the advantage of using middle retinal layer formed by bipolar, horizontal and amacrine cells. An electrical impulse is delivered by either micro-electrode arrays or micro-photodiode arrays. The former has a camera, processing unit and a transformer, which convert the light to electric impulses by a micro-electrode array while the latter has an array of photodiodes, which on receiving the light directly generate electrical current, so it does not need a camera, processor or transformer. On the other hand, micro-electrode arrays are able

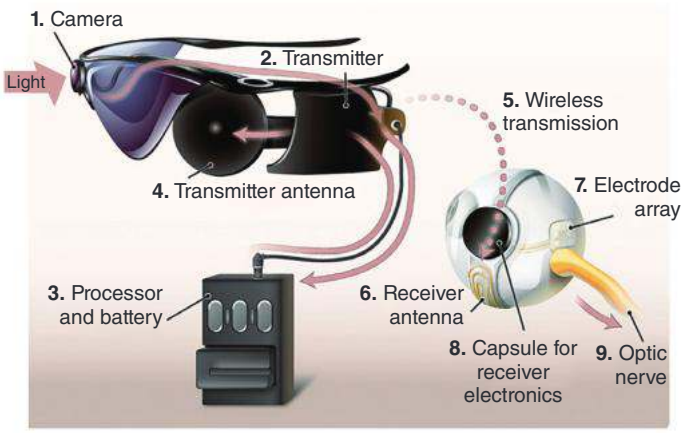


Fig. 10.10 *ARGUS II Retinal prosthesis.*

to generate larger electrical current and use various light-processing algorithms to highlight edges, contrast and other features. Two such devices, Argus II retinal prosthesis (Second Sight Medical Products, Sylmar, CA, USA) and Retina Implant Alpha IMS (Retina Implant AG, Reutlingen, Germany), are CE Mark approved and are currently being implanted to address blindness from advanced RP.

Argus II Retinal Prosthesis. This is the first prosthesis approved by the Food and Drug Administration. The Argus II is a micro-electrode epiretinal prosthesis, delivers electrical impulses to the retinal ganglion cells which produce phosphenes, the light spots. It consists of three internal components and three external components (Fig. 10.10). Patients require training and rehabilitative support to adapt to this system of artificial vision once it is implanted. Studies have shown improvement in visual function

tests in patients implanted with Argus II in terms of ability to recognize and discriminate forms, detect motion and navigate. The Argus II is indicated in patients with severe RP older than 25 years of age, have only or no light perception in both eyes, with a previous history of some useful vision. It is implanted in one eye, usually the worse-seeing eye.

Patient's willingness for the recommended post-implant follow-up, training and visual rehabilitation is a very important prerequisite.

External components: camera mounted on glasses, processor and transmitter. Internal components: receiver coil, electronic capsule and an array of electrodes.

Retina Implant Alpha-IMS. This is a micro-photodiode, subretinal prosthesis, implanted within the layer of degenerated photoreceptor cells. Electrical signals generated by the device stimulate bipolar cells in the middle retinal layers, which carry the impulses to retinal ganglion cells. It is a 1600-pixel micro-photodiode array relying on light to stimulate the optic nerve via remaining RPE cells. The implant includes a hand-held device that transmits energy via magnetic induction to a coil implanted under the skin behind the ear. It is indicated in patients with degenerative outer retinal disease.

BrainPort

BrainPort (Wicab, Inc., Middleton, WI, USA) provides artificial vision to patients who have previously experienced some sort of vision. It consists of a camera mounted on glasses, which captures and sends the image to a hand-held remote-control unit, where the image is converted into a black and white low-resolution photo. This is then transmitted to an array of electrodes placed on tongue, which sends sensory information to the brain. These impulses are then interpreted as visual signals and are redirected to the visual cortex, allowing the person to 'see'.

OTHER OPTICAL DEVICES

Absorptive Lenses

Absorptive lenses are used to reduce glare and dark-adaptation time and are especially useful while dealing with patients with albinism. The various types of absorptive lenses used are tinted lenses, photochromatic lenses and filters.

- *Tinted lenses*. Low-absorptive high-transmission tinted lenses are best for constant use.
- *Photochromatic lenses* are of help to people who are less light sensitive.
- *Polarization* reduces glare.
- *Filters.* Contrast can be enhanced by using spectacles with yellow and amber filters. Commercially available filters include:
  - Corning CPF filters (CPF-450, 511, 527 and 550)
  - Younger Protective Lens Series (PLS) filters (PLS-530, 540, 550)
  - Medical Technology filter (medium amber, 10%; medium green, 18%; dark amber, 2%)

Visual Field Enhancement Devices

These are used in patients with defects in the peripheral visual field. Devices used as field expanders include:

- Fresnel prisms,
- Pell's field expansion prisms,
- Hemianopic mirrors,
- Gottlieb field expanders, and
- Reverse telescopes.

1. Fresnel Prisms

- Fresnel prisms have been used successfully to treat field defects such as hemianopias and the restricted field found in patients with retinitis pigmentosa. The prisms do not expand the visual field, but they allow patients to become more aware of objects on the blind side by moving their eyes into the prisms.
- The prisms act by displacing the apparent position of objects in the blind field towards the primary visual direction.
- The prisms should be placed where they do not interfere with normal scanning eye movements when the patient is looking straight ahead.
- The powers of the prism can vary from 12 to 30 degrees, depending on the width of the area the patient can scan.

Multiplexing. Multiplexing refers to the transmission of multiple signals on the same channel so that all information can be used at the receiving

end. For visual field expansion, this means using prism in a new way. High power (300Δ–40Δ) base-out prism is mounted across the width of the lens in front of the eye ipsilateral to the field loss but above and below the line of sight, affecting the patient in all gaze positions.

2. Peli's Field Expansion Prisms

In patients with peripheral vision loss (PVL), for example, those with retinitis pigmentosa (RP), the conventional magnifying low vision aids (which are useful in patients with loss of central vision) often reduce their existing vision. So, for such patients, reverse telescopes which expand the visual field are more beneficial. However, the field expansion with reverse telescopes is associated with reduced visual acuity and so, even these are not usually preferred. Peli's Field expansion prisms which expands peripheral vision without reducing visual acuity are the best suited low vision aids for such patients.

In patients with homonymous hemianopsia, to expand their visual field in the direction of field loss, the Peli's field expansion prisms should be used with its base towards the affected side of the field defect. After leaving a central opening of about 12 mm of the spectacles, Peli's prisms should be placed on the posterior surface in the upper and lower quadrant.

In patients with tunnel vision, for example, cases of advanced RP, advanced glaucoma and choroideremia, the Trifield prisms is beneficial. These are placed on one eye, with base-out in the temporal quadrant and base-in in the nasal quadrant of the spectacle lens, providing peripheral vision and the other eye has central vision. As a result, visual field expansion occurs in all directions. The prisms are color coded to reduce double vision and confusion. After training exercise, once the patient is adapted to the field expansion, the Peli's prisms are permanently attached to the spectacle lens.

3. Hemianopic Mirrors

- Patients with right hemianopias have been prescribed a mirror attached to the nasal eye wire and angled before the right eye. The mirror blocks out most of the left visual field of the right eye, replacing it with a view of the right visual field.
- The mirror only allows the user to be continually aware of major changes occurring in the right visual field. The patient must make gross eye and head movements to actually look at an object of interest in the blind field.

Central Scotomata and Eccentric Viewing

- One of the most prevalent field defects among patients with low vision is a central scotoma resulting from age-related maculopathy.
- Eccentric viewing (EV) refers to using a non-foveal location to avoid the central scotoma and to obtain the best possible functional vision. Some patients will naturally use EV, whereas others will need to be trained. Training time will be shortened considerably if an orthogonal extrafoveal locus is used. Prism incorporated into reading glasses can aid patients with low vision by deviating light away from the non-functional foveal area.

NON-OPTICAL DEVICES

These are aids other than lenses that may supplement lenses or may be used independently. The various types of non-optical methods are as follows:

1. APPROACH MAGNIFICATION

The partially sighted patients should be encouraged to move as close as possible to the screen while watching TV.

2. LIGHTING ARRANGEMENT

- *Lighting necessity varies* for every individual and depends on the diagnosis and extent of pathology.
- *Diseases such as* aniridia, achromatopsia and albinism require low-level lighting, while glaucoma, retinitis pigmentosa, optic atrophy and nuclear cataract require high illumination.
- *Natural light* is the adequate lighting for most low vision children; however, artificial light allows better control of illumination.
- *Incandescent light* of 60–75 W is preferred because it provides a more continuous spectrum than fluorescent light but might be harder to find, particularly in the USA where some states have banned incandescent lighting.

- *Fluorescent light* emphasizes the 'cooler' blue spectrum, which can intensify glare. Everyone, even those without low vision, should avoid single-tube fluorescent lamps without a diffuser because they are intermittent and can cause eyestrain and inhibition of accommodation.
- *Light should be shone directly* on the reading material, avoiding reflective surfaces. The focus should be placed at shoulder height corresponding to the better-seeing eye, forming a 45 degree angle with the visual axis. When using natural light, the child should sit with his/her back to the window or on the side leading to the best lighting and visualization.

3. CONTRAST ENHANCEMENT AND GLARE REDUCTION

- *Reading is aided by* the use of a typoscope as a line guide and to isolate the reading material by reducing glare from the surface of white page.
- *Lighting control* is of great importance to enhance contrast and reduce the glare. The type, position and intensity of the light source should be monitored.
- *Absorptive lenses* in yellow for low-light environments and amber for more intense lighting are good prescription options.
- It is also important to support daily activities with aids such as black felt-tipped pen, bold lines and contrasting colours.

4. LINEAR MAGNIFICATION

Examples of this approach to low vision include large print books and periodicals, large print playing cards, enlarged telephone dials and high-contrast clock faces. The advent of enlarging photocopiers may be of help for reading specific documents.

5. PERSONAL ITEMS

Personal items like magnifying mirror and needle threader make the life of a visually impaired person easier.

6. AUDITORY AIDS

Auditory aids such as talking clocks and watches, computers with speech synthesizers and large print voice calculators are available for use by visually handicapped person.

7. ELECTRONIC MAGNIFIERS

Electronic magnifiers available for use in low vision include:

- Closed-circuit television,
- Portable Video Magnifier Headborne Elsectronic Glasses
- Large print computers,
- Low vision imaging system (LVIS; formerly called as low vision enhancement system) and
- V-max.

Closed-Circuit Television

In CCTV, the camera picks up the reading material, magnifies it and displays it on the TV screen. CCTV magnifiers provide excellent contrast and magnification and can also furnish colour and reverse contrast polarity. These can provide linear magnification electronically up to 60×. These can be modified for a variety of uses: reading, writing, computers, crafts, etc.

Advantages. A CCTV offers a number of advantages over optical systems. It provides a distortion-free, brighter, magnified image with enhanced contrast on a larger screen. White letters on a black field (reverse polarity) also help in improvement of image clarity in some cases.

Limitations. A CCTV is expensive, heavy and difficult to move around. It may be difficult for some patients to operate it.

Portable Video Magnifiers

The primary goal of most low-vision patients is to read standard print. Sometimes this can be accomplished with a stronger add at a closer working distance or with an optical magnifier. But patients often need more magnification or a larger field of view than these devices allow. Portable video magnifiers such as Smartlux® Digital by Eschenbach Optik have become quite affordable and allow patients to read fine print comfortably due to multiple magnification and colour settings.

Some video magnifiers also have optical character recognition. This feature allows users to switch between listening mode and scrolling text, which can be beneficial for patients **with eccentric fixation.**

Headborne electronic glasses

While wearable magnifiers have progressed significantly, they are still bulky and costly and, therefore, have had limited use in practice thus far. Headborne electronic glasses such as seeBOOST and OrCam project images from a video camera, allowing for enhanced contrast and magnification. Some models can read text aloud, as well as identify items by bar code and people by facial recognition.

Large Print Computers

Computers can provide enlarged print on the screen through either standardized or dedicated software. In some programmes, the image may be enlarged and moved in front of the observer's eye. Software is also available to provide speech for the computer, so that information presented on the screen becomes available to the user.

Low Vision Imaging System

LVIS, developed at John Hopkins University, is mains/battery operated video head-mounted device equipped with autofocus camera, variable magnification optics and contrast enhancement electronics (image processing capability). System contains two video cathode ray tubes mounted in the device's temple arms on each side of the head. Video screen images are magnified by aspheric lenses and imaged in front of eyes by mirrors and beam splitters. There are two monochrome charge-coupled device cameras mounted in front of eyes on line of sight (unmagnified binocular field of view for orientation) and a third, centre-mounted zoom camera (providing same image to both eyes with variable magnification). The third variable-focus camera can tilt down by 45 degrees for near vision/down gaze. Head-mounted design frees the user's hands. Magnification, contrast and brightness are under the user's control.

V-Max (Enhanced Vision System)

It is a battery-powered head-mounted unit but differs in that it uses colour camera and liquid crystal displays. Image processing is available in the form of edge enhancement technology and contrast reversal. Control box is smaller and simpler than that of LVIS.

8. WRITING AND COMMUNICATION DEVICES

Writing and communication devices include handwriting guides, signature guides, check guides, bold line papers, tactile or raised line paper, felt tip pens or markers (black) and in-built light pens.

Fibre-tipped pens with black ink provide best contrast while writing. The writing aids are quite useful for signature and cheque writing.

9. MEDICAL ASSISTIVE DEVICES

These are with large print or in talking mode, e.g. diabetic assistive devices, blood pressure assistive devices and thermometers.

10. ORIENTATION AND MOBILITY LVAs

Orientation and mobility LVAs can be divided into primary and secondary aids.

I. Primary Aids

Primary aids include sighted guide, canes of various lengths and dog guides.

i. ***Canes*** include:
- *Long canes:* For those with severe vision loss when people have problems detecting obstacles.
- *Identification canes:* Thin, light-weight cane positioned diagonally across the front of the body. For those who can detect obstacles but need help for depth perception.
- *Support cane:* For those who need extra support to lean upon and stability when walking.
- *Smart canes are equipped with ultrasound sensors* that can detect nearby obstacles above chest level and warn users with a tactile vibration. They can be linked with a smartphone to provide navigation assistance.
- *Smart paint infused with light-converting oxides* is being tested on the edges of crosswalks in some locations. When smart canes come in contact with the paint, they vibrate. The vibration helps pedestrians with low vision stay inside crosswalk lines. Researchers hope to use this paint to interact with GPS to identify the location of bus stops and businesses.

ii. ***Guide dogs:*** Help to travel around safely and independently and are most commonly Labradors and Golden Retrievers.

II. Secondary Aids: Electronic

These are used with the primary aids to provide additional information like overhead obstacles and location of doorways.

i. ***Electronic orientation devices:*** Most popular is the Miniguide which sends out ultrasonic beams and provides vibratory/auditory feedback to the user when met with obstacle.

ii. ***GPS devices:*** Global positioning systems (GPS) verbally guide the user along specified routes to destinations.

11. SENSORY SUBSTITUTE ASSISTIVE AND ADAPTIVE DEVICES

- *Auditory substitutions* are talking books, reader services and audio-descriptive devices.
- *Tactile substitutions* include Braille, paperless Braille outputs and non-Braille tactile output.

NEWER TECHNOLOGY LOW VISION AIDS

Advances in consumer electronics are also improving quality of life for people with low vision. These new advances are not a cure for all those with low vision, but for many people, they offer options for portable, lower-cost LVAs.

i. ***E-readers (kindle, i-pad):*** Portable and more affordable alternatives to CCTV, at one-tenth the price of CCTV in some instances. Allow users to adjust the font size and contrast settings of the display. Text-to-speech functionally present and can read aloud to the user.

Disadvantage: Cannot offer same level of magnification as CCTV.

ii. ***Smart phones and tablets:*** Both Apple- and Android-based smart phones and tablets offer a range of applications and built-in functions to help people with low vision:

- *Magnify:* iRead, iLoupe and Magnify use the device's camera and light source to magnify and illuminate text; portable and less expensive alternative to CCTV.
- *Sight book:* Digitally communicates vision changes to ophthalmologists (wirelessly) by measuring visual function with a set of near vision tests.
- *Map Quest:* (Apple and Android phones) Provides voice-guided directions and tells the driver when to turn.
- *Voice interface:* Siri, voice recognition system on i-phone 4S, allows user to check weather, email or calendar without navigating series of icons. Android-based phones also have voice-recognition capability, allowing user to dictate texts/emails without typing.

iii. ***Voice-activated digital assistants*** such as Siri, Google Assistant and Alexa can accomplish various tasks, including reading or sending a text, checking a calendar, making a list or looking up a phone number. In a smartphone's "accessibility" menu, patients can find the TalkBack (Android) or VoiceOver (iPhone) function that will read aloud words on the phone screen.

iv. ***Useful apps available*** for download include:

- *TapTapSee*. The user photographs an object by double-tapping the phone screen. The app announces a description of the image.
- *Be My Eyes*. Through a live video call, a volunteer network of sighted people provides task assistance, navigation and answers questions about what users are "seeing."
- *Blindfold Games*. This entertainment app provides people with visual impairments more than 80 games, such as puzzles and card, video and board games.

EVALUATION OF THE PATIENT WITH LOW VISION

The approach in managing a patient with low vision should not be that 'Nothing can be done for your disease', but rather, 'since not much can be done medically or surgically for your disease, you will be evaluated for enhancement in the vision with the help of visual aids'. After acquiring the patient's confidence, a systematic evaluation should be carried out. Patients with low vision

generally present more complex problems than the average patients. Careful planning and a trained staff with a well-equipped low vision clinic are necessary to provide a setting where patients with visual problems may be cared for efficiently. The evaluation of a case with low vision should be carried out as follows.

HISTORY TAKING

A concise history that can provide a fairly accurate idea about diagnosis, an information about the visual activities that present difficulties to the patient and what are the patient's expectations should include the following structured questionnaire:

- Date of onset and progression of the visual loss.
- The details of the diagnosis, investigations undergone and the type of treatment taken.
- Age, educational status and professional requirements of the patient.
- Low vision is more for near or distance or both.
- Patient prefers more or less light.
- List of the visual activities that present difficulties to the patient, including the ability to move independently.
- Medical, social and psychological build of the patient.
- Exact requirements of the patient in terms of near, intermediate or distance vision should be enquired into.
- Proactive questioning during the case history may uncover difficult to detect symptoms. Charles Bonnet syndrome (CBS) has been observed in persons with vision impairment, and it is characterized by complex visual hallucinations of a non-threatening nature. In addition, the person is aware that the hallucination is not real and that the images are benign.
- Does the patient have health problems or treatment requirements that will impact low vision recovery? If the patient is a diabetic, can the patient see to fill insulin syringes, read nutritional labels on food containers and see to monitor their foot care?
- Is the patient taking medications that may impact their vision and can the patient see to identify their medications?

Stages of adjustment of a patient with low vision are as follows:

- Denial
- Anger
- Bargaining
- Depression
- Acceptance

A practitioner must recognize these stages so that the timing of low vision treatment can be given accordingly.

OCULAR EXAMINATION

A thorough ocular examination is essential to decide whether an LVA can be prescribed or not; and if yes, what type of LVA will be most suitable in a particular case.

1. SLIT-LAMP EXAMINATION AND FUNDUS EVALUATION

The ocular examination should include anterior segment biomicroscopy and detailed posterior segment evaluation with indirect ophthalmoscopy and focal illumination techniques with a 90 or 78 D lens.

In addition, examination of a patient with low vision should also include the following tests.

2. REFRACTION

Refraction should be performed for far and near. It is important to establish the degree of refractive error, since it forms the basis of visual acuity tests for distance and near and influences the eventual power of the LVA.

- Assuming that the patient has reasonably sized pupils and relatively clear media, standard retinoscopy techniques may be used. However, when the reflex is dim, non-standard or 'radical', retinoscopy techniques may be preferable. A dim reflex may be caused by media opacities, but it may also be caused by a large, uncorrected, refractive error. Radical retinoscopy simply involves moving the retinoscope closer to the eye, and this may uncover large amounts of myopia when the quality of the reflex significantly increases.
- There are two common methods for determining the lenses to demonstrate when performing

a low vision refraction. The first is by determining the just-noticeable difference (JND), which is 'that amount of spherical lens change at which a change in clarity or blur is first noticed'. Consequently, to determine if there is a noticeable change, trial lenses of ±1.00 D would be compared to one another. Refraction must proceed until more blur is noted with both plus and minus lenses.

- Fully correcting the patient with low vision is important because he or she may appreciate a subjective increase in visual ability, even when there is little to no objective improvement. Proper refractive correction may also positively influence performance with low vision devices.

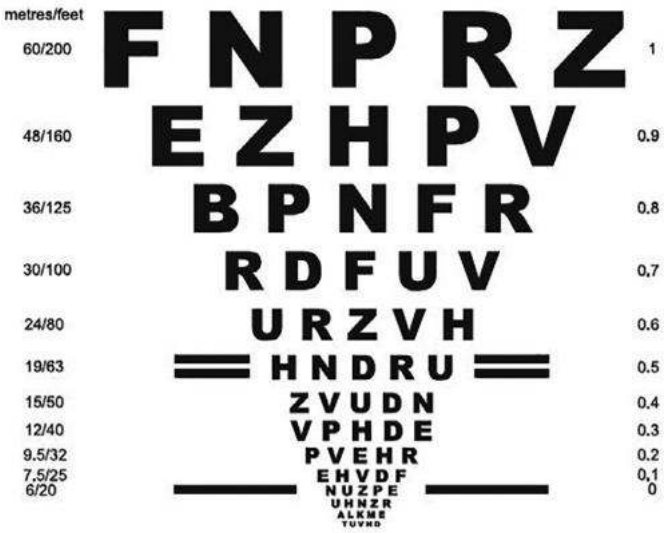


Fig. 10.11 *Bailey–Lovie logMar distance acuity and reading chart.*

■ 3. EVALUATION OF VISION

Evaluation of the vision for distance as well as near forms the key examination before prescribing an LVA. After testing the Snellen's visual acuity with full correction, following tests may be performed:

i. ***Pinhole test***. A pinhole mask should be used to test, if vision can be further improved with spectacles. This mask is an ordinary binocular occluder with 16 uniformly arranged perforations of 1 mm size, for each eye. Pinhole mask should be used when distant vision is worse than 6/18 Snellen.

ii. ***Special low vision charts*** should then be used for further assessment. These charts directly give the percentage of loss suffered and magnification required by a particular person. Some of the special low vision charts used for distance and near vision are as given:

- *Distance vision charts* that have been recommended for use are those of Bausch & Lomb, Sloan, Staub, Bailey–Lovie logMar (Fig. 10.11) and modified ETDRS (Early Treatment Diabetic Retinopathy Study) charts. These charts are designed to be used at distance of 3, 2 and 1 m and predict the approximate magnification required.
- *Feinbloom Distance Chart for the partially sighted.* It is commonly referred to as the Feinbloom chart. It uses number optotypes and consists of a spiral-bound book with 13 pages. The number of numerals per page varies from one numeral to rows of eight numerals, depending on target size. The chart was designed for use at 10 feet, but it can be used at any distance as long as a conversion for the test distance is made (e.g. 5/100 = 20/400 or 6/120). The main advantages of the Feinbloom chart are the ease of portability and the ability to measure even severely reduced visual acuity. The main disadvantage is the fact that there are limited numbers of optotypes at lower acuity levels.
- *Near vision charts* that have been recommended for use are Sloan's M charts, Keeler's chart and modified ETDRS charts with the spectacle correction for near work; the near visual acuity is measured at 16 in. (40 cm) monocularly and binocularly.

In reading acuity, assess:

- *Threshold.* Smallest text size that can be read.
- *Optimal size.* Size of the text that allows fluent reading for a longer period of time.
- *Reading speed.* Number of words read per minute of an age-appropriate text.
- *Reading comprehension* is also important.

Note. In patients with AMD, a discrepancy between single-letter and reading acuity may indicate difficulty with EV in the presence of central field loss.

- ***Assessment of magnification required for reading.*** Sloan's M charts are quite popular

and are available in sizes varying from M_1 to M_{20}. These directly give the magnification required. For example, if a patient reads comfortably M_4 chart, this indicates that he or she needs 4× magnification. Table 10.2 describes the Sloan's M chart system.

4. FUNCTION TESTS

Evaluation of the visual acuity by special charts is not sufficient. A comprehensive low vision evaluation includes following three additional visual function tests modified specially for low vision.

i. ***Amsler grid test*** should be performed to note how the scotomata influence the outcome. The scotoma density, position and the degree of distortion affect the ability to read print. For example, dense scotoma covering the central 10 degree requires higher magnification and is more difficult to overcome than the same scotoma above or to the left of the fixation. Some patients may not see a scotoma in spite of the documented retinal disease. These patients have learnt EV and thus have better prognosis for use of magnification.

ii. ***Contrast sensitivity function.*** Recently, it has been reported that patients with comparatively low contrast sensitivity function (CSF) might need double or triple the power of the lens that has been calculated on the basis of reciprocal of the acuity.

- The benefit of measuring the CSF for patients with low vision is that there may be preferential loss at certain spatial frequencies.
- High-frequency losses are associated with difficulties with tasks such as reading and facial recognition, and mid-frequency losses are associated with mobility difficulties.

iii. ***Glare test*** may be positive in patients with additional media opacities such as cataract, thickened posterior capsule or corneal oedema. If patients with low vision are disabled by glare from lens opacities or secondary capsular membranes, surgery should be considered, if potential acuity measurements indicate possible improvement.

Protecting shields that block ultraviolet light and increase contrast (yellow or light amber filters) or that reduce the effect of intense light (neutral grey filters) have been recommended for protection from glare.

5. VISUAL FIELDS

Evaluation of visual fields can provide information regarding the extent of intact central retina available for magnification. Visual fields can be

Table 10.2 *Sloan's system for determining visual acuity*

Size of print in Sloan M units	Acuity required at 40 cm	Equivalent distance acuity	Dioptric power (D) or reading addition required to read M print (assuming emmetropia and zero accommodation)
1.0	40/100	20/50	+2.50
1.5	40/150	20/75	+3.75
2.0	40/200	20/100	+5.0
2.5	40/250	20/125	+6.25
3.0	40/300	20/150	+7.5
4.0	40/400	20/200	+10.0
5.0	40/500	20/250 or 16/200	+12.5
7.0	40/700	20/350 or 11.5/200	+15.0
10.0	40/1000	20/500 or 8/200	+25.0
14.0	40/1400	20/700 or 5.8/200	+30.0
20.0	40/2000	20/1000 or 4/200	+50.0

evaluated by confrontation test, tangent screen test and perimetry.

- Each eye should be tested monocularly as well as binocularly during low vision rehabilitation.
- The location of the scotoma(s) may indicate a need for EV training before near device prescription.
- A newer technique is microperimetry, which uses the scanning laser ophthalmoscope (SLO) to project targets on to specific areas of the retina.
- A significant advantage of this technique over standard techniques is that the exact location of the patient's fixation is known and recorded. If the retinal area used for fixation is a non-foveal location, that location is referred to as the preferred retinal locus.

6. BINOCULAR VISION

It is important to assess ocular alignment to determine the possibility for developing or maintaining binocular vision, whenever possible. So, ocular motility should be carefully evaluated.

7. COLOUR VISION

Evaluation of colour vision gives functional information as to how the patient performs in the everyday environment.

- Acquired maculopathies such as those resulting from AMD, diabetes and hypertension typically cause blue-yellow defects, whereas retinal dystrophies such as Stargardt, Best and central areolar choroidal dystrophy usually cause red-green defects.
- Such defects can have educational, vocational and avocational implications that may be addressed during the low vision evaluation.
- The Farnsworth dichotomous test is the most commonly used colour arrangement test in low vision clinics.

8. SPECIAL TESTS

The use of a laser-scanning ophthalmoscope allows one to plot the precise area used by the patient with central retinal damage. The visual evoked potential or VE shows an increasing role in the assessment of patients with a brain injury. Electroretinograms are helpful in the differential diagnosis of many retinal diseases.

PRESCRIPTION OF LVAs

As stated earlier, if the prescriber possesses a sufficient knowledge about the various LVAs and has mastered the art of evaluating a patient with low vision, the job of prescribing LVA is simplified. Undoubtedly, the job is simplified but still it is not so easy. In fact, low vision care is more complex than the routine eye care.

GUIDELINES FOR PRESCRIBING LVAs

The practitioner should keep following points in mind while prescribing an LVA:

1. The aim should be to provide maximum vision without compromising with the mobility of the patient.
2. It should be borne in mind that as the magnification increases, both the working distance and field of vision decrease.
3. Preferably, the aid chosen should be simple, lightweight, portable and flexible. It is better to avoid complicated and cumbersome devices. As far as possible, the conventional spectacles with a high addition should be the first choice.
4. The patient's visual status, mental status, needs and motivation should be given due consideration while prescribing an LVA. Therefore, the aid needed may vary from person to person even though the cause of low vision may be the same.
5. All the devices with similar magnification should be tried before prescribing a particular LVA.
6. Both eyes should be corrected, if the difference in magnification is insignificant. However, if a complicated and cumbersome device is needed, only one eye may be used to avoid further complicating the situation.
7. A single-eyed person with markedly low vision may accept a telescope or high addition.
8. In old patients where keeping the print at a fixed focus may be difficult, it may be worthwhile to try without magnifier.

9. In children, persuasion and understanding is of paramount importance. Therefore, it may be worthwhile to defer prescription of the LVA till the child is old enough and understands their value.
10. To achieve better acceptance of any aid, consider the patient's needs, goals and ability to handle the aid, as well as the aesthetics, weight, cost and timing of the prescription.
11. For reading activities, besides achieving vision for a certain size of optotype, the patient should be evaluated for reading. In the presence of eccentric fixation or difficulties with the proposed aid, training should precede prescription.
12. Each category of visual device has its advantages and disadvantages. In low vision daily practice, it is common for a patient to have more than one aid.
13. The patient should be monitored frequently to evaluate the effective use of the aid prescribed and difficulties presented in daily activities and to set up more advanced goals.

■ DISPENSING AN LVA

Why and When to Prescribe LVAs

Why to prescribe. The prescription of low vision devices gives the patient

- Independence,
- Increased adaptation to the daily activities materials and
- Exposure to enriching experiences.

It constitutes an important factor for socioeconomic and cultural integration.

When to prescribe. Optical aids for near vision are introduced when the reduction of the distance between the object and the eye does not allow the necessary range or when the accommodative effort is too large.

At school age, with visual acuity (VA) up to 20/200, reducing the distance between the object and the eye is recommended until the second grade. From this stage, a stand magnifier or a hand magnifier can be used for reading small-print books such as dictionaries.

For VA less than 20/200 (0.1 logMar), optical aids should be prescribed earlier. If the VA is less than 20/400 and the central scotoma greater than 30 degrees, a video magnifier is indicated.

For VA equal to or less than 20/800, aids such as Braille and computer sound systems should be included, with or without other resources. Orientation and mobility techniques should be encouraged at all low vision levels.

How to Prescribe LVAs

A careful clinical history is important to setting goals based on real expectations. A patient who participates in selecting the aid is more likely to learn how to handle it. Important steps involved in prescribing LVAs include:

- Determining the best-corrected VA for near/distance.
- Determining the VA that the patient requires.
- Calculating the magnification needed to achieve the goal.
- Selecting the aid according to the characteristics of the device: the needs, goals and clinical aspects of the patient.

Magnification Trial

After a meticulously performed work-up, the magnification required should be calculated by the practitioner, taking into consideration the influence of scotometry, contrast and glare data. The power of reading correction should be adjusted until the patient can read the target size words and text.

Types of magnification. There are several types of magnification used when evaluating low vision:

i. *Relative distance magnification (RDM)* is the magnification achieved by viewing an object at a closer distance. RDM = reference distance/new distance.
ii. *Relative size magnification (RSM)* is achieved by actually making the object larger. RSM = new size/reference size.
iii. *Angular magnification* is produced when an optical device increases the angle subtended by

the object. Microscopes, magnifiers and afocal telescopes, all produce angular magnification.

iv. *Electronic magnification.*

Predicting magnification. Magnification needed by a patient of low vision can be predicted as follows:

- Magnification needed = reference acuity/goal acuity. This formula can be used for near or distance vision. For example, if the patient reads 5M and they desire to read 1M, the magnification needed would be 5/1, or 5×.
- After the amount of magnification needed is determined, the means by which to achieve that magnification must be determined.
- By dividing the desired magnification by the reference distance at which the near acuity was measured, the dioptric power of the add can be determined: F = (M/r), where M is the magnification; r is the reference distance, in metres, at which near acuity was measured; and F is the dioptric power of the predicted add.
- Alternatively, one may elect to estimate magnification for reading in terms of equivalent viewing distance (EVD) and its reciprocal, equivalent viewing power (EVP). Reference distance/reference acuity = EVD/goal acuity. Reference distance/EVD = reference acuity/goal acuity.

Kestenbaum's rule. The add required to read 1 m print can also be easily estimated from the measured visual acuity. The predicted add in dioptres = inverse of visual acuity fraction, e.g. if vision is 6/60 or 20/200, add required = 60/6 or 200/20 = +10 D. But it is not a precise method as described above.

Prescription of Appropriate Device

Various LVAs of the calculated power should then be tried systematically in sequence: convex lens first as a spectacle (either monocular or binocular with converging prism), second as a hand magnifier and third as a stand magnifier. The complex telescopes, microscopic doublet and electronic systems should be reserved only for desperate cases.

The major consideration in the choice between a telescope and hand magnifier is the work distance. Other considerations are weight of the spectacles, cosmesis, whether both hands are needed to be free during use, whether the hand-held magnifier will be steady and the field of view it enhances. In general, a telescope has a larger field of view than a hand magnifier of equivalent power, since they are closer to the eyes.

The user must finally determine what type of visual aid is best for him or her. Every person's adaptability to a particular degree of visual impairment is different, so are his or her needs.

Training to Use Appropriate LVA

Once the aid to be dispensed is finalized in view of the guidelines for prescribing an LVA, the patient should be taught how to handle the aid and how to hold the printed material. A common complaint with LVA is that it works much better in the doctor's clinic than at the patient's home. The possible explanation is that the lighting is much better in the doctor's clinic. So, along with the prescription of the visual aid, proper guidance should be given about optimal lighting arrangements as well.

Patients should also be trained to

- Take care of the device,
- Keep it clean and
- Decide when to use, where to use, for which activities to use and to explain to others why he or she cannot work without it.

Counselling and motivation are very important to encourage the patient to use LVA.

Periodic follow-up is important to assess the user's performance with the prescribed visual aid. Periodic follow-up visits should be scheduled to assess the amount of progress made.

The patient's visual acuity determines how close the working distance should be brought during near work to obtain an image large enough to be appreciated. The closer the working distance, the higher is the lens add required, assuming that the accommodation is negligible.

11 Refractive Surgery

Chapter Outline

REFRACTIVE SURGERY: AN INTRODUCTION

Surgery to correct refractive errors is becoming very popular. It should be performed after the error has stabilized – preferably after 18–20 years of age. Many surgical techniques have been developed over the years. Quite a large number of refractive surgical techniques have become obsolete and abandoned and a few are still in experimental stages. Such techniques are described briefly. Only those techniques which are presently in vogue are described in detail later in this chapter.

CLASSIFICATION

Refractive surgery techniques in general can be grouped as follows:

A. Keratorefractive procedures

1. *Incisional refractive techniques*
   - Radial keratotomy (RK)
   - Astigmatic keratotomy (AK)
   - Hexagonal keratotomy
   - Limbal relaxing incision (LRI)
   - Opposite clear corneal incision (OCCI)
2. *Lamellar corneal refractive procedures*
   - Freeze keratomileusis of Barraquer
   - Epikeratophakia (epikeratoplasty)
   - Non-freeze keratomileusis
   - Keratomileusis in situ (BKS technique)
   - Automated lamellar keratoplasty (ALK)
   - Small incision lenticule extraction (ReLEx Smile Technique)
   - Corneoplastique
3. *Laser ablation corneal procedures*

   Surface ablation procedure
   - Photorefractive keratotomy (PRK)
   - Laser subepithelial keratomileusis (LASEK)
   - Epithelial laser in situ keratomileusis (E-LASIK)

   Intrastromal ablation procedures
   - Laser in situ keratomileusis (LASIK)
   - Custom laser in situ keratomileusis (C-LASIK)
4. *Corneal shrinkage refractive procedures*
   - Thermal laser keratoplasty (TLK)
   - Conductive keratoplasty (CK)
5. *Corneal implants*
   - Intracorneal contact lenses
   - Intrastromal corneal ring segments (Intacs)
6. *Corneal tissue moulding*
   - Orthokeratology

B. Lens-based refractive procedures

1. Phakic refractive lenses (PRLs)
2. Refractive lens exchange (RLE)

C. Combined lens and corneal refractive procedures

1. Bioptics
2. Trioptics

PATIENT SELECTION AND PREOPERATIVE EVALUATION FOR REFRACTIVE SURGERY

PATIENT SELECTION

Like any elective surgery, meticulous patient selection and evaluation are essential to maximize good outcome from refractive surgery. The following factors should be considered before a patient is selected for refractive surgery:

1. ***Patient motivation.*** It is the most important factor, since an unmotivated patient has more chances of being unsatisfied. Motivation for keratorefractive surgery revolves around the desire to have functional vision without spectacles or contact lens correction. This motivation may be based on any of the following factors:
   - Occupational requirements, e.g. in actors and actresses
   - Desire for an improved cosmetic appearance is the most common motivational factor
   - Recreational needs
   - Contact lens intolerance

The patients must understand that while refractive surgical procedure often greatly reduces dependence on optical aids, it rarely eliminates the need for them entirely.

2. ***Age of the patient.*** Generally patients younger than 18 years should not be taken up for surgery because of unstable refraction. Refractive procedure should be attempted only when the refraction has been stable for at least 1 year. There is no upper age limit for refractive surgery (technically); however, patients older than 45 years should be operated sparingly. This caution is required because of two reasons: a greater risk of overcorrection and need for using presbyopic glasses.

3. ***Refractive error.*** The optimal range of refractive error varies from procedure to procedure.

4. ***Occupation of the patient.*** Preferably, RK should be avoided in individuals with the following occupations:

- Jobs requiring night driving, because of chances of troublesome and incapacitating glare
- Sportspersons and security personnel, because of danger of more chances of globe perforation following ocular trauma

5. ***Ocular abnormalities*** that are contraindications for keratorefractive surgery include the following:

Absolute contraindications

- Keratoconus
- Contact lens warpage
- Chronic steroid and antimetabolite use for immunosuppression
- Glaucoma
- Herpes simplex keratitis
- Connective tissue disease

Relative contraindications

- Blepharitis
- Dry eye
- Glaucoma
- History of uveitis
- Chronic eye rubbing
- Other ocular surface disorders
- Diabetes mellitus
- Single-eyed patient

6. ***Informed consent.*** Patient selection should always include a detailed informed consent. Patients must be made aware of the risks and benefits of the refractive surgery, the range of potential complications and the variable individual response.

7. ***Patient expectation*** particularly increases since he or she feels that laser surgery is very precise and accurate. Therefore, patient should be informed that it is not a foolproof procedure and that he or she may need further surgery to achieve the desired visual outcome. It should be made amply clear to the patient that the surgery usually does not eliminate the need for additional reading glasses.

PREOPERATIVE EVALUATION

Preoperative evaluation of each case selected for refractive surgery should include:

1. ***Slit-lamp biomicroscopy*** of the anterior segment to exclude other associated diseases.

2. ***Cycloplegic refraction*** may be helpful in avoiding overcorrection, especially in younger patients who may have excess accommodation.

3. ***Measurement of pupil size*** is essential as the optical function is influenced by the diameter of pupil. The pupil size should be measured under low light (mesopic) conditions (less than 5 lux), preferably with an infrared pupillometer or with the aberrometer. Ideally, the ablation-zone diameter should not be less than the diameter of dark-adapted pupil (which is normally 6 mm); otherwise the patient may complain of postoperative glare and halos.

4. ***Intraocular pressure*** (IOP) should be measured using applanation tonometer. Detailed glaucoma investigations may be required to exclude glaucoma in suspected cases.

5. ***Posterior segment evaluation*** with indirect ophthalmoscopy should be done in detail, considering that the retinal detachment may occur after refractive surgery in myopia.

6. ***Keratometry*** readings should be obtained but are of limited value in detecting barely noticeable irregularities.

7. ***Computerized videokeratography*** has been found to be of help in detecting patients with

early keratoconus, who otherwise may go unnoticed and get operated. ***Corneal topography measurement*** (see page 184) should be an integral component of preoperative evaluation for refractive surgery.

8. ***Corneal thickness evaluation (pachymetry)*** is extremely important to rule out the abnormally thin corneas. Preferably, this should be done prior to or during surgery. Ultrasonic pachymetry is currently the method of choice for corneal thickness evaluation because of its ease of operation, precision and ability to measure corneal thickness eccentrically. Also, the ultrasonic pachymeter is portable.

REFRACTIVE SURGERY FOR MYOPIA

The surgical techniques that have been employed for correction of myopia over the years include:

A. ***Keratorefractive procedures***

I. *Incisional procedures*
- Radial keratotomy

II. *Lamellar corneal refractive procedures*
- Freeze keratomileusis of Barraquer for myopia (KMM)
- Non-freeze keratomileusis
- Keratomileusis in situ (BKS procedure)
- ALK
- Small incision lenticule extraction (Smile)
- Corneoplastique

III. *Laser ablation corneal refractive procedures*

Surface ablation corneal refractive procedures include:
- Photorefractive keratectomy (PRK),
- LASEK and
- E-LASIK.

Intrastromal ablation corneal refractive procedures
- LASIK
- C-LASIK
- Intralase laser in situ keratomileusis (iLASIK)
- LASIK Extra-LASIK + C3R

IV. *Orthokeratology*

V. *Intracorneal implants*
- Intracorneal contact lenses
- Intrastromal corneal ring segments (Intacs)
- Gel injectable adjustable keratoplasty

B. Lens-based procedures

1. PRLs

2. RLE

C. Combined lens and cornea-based refractive procedures
- Bioptics
- Trioptics

KERATOREFRACTIVE PROCEDURES FOR MYOPIA

Keratorefractive procedures are the most popular approaches for correcting refractive errors because of the following reasons:

- Cornea contributes two-thirds refractive power of the eye.
- Cornea is readily accessible.
- Corneal curvature can be readily modified as an extraocular procedure.
- Small changes in corneal curvature can translate into greater amount of refractive correction with precision.

I. INCISIONAL CORNEAL PROCEDURES FOR MYOPIA

RADIAL KERATOTOMY

RK, as today, refers to making deep (90% corneal thickness) radial incisions in the peripheral part of cornea, leaving about 4 mm central optical zone (Fig. 11.1). These incisions on healing flatten the central cornea, thereby reducing its refractive power. The most accepted theory holds that normal IOP pushes the peripheral cornea weakened by the incisions, leaving a relatively flatter centre (Fig. 11.2). This procedure is effective in low to moderate myopia (–1.5 to –6.0 D).

RK, to correct myopia, was introduced by Sato in Japan in 1940s using 40 radial incisions

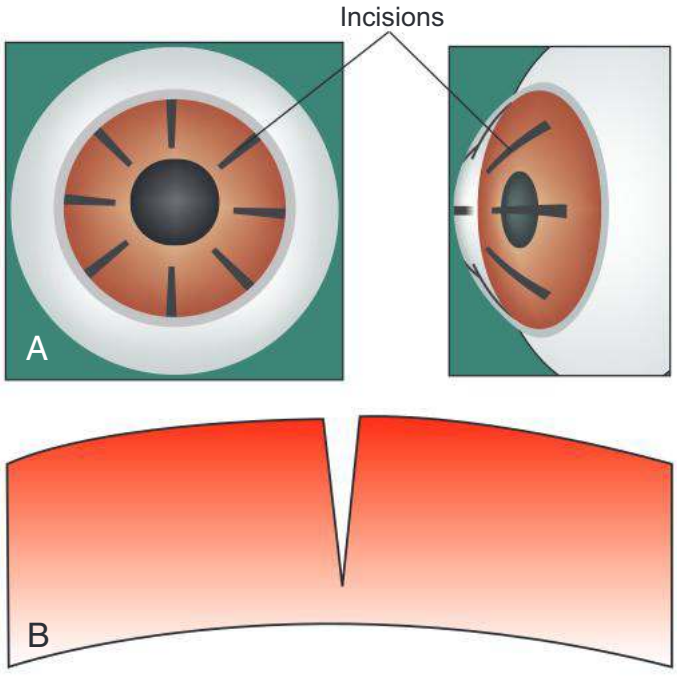


Fig. 11.1 *Radial keratotomy: A, configuration of radial incisions; B, depth of incision.*

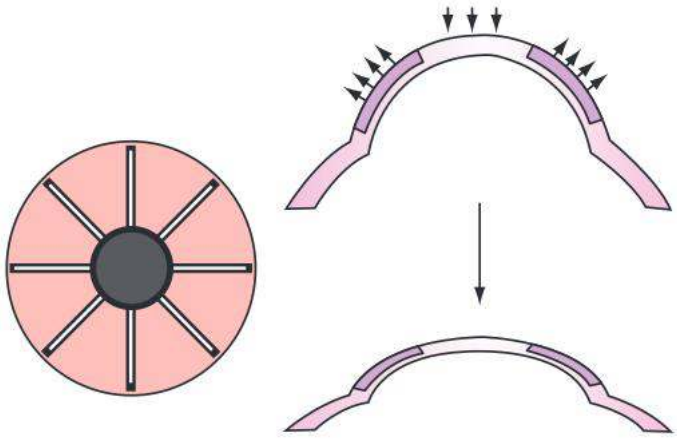


Fig. 11.2 *Mechanism of flattening of central cornea in radial keratotomy due to pushing of peripheral weakened cornea by the normal intraocular pressure.*

through the Descemet's membrane posteriorly and 40 radial incisions through the anterior surface of cornea. This approach fell to disfavour due to high incidence of bullous keratopathy. Russian investigators, predominantly Fyodorov, dramatically improved the procedure during the 1970s and 1980s by using only anterior incisions. Since its introduction to the USA in 1978, RK has undergone continual refinement based on ongoing experience with methods of incision placement, improved microsurgical instrumentation and advances in corneal topographic measurement.

Disadvantages of RK

1. Cornea is weakened, so chances of globe rupture following trauma are more after RK than after PRK. This point is particularly important for patients who are at high risk of blunt trauma, e.g. sportspersons, athletes and military personnel.
2. Rarely, uneven healing may lead to irregular astigmatism.
3. The patients may feel glare at night.

Note. With the advent of the safer technique LASIK, RK has been *abandoned* now because of its disadvantages.

Radial Keratotomy in Keratoconus

1. ***Mini-ARK (mini-asymmetric radial keratotomy)*** is an incision-based microsurgical technique that produces compaction of corneal stroma which is both lengthened and thinned by keratoconus. Microincisions of 1.5–2 mm length are made with a diamond-tipped scalpel only on the extroverted corneal region, outside the field of pupil, with approximately 30 degree increases from 90 to 270 degrees. It causes refractive functional recovery and decreases progression.
2. ***Mini-ASRK (mini-asymmetric selective radial keratotomy)*** selectively reduces the operated surface. This is achieved by introducing new concepts that further limit the sector, which is mapped out for surgery, minimizing the number and length of incisions made.

Both Mini-ARK and Mini-ASRK are usually followed by SACL (selective asymmetrical cross-linking) which is a non-invasive treatment, producing a better outcome by compacting collagen's helical structure with a mean refractive correction of 2–2.5 D (compared to 1–1.5 D by traditional cross-linking). It does

not remove epithelium and has 'selective asymmetrical' mode of treatment.

II. EARLIER LAMELLAR CORNEAL REFRACTIVE PROCEDURES FOR MYOPIA

Lamellar corneal refractive procedures have never been popular and are *obsolete*; however, as a tribute to the pioneer workers and to introduce the residents in ophthalmology with older techniques, the salient points of the lamellar corneal refractive procedures are mentioned in brief.

KERATOMILEUSIS

Keratomileusis, the term derived by Jose Barraquer in late 1940s, from the Greek words for carving or chiselling of cornea, is the grandfather of all lamellar refractive procedures and is the direct ancestor of modern LASIK procedures.

Freeze myopic keratomileusis of Barraquer (MKM) and hyperopic keratomileusis of Barraquer (HKM) in refined form involved a removal of a thin wafer of superficial corneal tissue with a microkeratome. The corneal wafer was then graved into a new shape designed to correct the desired myopia by a freezing technique using a cryolathe. The newly shaped corneal wafer was then sewn back to the patient's corneal bed.

Epikeratomileusis or epikeratophakia or epikeratoplasty was developed by Kaufman in 1979.

Non-freeze keratomileusis was described by Krumeich and Swinger in 1983.

Keratomileusis in situ (Barraquer–Krumeich–Swinger [BKS] technique) was then developed in 1985.

AUTOMATED LAMELLAR KERATOPLASTY

ALK was introduced by Ruiz in late 1980s. The ALK has been a breakthrough for lamellar surgeries. In ALK, two keratectomies were performed with an automated microkeratome.

III. LASER ABLATION CORNEAL REFRACTIVE PROCEDURES FOR MYOPIA

The laser-based corneal refractive procedures for myopia include:

- *Advanced surface ablation procedures*
  - PRK
  - LASEK
  - Epi-LASIK
- *Intrastromal laser ablation procedures*
  - LASIK
  - C-LASIK

LASERS USED FOR REFRACTIVE CORNEAL PROCEDURES

Before discussing the various laser-based corneal refractive procedures, it will be worthwhile to mention about the lasers available for corneal procedures, which include:

- Excimer laser,
- Solid-state UV laser and
- Infrared femtosecond laser.

Excimer Laser

It is the most commonly used laser for refractive corneal procedures. The term *excimer* is a contraction of 'excited dimer', although it is now used in a broad sense to include any diatomic molecule in which the component atoms are bound in the excited state but are not bound in the ground state.

When the two component atoms are electronically excited, they attract each other and form a stable molecule. However, in the ground state, the two atoms are usually not bound and indeed are mutually repulsive. Thus, in an excimer laser, when the excited molecule relaxes from excitations, the molecule decomposes and falls apart. This situation makes it attractive for laser action, because the ground state really does not exist and, therefore, one obtains a population inversion as soon as one has the molecules formed that are automatically in the excited state.

The most attractive excimer molecules are rare gas halides that do not normally occur in

nature but can be easily produced in properly controlled electrical gas discharge. The choice of gas mixture determines the output wavelength, e.g. ArF: 193 nm, XeCl: 308 nm, Kr: 222 nm, XeF: 351 nm and KrF: 248 nm. In these lasers, the majority of the gas mixture is a buffer gas that mediates energy transfer but does not participate in the lasing action. Usually helium and neon are used along with argon and fluoride.

Its applications in medicine have been primarily related to ablations of surface tissues – the cornea being of particular interest because of the high-absorption coefficient. Although frequency-quintupled and frequency-quadrupled Nd:YAG lasers, frequency-doubled organic dye lasers, etc. are able to produce laser outputs in the far-UV spectrum (280 nm), the excimer family of lasers seems to be most easily applicable to corneal incisions, excisions and reprofiling because of the following reasons:

- They have extremely short pulse duration (10–15 ns), which decreases thermal effect to infinitesimal levels because of the apparent lack of the time for thermal diffusions.
- Its pulse-to-pulse energy level is reproducible within acceptable limits and also the repetition rate of the pulse can be varied over a relatively large range, typically 1–50 Hz, etc.
- Sufficient energy is available (up to 450 mJ) so that a large beam can be produced to ablate or reprofile a 4–7 mm diameter portion of central cornea without energy limitation.

The limited penetration of 193 nm radiations cannot be overemphasized, since this is the single most important factor in prevention of damage to the deeper corneal stroma, Descemet's membrane and corneal endothelium. The same is not true for the longer wavelength; in fact, XeCl can damage the lens and can reach the retina in an aphakic eye. Also, photokeratitis, thermal damage and mutagenic property of UV rays are associated with longer wavelengths (>280 nm). Endothelial cell damage is greater at 248 nm than at any other wavelength. Therefore, ArF having 193 nm wavelength has been found to be of clinical use. It has the ability to remove minute amounts of corneal tissue (0.2–0.3 nm) with no observable thermal damage. With a precision that is determined by the energy per pulse and the number of pulses applied to a particular portion of the cornea, a precise, extremely smooth spherical surface can be produced in the stroma of the human cornea. Incisions as minute as 10 μm in width and extending to a depth of 95% thickness of the cornea can be created.

Classification of excimer laser machines into generations. Since its advent, the excimer laser machines have been updated constantly to provide the cutting edge technology. The excimer laser machines evolved over the years can be grouped into four generations:

- *First generation*. These machines used a broad beam, which meant beam irregularity and hence formation of central islands.
- *Second generation*. In these machines, the scanning slit was introduced, which reduced the irregularity to a certain extent.
- *Third generation*. The scanning spot was introduced in these machines.
- *Fourth generation*. The wavefront technology and eye trackers were introduced, which proved much more beneficial to the patients undergoing treatment.

Commercially available excimer laser machines. The details of the various commercially available excimer laser machines (Fig. 11.3) are beyond the scope of this book. However, names of few commercially available machines are mentioned here, without any commercial interests:

- STAR S4 IR (Abbott)
- EC 5000CX III (Nidek)
- MEL 90 (Zeiss)
- WAVELIGHT EX500 (Alcon)
- ZYOPTIX (Bausch & Lomb)
- Allegrato Wave IQ (Alcon)
- IDesign Refractive Studio (AMO).

Solid-State UV Laser

A continuous wave diode-pumped all solid-state UV laser (LaserSoft) has been introduced by Katana Technologies GmbH for refractive

Fig. 11.3 *A fourth-generation excimer laser machine.*

corneal surgery. The solid-state laser is not an excimer laser, since the UV laser ablation radiation is generated by non-linear frequency conversion of infrared laser light in a laser crystal. The wavelength of the laser radiation in solid-state laser is in the range of 208–210 nm.

Solid-state versus excimer laser. The solid-state laser is reported to be ideal for accurate custom ablation (C-LASIK) vis-a-vis excimer laser because of the following features:

- *Spot size*. Commonly available excimer laser machines generate a flying spot of 0.8–1.0 mm in size. The solid-state laser generates a flying spot of 0.2 mm in diameter, operating at a repetition rate of 1 kHz. This very small spot size fits the present requirements for effective custom ablation.
- *Beam quality*. Excimer lasers need beam-forming elements, i.e. mirrors in the beam pathway (multi-mode). Solid-state lasers produce Gaussian beam, i.e. they do not need beam-forming elements (single mode). Due to the accurate overlap made possible by the true Gaussian spot, the solid-state laser ensures an extremely homogenous cornea surface.
- *Repetition rate* in excimer laser is 50–500 Hz, while in solid-state laser it is 1 kHz. Because of high repetition rate, the energy per pulse is lower in solid-state laser than in the excimer laser.
- *Eye-tracker speed* in excimer laser is approximately 150 Hz, while in solid-state laser it is more than 1 kHz. The fast eye tracking in solid-state laser ensures a reliable centration of ablation for x–y directions as well as the rotation of the eye at high repetition rates.

Infrared Femtosecond Laser

Technology advances in high-power diode lasers have made it possible to develop infrared femtosecond lasers. The femtosecond lasers have the property of emitting ultrashort pulses with high crest power from low-energy pulse (1 fs = 10^{-15} s). It has a wavelength of 1053 nm and is based on the technology whereby focused laser pulses divide the tissue at molecular level through a process called *photodisruption*.

The femtosecond laser is being tried for ablation within the thickness of cornea (excimer lasers can only be used for surface treatments).

Advantages of femtosecond laser. The main theoretical advantage of femtosecond seems that it makes it possible to focus the beam very accurately (to within the order of a micrometre) in a transparent medium and it produces the local destruction of material without producing any heat damage in the surrounding tissue.

Uses of femtosecond laser include:

- Creation corneal flap in LASIK (femto-LASIK),
- Refractive lenticule extraction (ReLEx),
- Femto-assisted anterior and posterior keratoplasty,
- Femto-assisted implantation of intracorneal ring segments (ICRS) for keratoconus,
- Femto-assisted implantation of corneal inlay for presbyopia and
- Femto-laser assisted cataract surgery (FLACS).

Commercially available femtolaser systems:

- Intralase iFS (Abott Medical Optics)
- Visumax (Carl Zeiss)
- Wavelight FS 20-degree ultraflap laser system
- Wavelight ultraflap LDV (Ziemer Ophthalmic System, Switzerland)
- Femtec 20/10 lasers (Technolas Perfect Vision)
- LensX (Alcon)

- LensAR technology (Winter Park Florida, USA)
- Optimedica FS system (Catalys Precision Laser System, Santa Clara, USA)
- Victus Femtosecond Laser Platform (Bausch & Lomb and Technolas)

SURFACE-CORNEAL LASER ABLATION PROCEDURES

Corneal surface laser ablation in the form of '*PRK*' is the oldest technique of laser vision correction which became popular after Srinivasan, Brasen and Torkel, in 1983, thought that excimer laser can be used to cut cornea. The first PRK in humans was performed in 1988 by Professor Marguerite McDonald. The PRK procedure became unpopular with the advent of intrastromal ablation (LASIK) by Pallikaris in 1991, as the later technique had more patient comfort, early visual recovery and lesser complications.

Recently, there is resurgence of surface ablation procedures in the form of *advanced surface ablation* (ASA) *procedures* due to

- Their utility in thinner corneas,
- Avoidance of flap-related complications (cf. LASIK) and
- Less haze and regression because of adjuvant mitomycin C (cf. traditional PRK).

However, still due to raw healing surface, patients experience more discomfort and delayed visual recovery as compared to LASIK.

Indications for ASA

- Myopia up to 6 D
- Astigmatism up to 4 D
- Hyperopia up to 3 D
- Residual refractive error: post-cataract surgery, post-LASIK or post any other refractive surgery
- Preferred procedure when LASIK is contraindicated, e.g.:
  - Flat corneas (<40 D)
  - Steep corneas
  - Thin corneas with a residual bed thickness (<250 μm)
  - Deep set eyes
  - Epithelial basement membrane dystrophy
  - Refractive error with superficial corneal opacity

Contraindications

- Pregnancy at the time of surgery (to avoid increased corneal haze and regression).
- Systemic connective tissue diseases and other diseases which delay epithelial healing.
- All other contraindications to refractive surgery (see pages 393–394).

Terminology for Advanced Surface Ablation Procedures

Surface ablation with associated better technique of epithelium removal, larger ablation zone and use of mitomycin C to decrease the proliferative haze is called 'ASA'. Depending upon the method of handling of corneal epithelium, the ASA terminologies are as follows:

- *Advanced PRK*. Epithelium is removed mechanically with a beaver knife or a spatula or a specialized brush (epithelial scrubber) (Fig. 11.4A).
- *LASEK*. An epithelial flap is created with the help of alcohol. A pre-incision is made with a special microtrephine (8 mm, 70 μm deep). The trephine is calibrated to leave a ring of approximately 80 degrees in the 12 o'clock position; 20% alcohol is applied for 20 s via a 8.5 mm corneal well (Fig. 11.4D). After 20 s, the alcohol is adsorbed with a merocel sponge. Excess alcohol is irrigated away with balanced salt solution (BSS). The epithelial flap is raised and repositioned/removed at the end of surgery. The healing after LASEK, described by Camellin in 1998, is reported to involve less discomfort as compared to that with PRK.
- *Epi-LASIK*. Epithelial flap is created with the help of a blunt epikeratome (Fig. 11.4G) and is reposited at the end of surgery. Epi-LASIK, introduced by Pallikaris, in 2003, is preferred to LASEK, as it avoids the possibility of toxic effects from the alcohol.
- *Transepithelial PRK*. The epithelium is removed by the laser in PTK mode (photoablative de-epithelialization) followed by laser reshaping of the stroma in PRK mode.

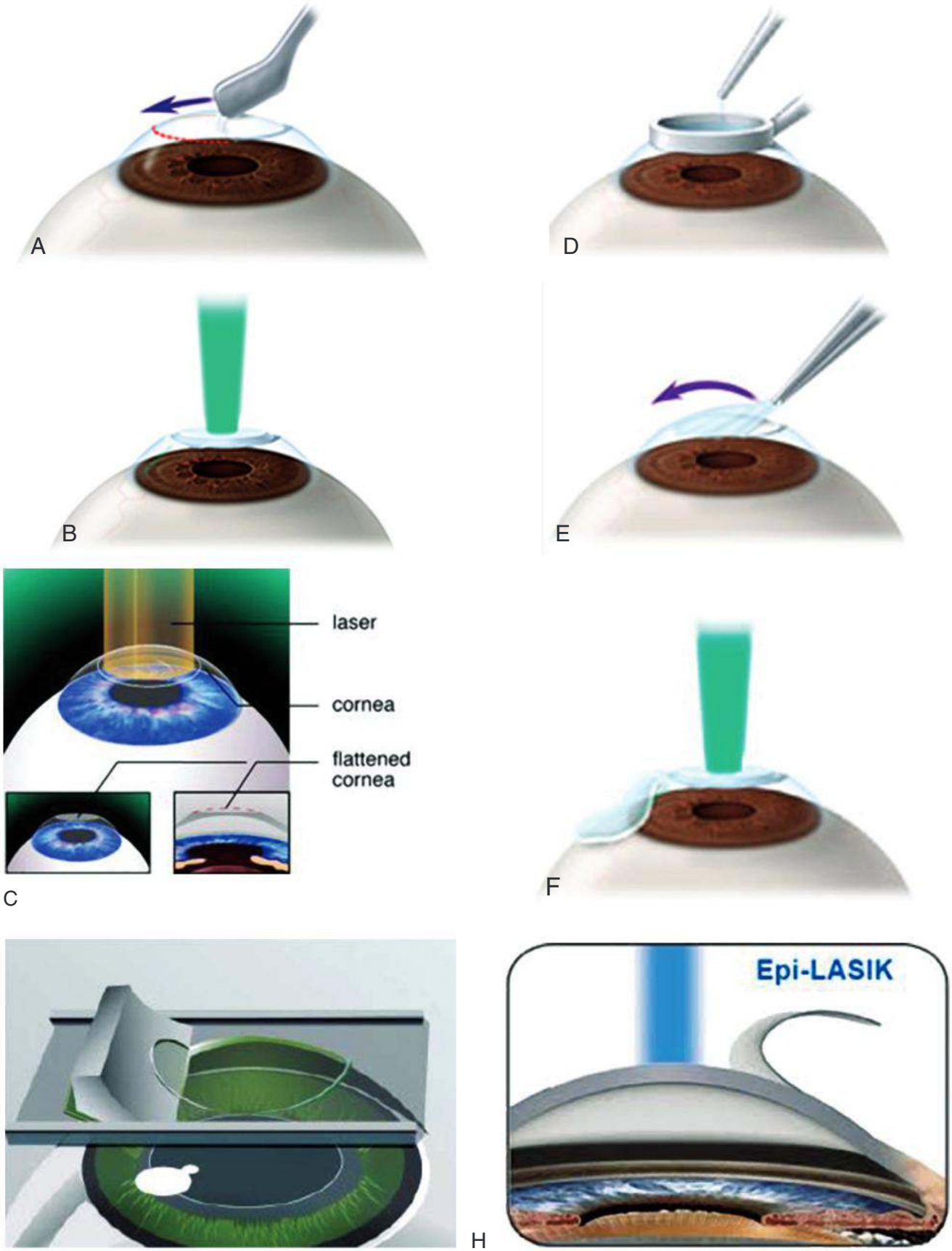


Fig. 11.4 *Advanced surface ablation (ASA) procedures: Advanced PRK (A–C); LASEK (D–F); Epi-Lasik (G and H).*

Surgical Parameters and Technique of Advanced Surface Ablation

In this technique, to correct myopia, a central optical zone of anterior corneal stroma is photoablated using excimer laser to cause flattening of the central cornea (Fig. 11.4). Surgical steps are as follows:

1. ***Anaesthesia.*** ASA can be satisfactorily performed under topical anaesthesia.
2. ***Epithelium removal.*** Epithelium can be removed by any of the following methods:
   - Mechanical debridement (PRK) (Fig. 11.4B)
   - Alcohol debridement (LASEK) (Fig. 11.4D)
   - Blunt epimicrokeratome (epi-LASIK) (Fig. 11.4G)
   - Photoablative de-epithelialization (Transepithelial PRK)

An attempt should be made to de-epithelialize 0.5–1.0 mm larger area than the desired ablation zone. The time lapsed from the removal of corneal epithelium to the application of laser energy should be minimized to prevent extreme drying or wetting of the corneal surface. Always avoid leaving any residual islands of epithelium.

3. ***Ablation zone diameter.*** Small ablative zones are known to cause symptomatic halos while driving at night. Increasing experience in PRK has showed that the ideal diameter of ablation zone for myopia is greater than 6.5 mm.
4. ***Fixation and centration of the ablation zone.*** Some surgeons use hand-held suction ring, while others promote the method of self-fixation by the patient during ablation. Fixation light on the microscope should be coaxial with the surgeon's and patient's lines of vision. Coaxiality of fixation light should be maintained with the laser light as well. The patient should always be explained that the clarity of fixation target will decline during ablation procedure, but it will be visible and that he or she should try to fix it. It is better to patch the fellow eye of the patient to prevent inadvertent cross-fixation during the treatment.

Laser beam should be aimed at the centre of the pupil. Decentration of ablation is something that should never occur. Modern lasers incorporate tracking technology to automatically stop the ablation, if excessive eye movement occurs (X–Y tracking control). The surgeon should still monitor the ablation to ensure that it is centred in the entrance pupil/visual axis.

5. ***Corneal ablation***
   - *Multi-zone and multi-step procedures* are advantageous, since most cases have a tendency for regression. A 1.5 mm white tapered transition zone bordering the refractive zone of 4 mm with overall treatment diameter of 6–7 mm usually results in better epithelial healing and lesser regression.
   - *Fluence and repetition rate.* Changes in laser fluence and repetition rate affect not only the rate at which the tissue is removed and the operation time but also the surface morphology of the ablated corneal tissue. Higher fluence rates ablate larger amount of tissue per pulse. Ablation time is less for a given repetition rate with higher fluences.
   - *Scanning laser beam.* The laser device can be smaller and cheap, if small-diameter circular or narrow slit-beam is used for scanning the ablated area. Surface roughness increases with small-diameter scanning PRK because of its influence on the involuntary eye movements, causing increased wound healing response and corneal haze.
   - *Aspheric ablations.* This is a unique advantage of PRK. Planned aspheric ablations are made in high myopia, which avoid central islands, thereby decreasing postoperative spherical aberrations.
   - *Correction of myopic astigmatism.* Astigmatism could be naturally occurring, post-traumatic, post-infections and post-surgical. Correction is done by ablating the superficial cornea in a cylindrical fashion, known as toric photoablation.
6. ***Application of mitomycin-C***. Mitomycin-C 0.02% is applied with a soaked pledget for

12 s. The cornea is then irrigated with copious quantities of chilled BSS.

7. ***Reposition of epithelial flap***, wherever possible, is then done.

8. ***Application of bandage soft contact lens***. After instilling a drop of ciprofloxacin eyedrop, a bandage soft contact lens is applied to the cornea.

Postoperative Management

1. *Bandage soft contact lens* is removed when the epithelium is healed (3–5 days postoperative).
2. *Topical NSAID* eyedrops are used four times a day. They reduce pain as well as inflammation.
3. *Topical steroids* are used after corneal epithelium heals up. These are tapered over a period of 2–3 months.
4. *Topical artificial tear drops* are used frequently.

Note. It is reported that keeping the cornea moist and well lubricated with tears and instillation of corticosteroids during the postoperative period definitely seems to have beneficial effect in wound healing modulation and in the prevention of corneal haze and regression.

Complications

1. ***Decentration of ablation zone***
   - *Causes.* Decentration of the ablation zone usually occurs either due to poor alignment with the patient fixation or due to eye movements during the surgery.
   - *Symptoms.* The patients with considerable decentration of the ablation zone experience degeneration of optical performance. Diplopia, glare, halos and induced astigmatism with loss of best-corrected visual acuity are the problems associated with decentration.
   - *Management.* Time taken and remoulding may lessen the effect of decentration. Otherwise, the patient should undergo computer-assisted corneal topographic analysis to determine the relative locations of the centre of pupil and centre of ablation zone. In an irregular orientation, 180 degrees from the first ablation, a second ablation is done which is decentred relative to the pupil by a distance equal to the first ablation. This will make the centres of the two ablation zones lie on a straight line bisected by the pupil.
2. ***Corneal haze.*** It is not uncommon.
   - *Causes.* Corneal haze may occur, specially, following PRK for high myopia (>6 D). The patients having severe dry eyes, severe atopic disease, pre-existing corneal scar are more prone to develop corneal haze. Increased number of activated keratocytes deposit new collagen and proteoglycans, which are responsible for the light scatter, resulting in corneal haze.
   - *Clinical features*. Maximum haze is noted between 1 and 3 months and decreases with time to complete resolution. According to subjective measurement criteria of Seiler and Fantes, corneal haze can be graded as follows:

Grade 0	Clear cornea
Grade 0.5	Barely detectable or trace haze
Grade 1.0	Mild haze with normal vision
Grade 2.0	Moderate haze that interferes with refraction
Grade 3.0	Marked haze that obscures iris
Grade 4.0	Severe haze

   - Up to mild grade corneal haze is clinically insignificant and most of the times not associated with symptoms.
   - Haze greater than grade 2 is referred as a scar.
   - *Management* is as follows:
     - *Topical steroids* are useful in resolving the level of haze as well as any refractive regression due to haze.
     - *Excimer laser re-treatment* may be required in cases where haze persists beyond 6 months and is associated with regression.
3. ***Night glare and halos.*** This used to occur with small ablated zones. Under scotopic illumination, dilation of pupil causes the light rays to pass through midperipheral cornea to reach the posterior pole. This causes halos, and night

driving becomes difficult. However, it is absent in 5–6 mm zones. This problem can be treated with a second ablation by increasing diameter to 6 mm.

4. ***Delayed epithelial healing.*** Keratoconjunctivitis sicca, topical anti-inflammatory drugs, prophylactic antibiotic therapy and bigger debrided area are the commonly known causes for delayed epithelial healing.
5. ***Recurrent epithelial erosions.*** These are known to occur, if epithelial defect made before ablation procedure is larger than the ablation zone.
6. ***Corneal infiltration.*** The sterile corneal infiltrates are usually focal but may be multi-centric. These appear days to weeks after surgery. If they are central, they may cause reduction in visual acuity.
7. ***Corneal ulceration.*** The patients getting bandage soft contact lens after PRK are prone for corneal ulcers.
8. ***Decreased corneal sensations.*** Patients with high myopia undergoing larger and deeper ablations show reduced sensitivity, more than others. A biphasic regeneration has been described. From the non-ablated areas, neurites enter the ablation zone and get degenerated by 2–3 weeks. Later, a more permanent regeneration occurs from non-ablated subepithelial nerves, beginning at 2–3 weeks.
9. ***Central islands.*** With computer-assisted topographic analysis, corneas show a central region of higher corneal refractive power compared to the adjacent paracentral cornea. These are the causes of undercorrection, asphericity and irregular astigmatism. Many theories have been put forward to explain their formation. These include (1) shock-wave formation and ejection of a plume of gaseous and particulate debris which interferes with the subsequent proper delivery of the laser, (2) undesired optics of the laser or variation in beam homogeneity, (3) differential hydration of the corneal tissue postoperatively and (4) healing being non-uniform leads to greater epithelial hyperplasia centrally.
10. ***Subretinal haemorrhages.*** During PRK, mechanical stress waves with an amplitude of 100 bars travel through the eye and might cause disruption of fragile subretinal vessels, causing these haemorrhages.
11. ***Raised IOP.*** This is thought to be a result of use of postoperative corticosteroids topically.

Re-treatment

PRK can be reperformed safely in cases with marked undercorrection. However, most patients do not require enhancement surgery. PRK should not be repeated under the following situations:

1. Slight undercorrection.
2. Before 6 months of the initial surgery.
3. Unless steroids have been stopped for more than 3 months.
4. If refraction is not stable.
5. When central islands are followed for less than 6–12 months.
6. When corneal haze is not accompanied with regression.

Advantages and Disadvantages of ASA

Advantages

1. No weakening of the globe unlike RK.
2. No flap-related complication (e.g. LASIK).
3. Results are excellent, with an accuracy of 95% in achieving a ±0.5 D correction in patients with a myopia of –2 to –8 D.
4. Can be performed in patients with thin corneas.

Disadvantages

1. Postoperative recovery is slower than LASIK.
2. The patients may experience pain or discomfort for several weeks.
3. Some residual corneal haze may occur.

■ LASER IN SITU KERATOMILEUSIS

LASIK is a keratorefractive surgery that combines the precision of excimer laser photoablation with the advantages of an intrastromal procedure that maintains the integrity of Bowman's layer and the overlying corneal epithelium. Currently, this procedure is being considered the refractive surgery of choice for myopia because of its definite advantages

over PRK. However, it requires greater surgical skills and the use of sophisticated and expensive mechanical equipment. LASIK can be used to correct:

- Myopia of <8 D,
- Astigmatism of <6 D and
- Hyperopia of <4 D.

Milestones in the Advent of LASIK

Various milestones in the history which have some direct or indirect bearing in the development of procedure of LASIK, though already mentioned, are once again summarized here:

- In 1949, *Barraquer* developed the myopic keratomileusis using freehand dissection of half-thickness corneal disc which was later (in 1963) shaped with cryolathe and then sutured on the recipient bed. LASIK is, in fact, the direct descendant of this technique.
- In 1983, *planer keratomileusis* that did not require freezing was developed by *Krumeich*.
- *Trokel and Srinivasan*, in 1983, had suggested that *excimer laser* can be used to ablate the corneal tissue.
- In 1986, *Ruiz* introduced in situ *keratomileusis* by performing two keratectomies using manual dissection.
- In ALK, two keratectomies are performed with an automated microkeratome.
- In 1990, *Pallikaris*, from Greece, used microkeratome to create a 120–160 μm corneal cap and then ablated the stromal bed using the excimer laser as in PRK and finally sutured the corneal cap.
- In 1991, *Pallikaris* introduced a *nasally hinged corneal flap* which did not need suturing in the end – the basis of LASIK. He also coined the term LASIK.
- In 1992, *Buratto*, from Italy, introduced the *cap mileusis* with excimer laser.
- In 1996, *Buratto* developed the technique of cutting a *superiorly hinged flap*, which is presently popular in LASIK.
- In 1999, femtosecond laser was introduced to create LASIK flap. The first FDA-approved femtosecond laser flap making system (intralase) was acquired by AMO in 2007.

Instrumentation

Microkeratome

Several automated microkeratomes (Fig. 11.5) have been developed to perform a uniform homogenous planar cut on the corneal surface. The aim is to cut a corneal disc of precisely calculated thickness and diameter with a sufficient hinge to maintain its position and apposition during replacement.

Components of the microkeratome are as follows:

1. *Corneal shaper head* is the main component of the microkeratome. It has an *oscillating blade* which is driven by a motor incorporated in the handle. The head also has a thickness plate

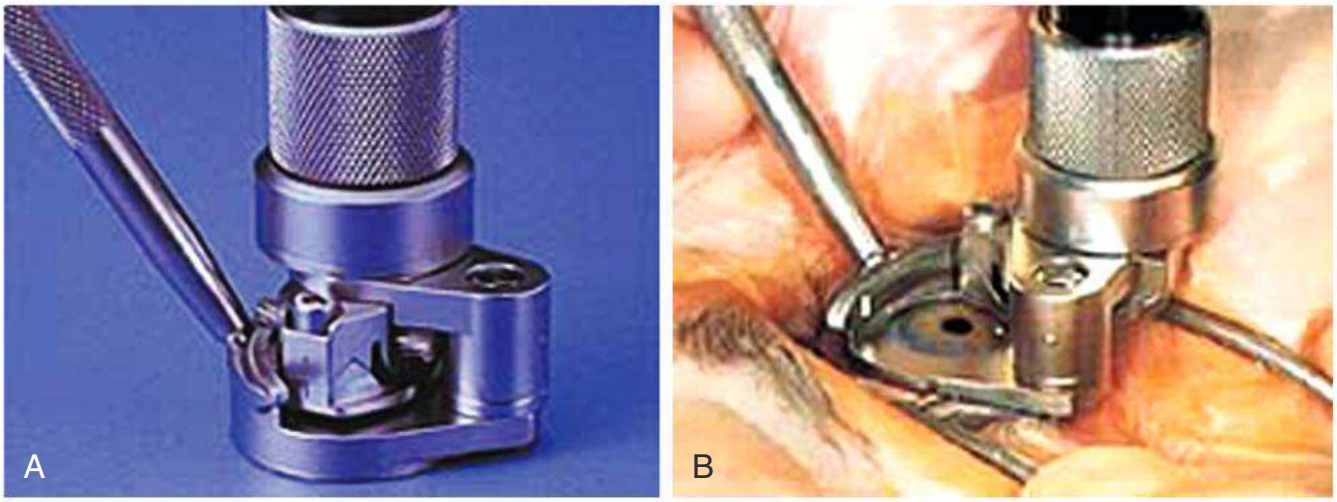


Fig. 11.5 *Microkeratome (A) in use (B).*

which sets the exact depth of the cut. The *thickness plate* can be varied in ALK (LASIK) machine, but not in the Hansatome which has two heads. One head is set at 160 μm and the other is set at 180 μm.

2. *Suction ring.* It is operated by a suction pump mechanism. It helps in fixing the globe and maintaining an IOP of 65 mmHg; the mechanisms that allow the excursion of a microtome head on a given track.

3. *Stop mechanism.* It ensures that the corneal shaper head stops at a preset distance in the track on the suction ring during the cut to maintain a hinge of the flap.

4. *Control unit.* It contains the electrical sources and a suction pump. The suction pump helps in fixing the suction ring. The electrical sources control the speed of movement of the head automatically on the track through a set of glasses.

Classification of microkeratomes into generations. The microkeratomes developed over the years can be grouped as follows:

- *First-generation* microkeratomes had linear cutting action, 0 degree plane and fixed thickness.
- *Second-generation* microkeratomes had pivoted rotational cutting action. Blade was modified to work at 26 degree angle and fixed thickness.
- *Third-generation* microkeratome has a pendulum-like cutting action – introduced in 2000 by Cesar Carriazo.
- *Fourth-generation* microkeratomes include bladeless keratomes, e.g. Hydrokeratome, Visijet microkeratome.
- *Epikeratomes* or microkeratomes for epi-LASIK are now available, which create much more smoother epithelial flaps than with alcohol and scraping.
- *Laser keratomes* have also been developed to provide more accurate and smooth flaps. These include Intralase femtosecond laser and Novatec laser microkeratomes.

Commercially available microkeratomes. A number of microkeratomes are now commercially available. The choice of which one to use is the surgeon's individual preference. Most of the newer microkeratomes vary little from each other in their capabilities. The description of each microkeratome is beyond the scope of this book. Names of a few commercially available microkeratomes (without any commercial interest) are mentioned below:

- Hansatome (newer version: Zyoptix XP)
- Amadeus II
- BD K-4000
- Moriamicrokeratomes
- Nidek MK-2000
- Carriazo-Pendular

Femtosecond Laser as an Alternative to Microkeratome

Although, modern microkeratomes give excellent results, many of the sight-threatening complications of LASIK occur due to mechanical microkeratome-related flap complications. *The quest to minimize flap complications in LASIK led to the introduction of femtosecond lasers for the creation of the corneal flap with greater precision and consistency.* Though, mechanical microkeratomes continue to be used more commonly at the present time, practice trends indicate a gradual but definite shift towards use of *femto-LASIK* because of its obvious clinical benefits, as the femtosecond laser minimizes most of the risks involved in making the flap.

Following terms have been used for LASIK when femtosecond laser is used for making the corneal flap:

- Femto LASIK
- All-laser LASIK
- No-blade LASIK

Advantages of femto-corneal flap

- Reduced symptoms of dry eye.
- Gentle approach with minimal or no transient visual loss (black-out period) due to close physiologic maintenance of IOP throughout the procedure.
- The suction needed here is mainly to steady the cornea and it is much less compared to the vacuum used in a mechanical device.
- The laser beam can be focused at any depth, so that a wide range of flap thickness can be obtained.

- The predictability of the flap thickness is comparatively reliable.
- There are also greater options in flap diameter, side cut angle, hinge position and hinge length.
- The chances for epithelial ingrowth are less since cells are not carried in by the blade.

Excimer Laser Machine

Other than microkeratome, excimer laser is the main machine required in LASIK for ablation of the stromal bed. Basic principles of this machine have already been described (see page 397).

Patient Selection and Evaluation

As mentioned earlier (page 393), the proper patient selection and critical evaluation is the most important aspect of any keratorefractive error. The important considerations for LASIK are once again summarized here:

1. *Adequate globe exposure* is mandatory for application of suction ring and microkeratome pass. Therefore, patients with sunken eyeballs and small palpebral apertures may pose a problem. This aspect has to be looked for before surgery.
2. *Corneal thickness* (judged on meticulously performed pachymetry) should be at least 450 μ in the centre. An adequate handling thickness of 500 μ provides about 90 μ for ablation since 180 μ is the thickness of flap and 250 μ stromal base is to be left behind. Therefore, a cornea with central thickness of less than 450 μ is a contraindication for LASIK.
3. *IOP.* The patient undergoing LASIK has to tolerate an IOP of at least 65 mmHg for up to several minutes during the procedure. Therefore, patients with glaucoma, retinal vascular disease and systemic vascular disease should be excluded.
4. *Pupil size.* Large optical zones are required for people with large pupils. Young patients with large pupils must be informed about the potential glare, halos and night driving problems.
5. *Contact lens wear.* Soft contact lens wear should be discontinued at least 2 weeks and in the case of rigid lens at least 3 weeks before the LASIK procedure is undertaken.

Essential Examinations

Following examinations and documentation are essential for a LASIK procedure:

1. **Visual acuity.** Uncorrected and best-corrected visual acuity should be noted.
2. **Refraction.** Subjective, manifest and cycloplegic refraction should be carried out.
3. **Biomicroscopic examination** should be conducted in detail.
4. **Indirect ophthalmoscopy** should be performed with dilated pupils with the use of scleral depressor.
5. **IOP** should be measured accurately.
6. **Corneal topography and pachymetry** are most essential before performing LASIK.

The most important purpose of topography, in LASIK patient selection, is to rule out subclinical ectatic disorders. The diagnostic criteria, described by Rabinowitz and modified later by Klyce and Maeda, are based on changes in curvature maps. These include:

- Steepness greater than 48 D.
- Difference in central K of more than 1 D between the eyes.
- Irregular astigmatism – principal axes of both corneas non-corresponding.
- Asymmetry – measured at about 3 mm on the steep axis – inferior–superior asymmetry more than 1.4 D – (inferior steepening).
- Non-orthogonal axes – principal axes not at right angles to each other.
- Skewing of the steep axis – Lazy C appearance of the bow-tie or claw pattern in an against the rule astigmatism.

Note. Some topographers incorporate a keratoconus diagnosing software to analyse these parameters and give a keratoconus (KC) index.

Other uses of topography include:

- To verify the astigmatism axis identified by refraction.

- To diagnose irregular corneal surface as in decentred ablation or post-trauma, a conventional ablation will reproduce the same irregular surface after treatment.
- To analyse the centration and uniformity of the ablation during post-treatment follow-up.
- To detect post-LASIK ectasia.

Surgical Work-up and Technique

1. ***Broad-spectrum antibiotic eyedrops*** should be used four times a day, 3–4 days preoperatively.

2. ***Pilocarpine 1%***, which helps to maintain pupillary miosis to assist centration, is used by some surgeons.

3. ***Anaesthesia.*** The procedure is normally performed under topical anaesthesia with proparacaine or xylocaine eyedrops.

4. ***Cleaning and draping*** should be performed meticulously as for any other intraocular surgery.

5. ***Exposure*** is obtained adequately by using a wire speculum.

6. ***Corneal marking.*** The cornea should be marked with a marker using gentian violet. An ideal marker is one that has two radial and one pararadial marks. A specially designed marker (Fig. 11.6) is very useful. It consists of an inner circle 3.0 mm in diameter, joined by paired pararadial lines to an external circle of 10.5 mm. The inner circle should be placed concentrically with the pupil to aid the centration. The outer circle aids the concentric placement of suction ring. The pararadial lens facilitates the correct alignment in the rare free flap situation.

7. ***Fixation of suction ring.*** The pneumatic suction ring is fixed in place on the sclera with slight decentration towards the side of the hinge. Then, the suction is activated and IOP elevated to about 65 mmHg. This is required to obtain a resection of appropriate diameter and thickness of corneal flap. The IOP may be checked with a Barraquer tonometer. For a correct reading, the corneal surface and tonometer should be dry.

Following four signs indicate that adequate IOP has been achieved:

- Barraquer's tonometer
- No vision
- Dilation of pupil
- Reading on the gauge

8. ***Preparation of corneal flap***

Preparation of corneal flap with automated microkeratome. The cornea is moistened with BSS to facilitate a smooth movement of the microkeratome. The microkeratome head is then inserted in the track on the suction ring. Then the forward foot pedal is depressed and the microkeratome makes it pass on the track and cuts the corneal flap/disc. Then the reverse foot pedal is depressed so that the microkeratome returns to its original position, leaving behind a good corneal lamellar hinged flap/disc. The surgical area should be irrigated constantly

Fig. 11.6 *Corneal marker for LASIK: A, Lu; B, Mendez.*

with BSS to keep the flap moist. At the same time, a cellulose sponge should be used to remove the fluid or debris collection on the stromal bed. The important principle to be remembered is *cut wet; ablate dry*. Care must be taken for inadvertent occurrence of free flap at this juncture. Till recently, a superior hinged flap (Fig. 11.7A) was preferred to nasally hinged flap for its obvious advantages. However, most recently it has been a matter of concern that the flap created for LASIK results in the loss of majority of corneal nerve fibres. A nasal hinge is supposed to preserve the corneal nerve fibres better than with a superior hinge. This is because most of the corneal nerve fibres enter the cornea nasally. It is an irony that the initial flaps were nasal flaps. Then most surgeons shifted to superior flaps, and now many surgeons are again shifting to nasal flaps. The disadvantage with the nasal flap is that there is a small risk of the flap being displaced by the movement of the upper lid.

Note. Once the corneal flap is created, the suction should be released immediately so that the period of raised IOP should be as short as possible to avoid damage to the optic nerve head.

Recommendations for achieving a good quality cut. For achieving a uniform, smooth and precise cut, the following points should be taken care of:

i. *The microkeratome* should be prepared before starting the surgery. A new blade should be inserted into the shaper's head for each procedure.

ii. *An ideal flap* is 130–160 μ in thickness. Before starting the procedure, it should be noted that for patients with myopia of 15 D or more, or when central corneal thickness is less than 530 μ, a thinner flap (130 μ) or shallower ablation or both are required.

iii. *Speed of the pass* affects the quality of flap. A rapid pass produces a thin cut, while a slow pass produces a thicker corneal flap. This is where an automated system scores over the manual system.

iv. *Oscillation of the blade* affects the flap, as:

- A slow oscillating speed of blade may produce a rougher surface, which may affect the quality of visual outcome.
- A higher oscillating speed of the blade produces greater friction of the movement, resulting in greater heat production and dispersion, which may cause damage to corneal tissue. Greater oscillations may also damage the blade and its housing, leading to dispersion of metallic debris along the track of microtome.

v. *The IOP* should be between 60 and 65 mmHg during cutting. IOP lower than this may result in a flap of variable and suboptimal thickness and diameter.

vi. *The cornea should be well-irrigated* with BSS to prevent friction with the thickness plate of the microtome.

vii. *Adequate exposure* of the eye is very important to achieve a good quality cut.

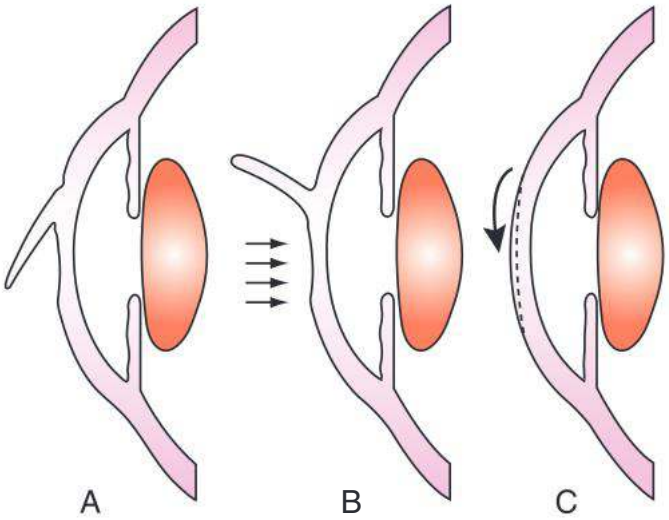


Fig. 11.7 *Procedure of laser in situ keratomileusis (LASIK).*

Creation of corneal flap with femtosecond

The laser beam is focused on a pre-programmed depth and position within the cornea with each pulse forming a microscopic bubble. As the laser moves painlessly back and forth, the bubbles connect to form a flap with no trauma to adjacent tissue, the entire process taking around 10–20 s. The surgeon then lifts the flap

to allow treatment by excimer laser. Laser specifications which can be modified to meet individual patient's needs include flap diameter, depth, hinge location and width and side-cut architecture. The laser also creates a distinctive bevelled edge flap which allows for precise repositioning and alignment after LASIK is completed.

9. ***Stromal ablation.*** The corneal flap is retracted along the hinge and the stromal bed is dried. The ablation is then carried out with predetermined correction by the excimer laser unit (Fig. 11.7B). Important points to be remembered are as follows:

- Care should be taken that no fluid reaches the area when the ablation is in progress (cut wet; ablate dry).
- Protect the hinge during ablation.
- For myopia of more than 8 D, two-zone ablation may be required.
- In no case should residual bed thickness after laser ablation measure less than 250 μ to avoid progressive central corneal ectasia.
- Ideally, ablation should be done within 30 s of preparation of corneal flap.
- Ensure central ablations – modern excimer laser machines utilize an eye tracker to track the movement of the eye which ensures central ablation. If the laser machine is not equipped with the eye tracker facility, then a Thornton ring can also be used to stabilize the eye.

10. ***Reposition of corneal flap.*** After the ablation is completed, the irrigation is done under the flap and over the stromal bed to remove any debris and to allow the disc to smoothly float and settle on the stromal bed (Fig. 11.7C). Excess fluid is then sucked out with the help of a cellulose sponge. The corneal flap is aligned and distended properly. Once flap is repositioned, it is allowed to air-dry naturally for 3–5 min to allow firm adhesion of the flap to stromal bed. This should be confirmed by the *striae test*, whereby a dry cellulose sponge is used to depress the corneal periphery near the limbus, producing striae which can be seen radiating on the flap.

11. ***Removal of speculum and drape*** is then performed gently so as not to cause an epithelial abrasion or displacement of flap. The patient is asked to blink, and this should be observed under the microscope by the surgeon. The flap should appear well adhered and perfectly aligned. Antibiotic and anti-inflammatory drops and lubricating gel is instilled in the eye. The status of the flap should be reassessed after 1 h by performing slit-lamp biomicroscopy.

Postoperative Management

1. *Patching/dark goggles.* Patching for 24 h is performed by a few surgeons. Most surgeons prefer the use of dark goggles.
2. *Systemic analgesics* may be given for 1–3 days postoperatively.
3. *Antibiotic eyedrops* four to six times a day should be used for 7–14 days.
4. *Topical steroid* eyedrops may be used four times a day for over a month.
5. *Artificial tears* eyedrops should be used four to five times a day for over a month.
6. *Home advice* for the LASIK patient is as follows:

- Home rest for 24–48 h, after which the patient can be allowed routine activities.
- Eyes should be neither touched nor rubbed for at least 2 weeks.
- No swimming for at least 1 month.
- Avoid exposure to strong light.
- Avoid overuse of the eye for long periods.
- Driving should be avoided for 2 weeks.
- Report to the doctor in case of pain or marked blurring of vision.

Follow-up Examination

Slit-lamp biomicroscopic examination and visual acuity testing should be performed on the following days:

- One day after operation
- One week after operation
- One month after operation
- Three months after operation

- Six months after operation
- One year after operation

Complications

I. Intraoperative Complications

Intraoperative complications which can occur during various surgical steps of the technique are as follows.

1. *During application of the suction ring,* the following complications have been reported:

i. *Conjunctival chemosis* may occur, which may occlude the pneumatic ring suction part.

ii. *Severe hypotension* resulting due to ciliary body shut down because of the vacuum created by the suction ring has been reported in a case.

2. *During preparation of corneal flap,* the following complications can occur:

i. *Flap of variable and suboptimal thickness and diameter* may be formed, if:

- IOP of 60–65 mmHg is not achieved.
- Blade is of poor quality.
- Speed of the pass is not optimal.

ii. *Incomplete flap* can result due to some foreign material, debris getting into the microtome gear mechanisms, suction loss or motor failure.

iii. *Tear or button hole in the flap* can occur in steep cornea, due to inadequate suction and poor blade quality.

iv. *Perforation of the cornea* can occur during microtome use in patients with thin cornea.

v. *Free cap* instead of a hinged flap may result, sometimes. Common factors that contribute to free cap formation are as follows:

- Flat cornea
- Intraoperative IOP less than 65 mmHg
- A small cornea (<10.5 mm)
- Not fixing the keratome stopper

vi. *Damage, destruction or dislocation* of the flap can occur due to inadvertent trauma.

vii. *Loss of flap* can also occur rarely.

viii. *Irregular stromal bed* is a microkeratome-induced complication.

ix. *Hydration or desiccation* of the stromal bed may occur if a time lapse of more than 30 s occurs between the creation of the flap and laser ablation.

x. *Intraoperative contamination of the surfaces/interface debris* may occur. Some recommendations to avoid this complication are as follows:

- Avoid use of powdered gloves.
- Instruments used should be kept on a plastic surface to avoid contact with fibres.
- Instruments should be properly cleaned.
- Vigorous irrigation of the posterior surface of the flap should be done.
- Avoid excessive use of topical anaesthetics, which can lead to epithelial defects.
- Avoid touching the posterior surface of the flap.

3. *Complications during laser ablation of the stromal bed*

i. *Decentration of ablation* may lead to various complications like monocular diplopia, loss of best-corrected visual acuity and glare.

ii. *Incorrect ablation* may result in unpredictable results.

iii. *Ablation of the hinge* may result in prismatic effect.

iv. *Interruption of ablation* may occur due to technical problems.

v. *Poor ablation* occurs when liquid and/or impurities are present.

4. *Complications during flap reposition*

i. *Irrigation complications* include oedema of flap and decreased adherence due to excessive irrigation.

ii. *Interface deposits* such as lint deposits, metallic deposits, lipoid deposits or blood may occur inadvertently.

iii. *Incorrect replacement of the flap* can occur, if proper care is not taken.

iv. *Wrinkling on reposition* may occur, if the flap is very thin.

v. *Flap can be damaged* due to rough handling during reposition.

5. *Complications during removal of eye speculum*

Flap can get dislodged during removal of the eye speculum.

II. Postoperative Complications

1. ***Poor adhesion and anchoring*** of the flap with stroma may occur postoperatively, if the flap is not properly formed and/or reposited.
2. ***Flap striae*** seen immediate postoperatively can be either macrofolds or microfolds.
   - *Macrofolds* are easily visualized and are a result of flap slipping. These can cause visual deterioration and can cause full thickness flag tenting.
   - *Microfolds* are within the flap itself in the form of wrinkling in the Bowman's membrane or in epithelial basement membrane. These are related to flap setting and not flag slipping.
3. ***Infectious keratitis*** is undoubtedly a potential danger; however, hardly few cases have been reported till date.
4. ***Diffuse lamellar keratitis or Sands of Sahara syndrome.*** It occurs in early postoperative period as non-specific intrastromal/intralamellar keratitis. Aetiology is doubtful. Treatment consists of anti-inflammatory drops and antimetabolites.
5. ***Epithelial ingrowths*** under the flap are reported frequently. If they are in the centre, they can affect visual acuity, and if in the periphery can cause thickening of one edge of the flap and may induce regular or irregular astigmatism. However, if diagnosed well in time, they are not a major problem. The flap can be lifted, the epithelium scraped off and the flap repositioned.
6. ***Lost flap postoperatively*** has also been reported a few days or even weeks after the procedure. It results due to incomplete adherence to the bed. Perhaps, there is no need of lamellar grafts in these cases. Epithelium grows over the residual stroma and the cornea may function normally with some haze (Caplen technique).
7. ***Central islands*** or the so-called induced topographical alteration may result due to intrastromal ablation. If no sign of resolution is seen even after 3 months, the central islands can be treated by mobilizing the original lamellar flap.
8. ***Undercorrections and overcorrections*** are not uncommon. These can be treated with repeat procedures within 3 months as the flap can easily be reflected.
9. ***Regression*** of up to 2 D has been reported following LASIK. The refractive result stabilizes from the third month onwards in most of the cases.
10. ***Induced astigmatism***, both regular and irregular, is reported to occur.
    - *Regular astigmatism* can result due to:
      - Decentration of the ablation zone,
      - Variation in flap healing and
      - Presence of epithelial cells under the flap.
    - *Irregular astigmatism* can result due to:
      - Eccentric ablation,
      - Suturing of the flap,
      - Interface remnants,
      - Epithelial islands or
      - Irregularly reposited thin flap which produces wrinkles.
11. ***Halos and glare*** may be experienced by some patients postoperatively. Common causes are as follows:
    - *High-order aberrations* resulting from subclinical decentration.
      - *Optical treatment zone* smaller than the size of pupil during mesopic dilation.
      - *Irregular astigmatism* induced due to flap folds, typographic abnormalities or irregular epithelial surface.
12. ***Haze at the interface*** has been reported in a few cases. It occurs due to cellular response to toxic substances introduced during surgical procedure.
13. ***Corneal ectasia*** can occur subsequently, if the corneal base is thin due to the formation of a thick flap. This is owing to the fact that the flap hardly serves as a support to the corneal base, since even after 1 year it can be lifted up easily with the help of an iris repositor when treatments are required for undercorrections.
14. ***Dry eyes***. Many patients experience temporary dry eye symptoms after LASIK. This may

occur due to decreased corneal sensation resulting from severing of corneal nerves with subsequent decreased blinking.

15. ***Loss of contrast sensitivity*** is related to oblate shape of the cornea following LASIK.

III. Femtosecond Laser-Specific Complications

1. ***Cavitation gas bubbles (known as opaque bubble layer [OBL]).*** The exact origin of these bubbles is unknown. One theory suggests that they originate from stray laser pulses into the aqueous humour. Another thought is migration of the corneal stromal gas bubbles retrograde through Schlemm's canal into the anterior chamber. They tend to disappear within minutes. Modifications in flap design can reduce their incidence but their presence can impede the surgeon and the excimer laser's eye tracker to visualize and locate the pupil, respectively. Alterations in pulse duration that enable reduction in collateral tissue damage could help to reduce the formation of cavitation bubbles.

2. ***Transient light sensitivity syndrome (TLSS).*** It is usually encountered within the first few weeks of the femtosecond LASIK procedure. It is characterized by photophobia of variable severity associated with little or no corneal inflammation. It is believed to be due to a biochemical response of corneal keratocytes to near-infrared laser energy or an inflammatory response of the adjacent tissues to gas bubbles.

3. ***Rainbow glare.*** It is induced from light scattering at the posterior surface of the interface. Patients describe it as seeing between 4 and 12 bands of colour, and this phenomenon has no predilection to age, gender or refractive error. The incidence of rainbow glare appears to have faded with the newer generation of femtosecond lasers that provide improved focusing optics.

4. ***Diffuse interstitial keratitis.*** Some studies found a higher incidence of diffuse lamellar keratitis (DLK) in femtosecond LASIK compared to microkeratome. This increased rate of DLK seems to be attributed to higher flap interface inflammatory response due to laser energy and gas bubbles that cause increased activation of anterior stromal keratocytes.

IV. Inherent Problems After LASIK

1. ***Inaccurate measurement of IOP***. Applanation tonometry underestimates the IOP after the LASIK due to a decrease in the corneal thickness. Therefore, unless the IOP is corrected for the corneal thickness, routine tonometry may be fallacious and may create problems in the detection of glaucoma.

2. ***Inaccurate intraocular lens power calculation***. It has been seen that after LASIK, the use of the mean keratometry in the formula for intraocular lens (IOL) power calculation results in an inaccurate emmetropic IOL power, afterwards leading to hyperopia.

3. ***Difficulty in contact lens fitting*** occurs due to disturbed corneal topography.

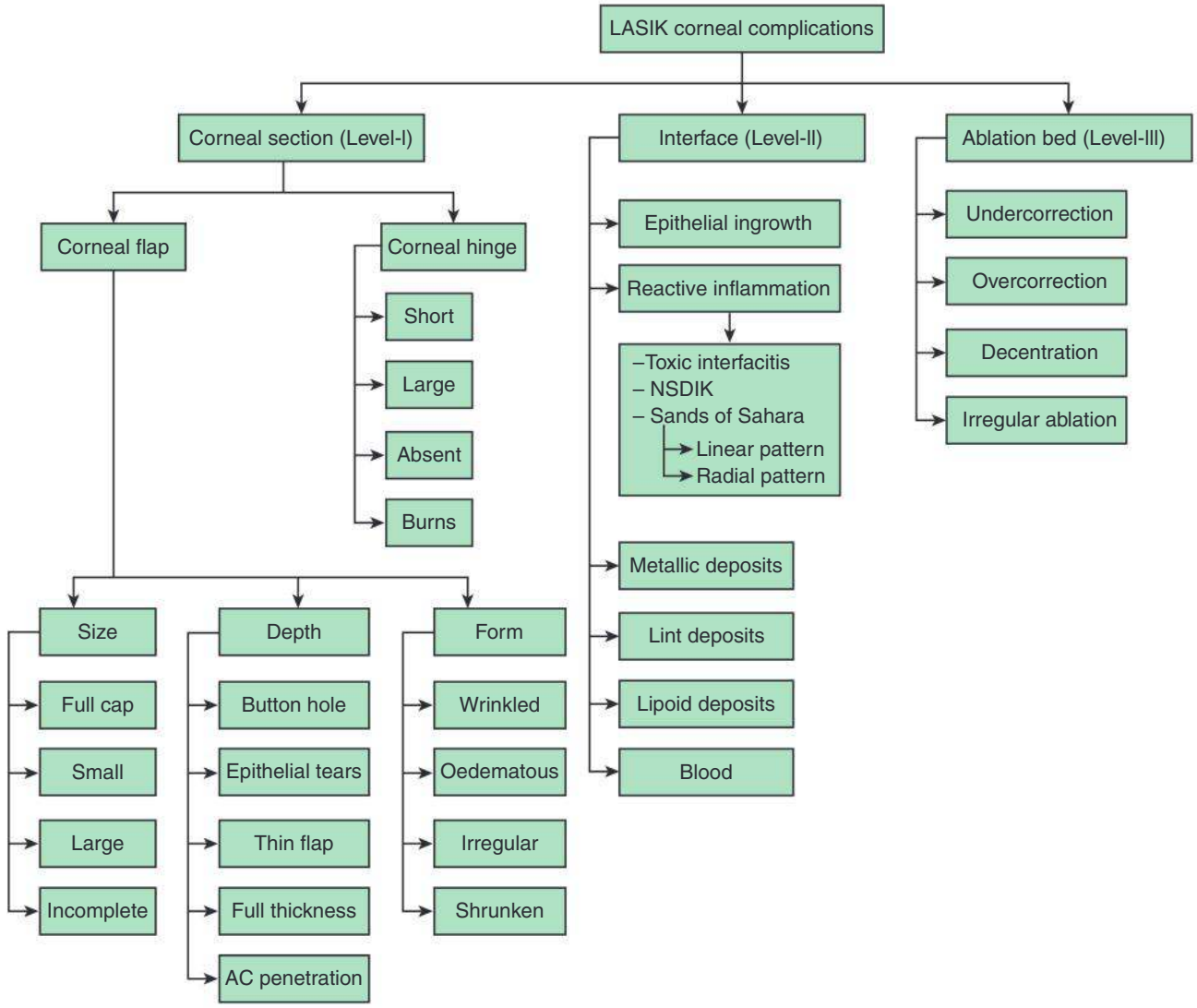
Topography-guided custom transepithelial 'no touch' (cTEN) technique for post-LASIK irregular cornea due to flap-related problems.

In a retrospective study published in *Refractive Journal of Ophthalmology*, topography-guided custom transepithelial 'no touch' (cTEN) technique of ablation using excimer laser was found to be effective in corneal regularization and removal of underlying flap/interface pathology, following LASIK flap/interface complications that led to visually disturbing irregular astigmatism and light scattering (irregular flap, striae, folds, epithelial ingrowth, etc.). cTEN ablation was performed by iVIS Suite, an integrated system consisting of precise topographer/tomographer, pupillometer, corneal interactive programmed topographic ablation (CIPTA) planning software and IRC-s excimer laser. Aim is to reshape the detected irregular corneal surface into a regular aspheric surface within a treatment zone suggested by pupillometry.

Summary of LASIK corneal complications. Gulani has summarized corneal complications of LASIK at three levels (Flowchart 11.1).

LASIK Versus PRK

Advantages and disadvantages of LASIK vis-a-vis PRK are shown in Table 11.1.



Flowchart 11.1 *Summary of LASIK corneal complications (Guliani).*

Table 11.1 *LASIK versus PRK*

Feature	LASIK	PRK
Postoperative pain	Less	More
Ocular patching	Not required	For 2–3 days
Visual rehabilitation	Early	Comparatively late
Stability in refraction	Usually within 1 month	4–8 months
Stromal haze	Usually not present	Present
Long-term regression	Less common	More common
Predictability	High	Low
Correctable range	1–30 D	1–12 D
Topical eyedrops required for	2–3 weeks	4–8 months
Repeat procedure can be done	3 months after simply lifting the flap	After 1 year
Surgical skill required	More	Less
Potential risk of flap complication	Present	None
Microkeratome	Required	Not required

Comparison of Methods and Results of Various Studies

The methods of surgical techniques used and the results obtained in some of the studies are shown in Table 11.2.

Advantages and Disadvantages of LASIK Over RK and PRK

Advantages

1. Minimal or no postoperative pain.
2. Recovery of vision is very early as compared to PRK.
3. No or little risk of perforation during surgery and later rupture of globe due to trauma unlike RK.
4. No residual haze unlike PRK where subepithelial scarring may occur.
5. LASIK is effective in correcting high myopia of –6 to –30 D.

Disadvantages

1. LASIK is much more expensive.
2. It requires greater surgical skill than RK and PRK.
3. There is potential risk of flap-related complications, which have been mentioned above.

LASER SUBEPITHELIAL KERATOMILEUSIS

LASEK combines advantages and features of both PRK and LASIK. It involves removal of an epithelial flap (chemically loosened with alcohol) before ablating the corneal stroma with excimer laser. It was introduced by Massimo Camellin in 1999.

Surgical Parameters and Technique

LASEK resembles PRK more than does LASIK, so surgical considerations are similar (see page 404) except the following features:

Epithelium removal in LASEK is in the form of hinged flap (cf. PRK). The steps are as follows (Fig. 11.4D–F):

- *Trephining*. An epithelial trephine (8.5–10.5 mm in size) is placed on the centre of anaesthetized cornea. A 4 mm segment of the trephine is blunt (for sparing the intact epithelium as hinge). By gentle pressure on the cornea, the trephine cuts the epithelium, sparing the underlying stoma and 4 mm epithelial hinge.
- *Alcohol treatment*. After epithelial trephining, a similar-sized alcohol well is centred on the cornea. The well is filled with 20% ethyl

Table 11.2 *Comparison of methods and results of various studies on LASIK*

Surgeon	Gimbel (1996)	Pallikaris (1994)	Bas (1995)	Kremer (1995)	Gomes (1995)	Brint (1996)	Fiander (1995)
Flap thickness (mm)	160	150	130–150	160	180	160	130–160
Flap diameter (mm)	8.9	8.9	7.2	8	8	7.4	7–8
Ablation zone (mm)	3.75–5.50	Not mentioned	Not mentioned	5–6	4.5–5.0	5–6	4–5
IOP during the procedure (mmHg)	60	60	65	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Postoperative steroids	Yes	Yes	Yes	Yes	No	Yes	No
Postoperative corneal haze	Minimal	Minimal	Minimal	Nil	Nil	Yes	Nil
Irregular astigmatism	Yes	Yes	Yes	No	No	Yes	No

alcohol and kept in position for 60 s. The alcohol is then removed with a cellulose sponge and the well is taken off the cornea and epithelium is washed with BSS.

- *Separation of epithelial flap*. After waiting for a minute (during which the alcohol-treated epithelium is loosened from the underlying Bowman's membrane), a microhole is used to pick up the epithelium from the edges of trephine marks. After this, the epithelial flap is rolled slowly towards the hinge with the help of a hockey-shaped spatula, exposing a clean Bowman's to work.

Corneal stromal ablation is then carried out to correct refractive error (as described in PRK).

Reposition of epithelial flap. After ablation, the corneal surface is washed thoroughly and scrapped to rid of the debris and the condensed plume. Then the epithelial flap is carefully rolled back with the help of an irrigating cannula.

Bandage contact lens is then applied over the cornea for 5–7 days.

LASEK with mitomycin-C. Some surgeons use 0.02% mitomycin-C for 30 s after corneal ablation and a thorough wash with BSS before repositing the epithelial flap. Mitomycin-C is useful in curtailing the fibroblastic activity and thereby reducing and delaying the chances of corneal haze – more so when treating high myopia.

Postoperative Management

Postoperative management is similar to that in PRK (page 403) and LASIK (page 410).

Advantages of LASEK

Advantages of LASEK Over PRK

- Less postoperative pain.
- Early recovery and less postoperative haze due to improved epithelial healing.

Advantages of LASEK Over LASIK

- Corneal ectasia is less likely as residual corneal bed thickness is more.
- *Flap-related complications* like button hole, partial flap, free caps, lost flap, flap wrinkling and epithelial down growth are not known.
- *Additional correction of myopia* up to 5 D more than LASIK is possible, as another 90 μ of corneal stroma is available for ablation.
- *In thin cornea*, LASEK is a better option than LASIK. An individual with a corneal thickness of 490 μ may still have an option of 6 D myopia correction.
- *Increase in high-order aberrations*, noted with LASIK, is excluded with LASEK.
- *Postoperative dry eye* chances are less as the corneal nerves are not severed as with LASIK.
- *Large-zone treatment* is possible with LASEK. In LASIK, the flap size is a restricting factor to the size of treatment zone.

LASEK Versus LASIK: Present Status

Presently LASEK is a good alternative to LASIK where the latter is a handicap, e.g. in patients with myopia >8 D and in those with thin cornea. However, LASEK is not preferred to LASIK because of the following ***disadvantages***:

- *Postoperative pain* is more.
- *Delayed recovery*; i.e. vision remains blurred for 7–10 days.
- *Corneal haze* similar to PRK is definitely encountered on long-term follow-up.

EPIPOLIS LASER IN SITU KERATOMILEUSIS (EPI-LASIK)

The name epi-LASIK is derived from the Greek word 'epipolis', which means superficial and the LASIK. Epi-LASIK is just like LASEK except that in it the epithelial flap is created with the help of an epikeratome, and thus the epithelial cells are not damaged by chemical toxicity of alcohol. It was introduced by Pallikaris in 2003.

Surgical Techniques and Postoperative Management

Surgical technique and postoperative management of a case of epi-LASIK is same as that of LASEK except the technique of creation of epithelial flap which is described below.

Creation of epithelial flap. The epithelial flap (Fig. 11.4G and H) is created with the help of epikeratome (Fig. 11.8). With the increasing

Fig. 11.8 *The epikeratome.*

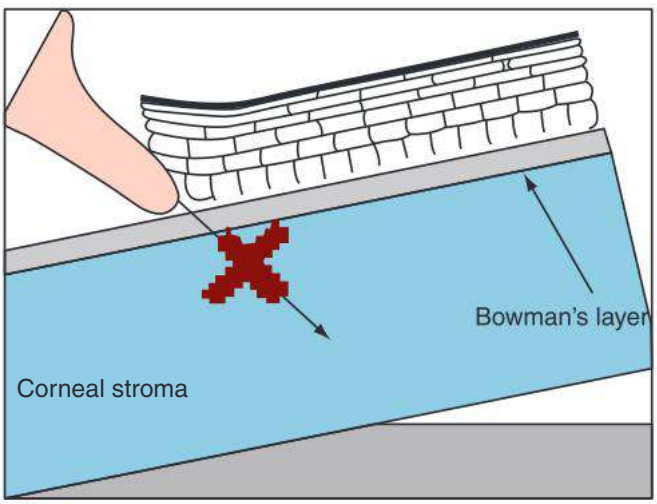


Fig. 11.9 *The dull plastic separator moves across the cornea in epi-LASIK, passing just above Bowman's layer.*

popularity of epi-LASIK (especially in patients with myopia >8 D and those with thin cornea), a new array of epikeratomes have come in the market. Commercially available epikeratomes include Centurion Epiedge, Amadeus II, Morias Epi-K and Gebauer Epilift.

Technique. The epikeratome travels across the eye more slowly than the microkeratomes. This gives better control over the separation. Epikeratome has a blunt blade or separator made of either plastic or stainless steel, which cleaves or pushes away a much more smoother epithelial flap (Fig. 11.9).

Advantages of Epi-LASIK

Advantages of epi-LASIK over PRK and LASIK are same as those of LASEK (page 416).

Advantages of epi-LASIK over LASEK. The use of epikeratome eliminates the need for the alcohol used in LASEK. Since alcohol is toxic to epithelial cells, avoiding alcohol application in epi-LASIK results in:

- Less pain,
- Faster healing and
- Less corneal haze.

Epi-LASIK Versus LASEK Versus LASIK: Present Status

Decidedly, epi-LASIK has replaced LASEK; presently, status of epi-LASIK versus LASIK is same as that of LASEK versus LASIK (see page 416).

CUSTOM LASER IN SITU KERATOMILEUSIS

Introduction

Conventional LASIK is currently the undisputed leader within photorefractive procedures. This procedure corrects only low-order aberrations such as spherical and cylindrical refractive errors. The high-order aberrations, which affect the quality of vision but not significantly the Snellen visual acuity, are not corrected by standard LASIK procedure. Rather, the conventional laser treatment on the cornea increases high-order aberrations, especially at night when the pupil dilates. The aberrations are increased because the normal cornea is prolate in shape (steeper in the centre), but it becomes oblate (steeper in the periphery) after conventional ablation profile. These aberrations are probably the reason for deterioration of visual performance in some eyes after conventional photorefractive procedures. Besides this, there are cases with irregular astigmatism following penetrating corneal grafts, penetrating injuries or peripheral corneal scar, for example, which are not amenable to conventional ablation procedures.

Refractive surgeons are constantly making efforts to tackle the above-listed problems. C-LASIK is one step towards it. On 12 June 1999, Theo Seiler treated the first patient with customized corneal ablation. In 2002, Alcon was

the first company to receive FDA approval for customized LASIK surgery using LADARvision 4000 Excimer laser.

Definition

C-LASIK, also called 'customized ablation LASIK', is a revolution in photorefractive procedures. Custom ablation is an ablation pattern that attempts to optimize the eye's optical system using a variety of spherical, cylindrical, aspherical and asymmetrical treatments based on the individual eye's optic and anatomy as well as the patient's needs. The exact assessment of individual eye's optics is made by corneal topography and aberrometry. (For details see pages 184 and 210, respectively.) The term customized ablation highlights that it selectively corrects the inherent aberrations of each individual eye. Thus, we can compare the use of standardized and symmetrical ablation pattern in conventional LASIK with buying a suit 'off-the-rack' and customized ablation pattern with 'tailor-made suit'.

Types of customized ablation. There are two forms of optical aberration customization:

- Corneal topography-guided ablation
- Wavefront-guided ablation

1. ***Corneal topography-guided ablation*** takes care of the ocular aberrations detected by corneal topography and treats the irregularities as an integrated part of the laser treatment plan.
2. ***Wavefront-guided ablation*** treats the aberrations of the entire human optical system that are measured by a variety of wavefront measurement devices.

C-LASIK. To be precise, presently C-LASIK refers to customized corneal ablation, which is based on both the corneal topography and wavefront aberrometry.

PROCEDURE AND ADVANTAGES OF C-LASIK

Procedure

The procedure of performing a customized ablation includes the following steps:

1. ***Measurement of optical aberrations of the eye***. Corneal topography and wavefront aberrometry systems have been developed to measure all the optical aberrations of the eye. (For details see pages 184 and 210, respectively.) These measuring devices have the ability to measure refraction to submicron level of about 0.01 D. A wave print of the eye is created. This information is used to prepare a customized laser ablation pattern.
2. ***Linking the measured optical aberration to the laser machine***. A software is available that combines all the measured data which is then downloaded into a storage device and inserted into the laser machine computer.
3. ***Creation of corneal flap.*** As in conventional LASIK, the corneal flap can be created with:
   - Microkeratome (see page 405) or
   - Femtosecond laser (see page 422).

Note. Femtosecond laser should be preferred to mechanical microkeratome.

4. ***Laser ablation***. Customized ablation requires a flexible laser system that can deliver a small spot (less than 1.0–2.0 mm) or use an erodible mask customized to a very subtle level and an excellent eye tracking system or an eye immobilizing system. Linking of measured optical data with laser machine is presently the most challenging step, as it requires an accurate orientation and registration of the wavefront data with the laser optics and eye tracker to the eye undergoing laser ablation to achieve accurate ablation.

Advantages

Advantages of wavefront-guided customized LASIK include:

1. ***High-quality vision***. C-LASIK in comparison to standard LASIK provides a high-quality vision which is comparatively free from night glares and halos and has improved contrast sensitivity.
2. ***Supervision***. It is a well-known fact that human retina has a much higher resolving power and a much better potential visual acuity of about 6/2 to 6/1.5, but this is greatly reduced by diffraction of light and the high-order aberration of the eye. Therefore, by customized

ablation, which takes care of the aberrations of the eye, it is possible to achieve supervision to the tune of 6/4 or 6/3.

3. ***Less invasive technique***. It is comparatively less invasive in the sense that lesser amount of tissue ablation is required to achieve the given effects.

4. ***Can correct irregular astigmatism*** to some extent in cases following penetrating corneal grafts, penetrating injuries or peripheral corneal scars. Furthermore, as many as 40% of eyes show some degree of corneal irregularities, and all these eyes would be far better off with a customized laser ablation.

iLASIK

iLASIK refers to wavefront-guided LASIK in which the corneal flap is made with the help of femtosecond laser (rather than microkeratome) which allows greater precision and consistency. Other popular names for this technique are Femto LASIK or all-laser LASIK or no-blade LASIK.

WAVEFRONT-GUIDED LASIK SYSTEMS

Wavefront technology-based systems have been primarily evolved for customized corneal ablation. These systems are basically a combination of the following:

- *Corneal topography* and *wavefront aberrometry system* that can measure all the optical aberrations of the eye,
- *A flexible laser delivery system* that can deliver a small spot (less than 1.0–2.0 mm) or use an erodible mask customized to a very subtle level and
- *An excellent eye tracking system* or an eye immobilizing system.

Commercially available systems for customized ablation include:

- Zyoptix (Bausch and Lomb)
- ORK Corwave (ORK-W)
- Nidek NAVEX LASIK system with optical path difference (OPD) scan
- Visx CustomVue
- LADARvision Custom Cornea
- Allegretto Wave IQ (Alcon).

The Zyoptix System

The Zyoptix system (Bausch and Lomb) utilizes combination of wavefront analysis and corneal topography for optical aberration customization. It comprises the following components:

- Zywave
- Orbscan IIz
- Zylink
- Technolas 217 excimer laser.

Zywave. It is a Hartmann–Shack aberrometer in which a laser diode (780 mm) generates a single laser beam, which is projected as a spot on the patient's retina. (For details see page 214.)

Orbscan IIz. It is corneal topography system that uses a scanning optical slit scan that is fundamentally different from the corneal topography that analyses the reflected images from the anterior corneal surface. (For details see page 199.)

Zylink. It is a software that combines the data obtained from Orbscan and Zywave and translates into treatment plan. The treatment plan is then copied to a floppy disk and inserted into the laser machine computer.

Technolas 217 excimer laser is a flexible laser system that can deliver a small spot (1–2 mm) and is equipped with an excellent eye tracking system.

Advanced Personalized Technology

Advanced personalized technology refers to the upgradation and improvement made by Bausch & Lomb in their Zyoptix system in the form of an optimized Zyoptix platform which includes (Fig. 11.10):

Zyoptix diagnostic work station. It comprises:

- *Zywave* (aberrometer) with advanced software and incorporating graphical user interface and an integrated 'no dilation zyoptic algorithm (NoDiZy)', which offers wavefront-driven procedures without the need for pharmacological pupil dilation.
- *Orbscan* with improved software.

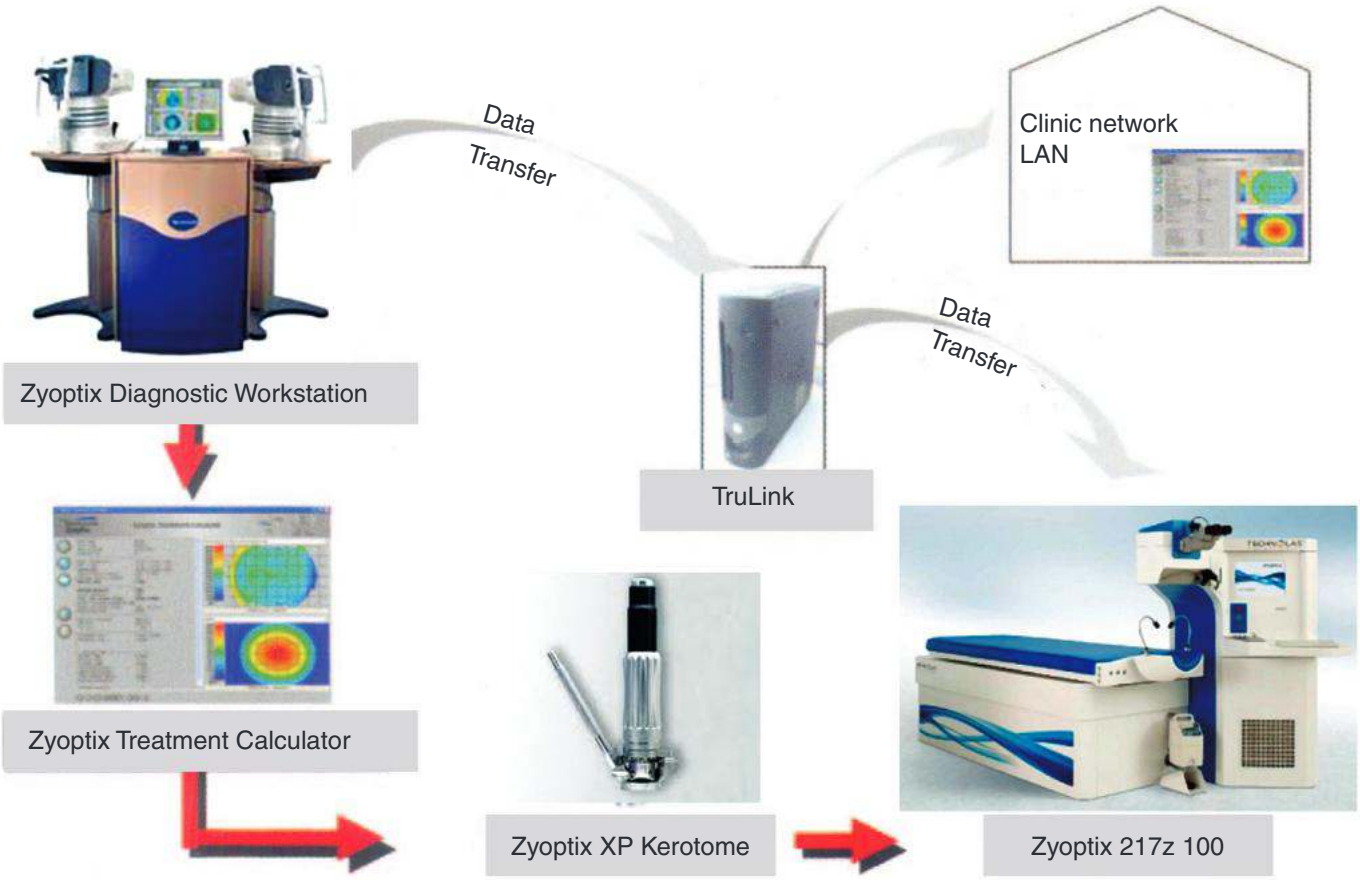


Fig. 11.10 *Overview of the optimized Zyoptix platform.*

Zyoptix treatment calculator, an advanced form of Zylink, is the key element of advanced personalized technology. It incorporates a new software tool including 'Advanced Zyoptix Personalized Nomogram' to calculate Zyoptix personalized treatment plans.

Zyoptix Trulink is a network-based computer server that not only connects all Bausch & Lomb's equipment in a small local area network but also can be connected with surgeons' local area networks to enable data manipulation and transfer, which renders all removable media including CDs and floppy disk obsolete.

Schwind ORK Corwave System

ORK Corwave (ORK-W) or ORCA WAVE corneal wavefront-guided LASIK system used for C-LASIK comprises the following components:

Optikon Keratron Scout Topographer, which is a placido-disc-based videokeratoscope.

ORK wavefront analyser, i.e. ORK-W or corneal wavefront technology provides a corneal wavefront map.

Schwind ORK custom manager software is an intelligent revolutionary software which forms the most important link between the diagnostic unit (topographer and aberrometer) and the excimer laser. It creates a short file, i.e. an ablation pattern for an optimized refractive keratectomy.

Schwind excimer laser ESIRIS. Its salient features include:

- 200 Hz pulse frequency,
- 330 Hz active high-speed eye tracking and
- 0.8 mm scanning spot with Gaussian beam profile.

Nidek NAVEX LASIK System With OPD Scan

This system, used for C-LASIK, comprises:

Nidek OPD scan. This OPD scan provides accurate information of the corneal wavefront map.

Nidek software that links the OPD scan with excimer laser.

Nidek EC-5000 excimer laser is well equipped for customized ablation (Fig. 11.11).

Visx CustomVue

- The Visx S4 laser is based on a broad-beam platform and has recently incorporated an active tracker and a variable spot scanning system to allow the spot size to change from 0.65 to 6 mm during treatments.
- Astigmatism is corrected by reducing the diameter of the ablation zone in one meridian, resulting in more correction along the shorter diameter.
- The Visx CustomVue approval is for treatments of up to –6 D spheroequivalent with up to 3 D astigmatism. The optical zone diameter is 6 mm.

LADARvision Custom Cornea

- Alcon LADARvision 4000 Custom Cornea Wavefront Laser Diagnostic and Ablation, also known as Custom Cornea, Ladar Vision and Alcon Laser.
- The laser is a flying spot laser with an active tracking device.
- Its Custom Cornea approval is for spherical treatments up to –7 D of myopia with less than 0.5 D of astigmatism and it uses a 6.5 mm optical zone.

Allegretto Wave IQ (Alcon)

The Allegretto Wave was developed specifically for wavefront treatments—with a fast, accurate tracker, a small 0.95-mm spot size, a rapid 200-Hz repetition rate and a Gaussian beam profile that is particularly well-suited to treating localized aberrations.

Advantages and Drawbacks of Wavefront-Guided LASIK Systems

Advantages include:

- Average recovery time is 2 days to 1 week.
- 25 times more precise than non-wavefront methods.

Drawback

- More expensive than traditional LASIK.

TOPO-GUIDED LASIK SYSTEMS

Contoura Vision LASIK

Contoura vision LASIK is a Topography Guided LASIK system from Alcon/Wavelight EX 500. It is an advanced version of laser vision correction surgery. It utilizes a three-step correction

Fig. 11.11 *Nidex EC-5000 Excimer laser.*

technique using the ablation and reshaping of cornea in Contoura vision which is customized to each eye. It can provide refractive correction even for patients with irregular corneas who are otherwise not eligible for conventional LASIK. It is based on a comprehensive algorithm which captures more than 22,000 unique data points on the surface of cornea by Topolyser. The Excimer laser then modifies them individually to correct minute variations of curvature at each point and provide precise vision. Contoura vision offers lesser chances of side effects like halos, glare, etc. along with better contrast sensitivity, compared to conventional LASIK. In contoura vision LASIK, the flap can be created either with the micro keratome or with femtosecond laser. Contoura vision laser correction can even be carried out as surface ablation without flap.

LASIK XTRA

LASIK Xtra procedure involves a combination of LASIK and collagen cross-linking with riboflavin (C3R or CXR). It is aimed at restoring strength to the cornea, increasing stability in visual outcome and increasing the accuracy of the refractive correction.

Procedure

The LASIK Xtra procedure is performed as follows:

- *Creation of LASIK flaps* by either using a femtosecond laser or a microkeratome tool.
- *Excimer ablation* is then performed in the usual manner.
- *Collagen cross-linking with riboflavin (C3R or CXR).* At the completion of the excimer ablation, eyes received 1–5 drops of dextran-free riboflavin formulation, carefully applied to the stromal bed (avoiding application to the LASIK flap). The riboflavin solution is allowed to soak for a period of up to 90 s, after which the riboflavin is rinsed from the stroma using a BSS.
- *Reposition of LASIK flap*. Once well rinsed, the LASIK flap is repositioned into place and the flap interface copiously irrigated and stroked into place. A 375 nm UV source with homogenous 30 mW/cm^2 top flat beam profile is then used to apply a 2.7 J/cm^2 dose of irradiation through the closed flap.

Advantages

- Delays or stops the progression of keratoconus.
- Can also be used to treat keratoconus.
- Extends the longevity of LASIK results.
- Decreases the need for touch up procedure later in life.
- Reduces risks of long-term vision changes.

Disadvantages

- Higher risk of infection in the eye due to contamination of riboflavin.
- This surgery is also more expensive than standard LASIK

IV. NEWER LAMELLAR CORNEAL REFRACTIVE PROCEDURES

REFRACTIVE LENTICULE EXTRACTION

ReLEx is a new all-in-one bladeless femtosecond laser surgical technique, described first of all by Sekundo and colleagues in 2008, to correct myopia with or without astigmatism up to –10 D.

Femtosecond Laser for ReLEx

Basic features of femtosecond laser are described on page 399.

Commercially available femtosecond laser systems include:

- VisuMax (Carl Ziess)
- IFS Advanced (Abbott)
- WAVELIGHT FS200 (Alcon)

VisuMax (Carl Zeiss Meditec AG) femtosecond laser system (Fig. 11.12) is equipped for ReLEx. It is a 500 kHz femtosecond laser with extremely low energy settings (typically less than 200 nJ) that make it an excellent tool for precise sculpting within the intact cornea for refractive vision correction. Small, closely placed spots enable easy separation of tissue bridges and give a smooth lamellar surface. The curved

Fig. 11.12 *Visumax femtosecond laser system.*

contact glass interface greatly helps in autocentration during the docking procedure.

Surgical Technique of ReLEx

ReLEx, fundamentally is a refractive lamellar corneal surgery, which attempts to remove, add or modify the corneal stroma so that radius of curvature of the anterior corneal surface is altered as desired. Since the technique is accomplished by femtosecond laser alone, so it is also called '*All-femtolaser vision correction*'.

Types of ReLEx Surgical Approach

Depending upon the method of extraction of stromal lenticule, two different approaches of ReLEx have been described:

1. ***FLEX (Femtosecond Lenticule Extraction)*** approach of ReLEx refers to extraction of intrastromal lenticule after making a full corneal flap.
2. ***SMILE (Small Incision Lenticule Extraction)*** approach of ReLEx, as the name indicates, refers to extraction of the refractive lenticule through a small cut in the anterior flap.

Surgical Steps of ReLEx

1. ***Creation of intrastromal lenticule:*** The intrastromal refractive lenticule of calculated parameters is created by four femtosecond incisions (photodisruption plane) as follows:
   - *First photodisruption plane* is created along the *posterior surface* by applying laser pulses from periphery to the centre of the proposed intrastromal lenticule (usually 6–7 mm optic zone size) (Fig. 11.13B).
   - *Second photodisruption plane* is a 360 degree *vertical side cut* along the periphery of the proposed lenticule (Fig. 11.13C).
   - *Third photodisruption plane* is made along the *anterior surface* of the lenticule starting from centre to the periphery and extending 0.5–1 mm beyond the vertical side cut of the lenticule (Fig. 11.13D).
   - *Fourth photodisruption plane* is a vertical cut in the anterior corneal flap (*anterior side*

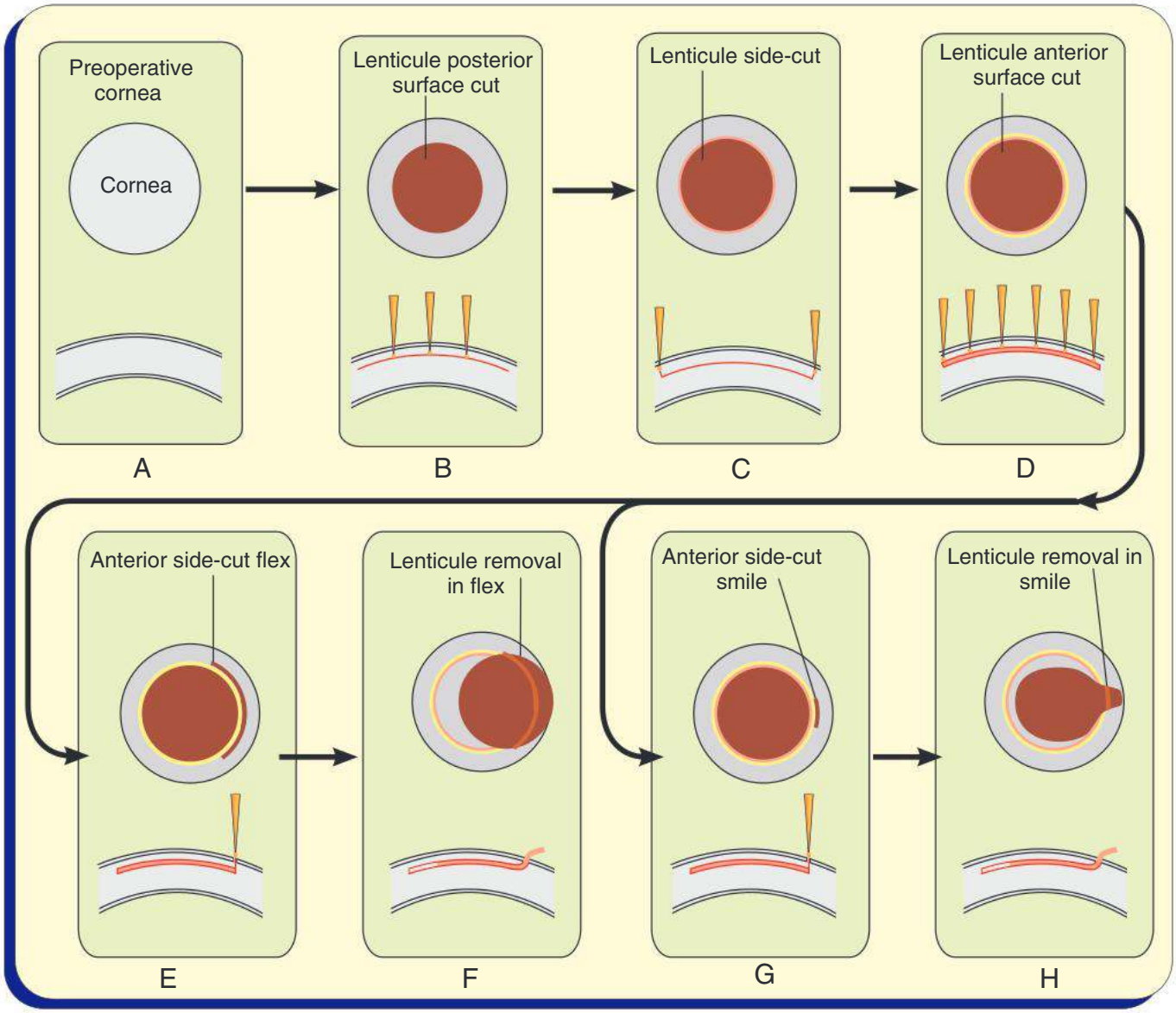


Fig. 11.13 *Surgical steps of refractive lenticule extraction (ReLEx). For explanation of each step, see text.*

cut). The extent of this cut varies depending upon the approach:

- *In Flex approach,* the extent of anterior side cut is 250–300 degrees along the selected optic zone making a hinged anterior corneal flap (similar to that of LASIK flap) (Fig. 11.13E).
- *In Smile approach,* the extent of anterior side cut is only 40–60 degrees (Fig. 11.13G).

2. *Removal of lenticule and reposition of anterior corneal flap.* The technique of removal of created lenticule is different in Flex and Smile approaches.

In Flex approach, the steps are as follows:

- The hinged anterior corneal flap is separated from the anterior surface of the lenticule with the help of a specially designed ReLEx manipulator.
- The anterior corneal flap is then lifted to the side as in standard LASIK.
- The intrastromal lenticule is then separated all along its peripheral edge and separated posteriorly from the bed with the help of ReLEx manipulator.
- The freed lenticule is then removed away with the help of a forceps (Fig. 11.13F).

- A drop of irrigating fluid is placed on the bed and the anterior corneal flap is repositioned gently as in standard LASIK.

In Smile approach, the anterior surface, peripheral margins (360 degree circumference) and posterior surface of the lenticule is separated from the surrounding tissue with the help of ReLEx manipulator inserted through the 40–60 degree cut made in the anterior corneal cap. A 21-gauge forceps is then introduced through the smile incision, the edge of the lenticule is firmly grasped and the lenticule is gently pulled out of the incision (Fig. 11.13H). The anterior corneal surface is gently pressed to snugly oppose the anterior and posterior raw surfaces of the intrastromal tunnel.

Postoperative Management

- *Topical antibiotics* are prescribed for a week.
- *Topical steroids* are prescribed for 2–3 weeks.
- *Topical lubricants* are prescribed for 4–6 weeks.

Advantages of Flex Over Femto-LASIK/ Conventional LASIK

- Excimer laser-related complications are eliminated.
- Microkeratome-related complications are eliminated (cf. conventional LASIK).
- Refractive results are more accurate especially in myopia of –6 to –10 D.
- Potential for stromal drying is less.
- Induction of optical aberration is minimized.
- Reduction of the effective optical zone does not occur.
- Low potential for flap misalignment error.
- In case of suction, loss procedure can be completed on the same day, without any risk of visual loss.
- Risk of corneal ectasia is less.

Additional Advantages of Smile ReLEx

- Flap-related complications are gone.
- Healing is much faster.
- Lower potential for dry eye as fewer corneal nerves are cut.
- As flap is not made, so better long-term biomechanical stability of cornea.
- Further, reduced risk of corneal ectasia.

V. CORNEAL REFRACTIVE THERAPY (ORTHOKERATOLOGY)

Corneal refractive therapy (CRT), also called orthokeratology, is a non-surgical reversible method of moulding the cornea with overnight wear of unique rigid gas-permeable contact lenses to correct myopia.

Procedure of orthokeratology involves the following steps:

- *Meticulous refraction* to ascertain the exact amount of spherical and cylindrical lens to correct the myopia.
- *Corneal topography* to map the shape of anterior surface of cornea.
- *Calculations of parameter of corrective contact lens*es are then made from the observation of corneal topograph and exact amount of refractive error to be reversed.
- *Manufacturing of special contact lenses* which will produce the desired effect for reshaping of the patient's cornea is ordered.
- *Wearing schedule*. Initially, the precise specially shaped contact lenses are worn daily for 8 h until proper correction is achieved and vision is improved. Most of the times, an overnight wear schedule (while sleeping) is prescribed. After the desired correction is achieved, the lenses may only be needed to be worn a few hours a day for about 3 days a week to keep the cornea in the shape necessary to see clearly without glasses and without contact lenses.

Indications. Orthokeratology is useful at any age with spherical prescription less than –4 D and astigmatism less than –1.5 D. This is a great temporary alternative for

- Those who are too young to consider LASIK of any age below 18 years.
- Those whose prescriptions are continuing to change; i.e. refractive error has not stabilized.
- Those youngsters and teenagers who are involved in sports where wearing contact lenses or glasses might be limiting their sports activity.

Advantages of orthokeratology:

- Non-surgical method
- Available for most people, even younger

- Freedom from constant corrective lens wear
- Better vision improvement
- Reversible method

Disadvantages of orthokeratology:

- Longer result time
- Not a permanent solution
- Higher startup cost than regular contact lenses or eye glasses
- Currently only for myopia

VI. INTRACORNEAL IMPLANTS

Intracorneal implants used as refractive corneal procedures include:

- Intracorneal rings,
- Intracorneal contact lenses,
- Gel injectable adjustable keratoplasty and
- Plastic inlay (PAI-LASIK).

INTRACORNEAL RINGS

Intracorneal rings or ICRS or intrastromal corneal ring segments (INTACS) were approved in the USA, by FDA, for correction of low myopia in April 1999. The intracorneal rings are implanted into the peripheral cornea, producing a vaulting effect that flattens the central cornea and corrects myopia of up to 3 D.

Features of Intracorneal Rings

- Made of PMMA (polymethyl methacrylate)
- Outer diameter – 8.1 mm
- Inner diameter – 6.7 mm
- Arc length – 150 degrees
- Positioning hole diameter – 0.28 mm
- Rings cross-section – hexagonal
- Each package contains two rings – right and left
- Thickness – available in five different thickness inserts, 0.25, 0.30, 0.35, 0.40 and 0.45 mm

Nomogram for Intacs Inserts Selection

The average correction of myopia achieved with different thickness Intacs is as follows:

0.25 mm – 1.3 D (1.0–1.6)
0.30 mm – 2.0 D (1.7–2.3)
0.35 mm – 2.7 D (2.4–3.0)
0.40 mm – 3.4 D (3.1–3.7)
0.45 mm – 4.1 D (3.8–4.4)

Indications of Intacs

- *Myopia*. Patients with low-degree myopia, –1 to –3.5 D, who are willing to get rid of glasses and/or contact lenses and are highly motivated and realistic patients.
- *Other indications* where Intacs are useful include keratoconus, pellucid marginal degeneration and post-LASIK corneal ectasia.

Contraindications are patients with collagen vascular, autoimmune or immunodeficiency diseases, pregnant or nursing women, presence of ocular conditions such as recurrent corneal erosion syndrome and corneal dystrophy that may predispose the patient to future complications and patients who are taking any of the following medications: isotretinoin, amiodarone, sumatriptan.

Surgical Technique

Surgical technique for insertion of the desired intracorneal ring involves the following steps:

- *Topical anaesthesia* is achieved with anaesthetic eyedrops.
- *Marking of geometric centre of cornea* is done with the help of 11 mm zone marker – Sinskey hook.
- *Corneal thickness* is measured at the site of the planned incision.
- *An incision*, 1.2 mm in length is made with a sharp diamond blade at 12 o'clock position, approximately 2 mm from the links.
- *Corneal tunnels* (pockets) are then created at approximately two-thirds stromal depth using a pocketing hook, stromal spreader and clockwise and anti-clockwise dissection glides, under suction created by a vacuum centring guide.
- *The femtosecond laser* is also being used for insertion of ICRS in the treatment of low myopic keratoconus and corneal ectasia, especially those occurring post-LASIK. Instead of using a mechanical spreader, the femtosecond laser is used to create channels at a predetermined depth with a high degree of accuracy. The laser parameters which need to be specified include channel depth, entry incision length and width and inner and outer diameters of the channels. The narrower the channel the

greater the effect. However, a narrower channel also results in increased difficulty in inserting ICRS. A compromise between maximal outcome and ease of insertion is achieved.
- *Insertion of Intacs* is then accomplished in the clockwise and anti-clockwise tunnels, maintaining a space of 2 mm between their ends at 6 o'clock position and a space of 1.5 mm between their ends and the edge of the incision at 12 o'clock position.
- *Closure of incision* is then achieved with a single interrupted 10–0 nylon suture that is removed 2 weeks after surgery.

Postoperative Treatment
- *Antibiotic/steroid* combination eyedrops four times a day for 2–3 weeks and
- *Lubricating artificial tear*, preservative-free eyedrops frequently for 2–3 weeks.

Advantages of Intacs Over LASIK
- *Maintain normal positive asphericity*, i.e. natural prolate corneal shape; LASIK frequently produce oblate cornea.
- *Preserve corneal stroma*, i.e. alter the shape of cornea without removing corneal tissue from the central optical zone.
- *Reversibility*, i.e. can be removed with minimal lasting effect. Thus, patients who elect to have Intacs are not 'locked in' to the procedure forever, as are patients who undergo other refractive procedure such as LASIK and PRK.
- *Changeable*, i.e. if one's vision needs a change, they can be replaced with appropriate thickness rings.
- *Rapid visual recovery*. Eighty per cent patients achieve very good vision (6/9 to 6/12) after the surgery.
- *Safety and cost-effectiveness* are other advantages of Intacs.

Disadvantages of Intacs
- *Not effective* in myopia of more than 4 D.
- *Complications* like under- or overcorrection, migration of segments towards the wound, neovascularization, extrusion and visual side effects (glare and halos) are also known.

INTRACORNEAL CONTACT LENSES
Intracorneal contact lenses have also been tried but never became popular.

GEL INJECTABLE ADJUSTABLE KERATOPLASTY
Gel injectable adjustable keratoplasty is being tried in patients with –1 to –4 D myopia. In it, a non-toxic semi-solid gel (polyethylene oxide) is injected in paracentral stroma after making a tunnel as described in Intacs. Potential advantages of this technique include ease of manipulation, adjustability and reversibility.

PAI-LASIK
- Currently the LASIK procedure is irreversible, unable to correct high refractive errors and if excessive tissue is ablated, can cause corneal ectasia.
- Gholam A. Peyman, MD, invented the concept of *photoablative inlay (PAI).* Because no corneal tissue is ablated, the problems associated with LASIK do not occur.
- A *plastic inlay* is sculpted using Excimer laser and is left between flap and stroma. However, this concept is *still at a very early stage.* Animal studies have not yet begun.

B. LENS-BASED REFRACTIVE SURGERIES FOR MYOPIA

REFRACTIVE LENS EXCHANGE (EXTRACTION OF CLEAR CRYSTALLINE LENS)
Extraction of clear lens had been advocated for myopia of –16 to –18 D, especially in unilateral cases, even before the IOLs became popular (Fucala's operation, 1890). Nowadays, many surgeons prefer to treat myopia of –16 to –30 D with clear lens extraction by phacoemulsification with appropriate IOL implantation (RLE). With phacoemulsification, recovery is very early, continuous curvilinear capsulorrhexis offers good IOL centration, a posterior chamber IOL hugs the posterior capsule and thus chances of posterior capsule opacification (PCO) are reduced. Therefore, now it is accepted that a zero-power IOL is better than no IOL, since it not only retards

PCO but also minimizes the incidence of retinal detachment.

With this procedure, there occurs an increase in best-corrected visual acuity by one to two lines on the Snellen's chart, probably because of the removal of the minification effect of high concave glasses.

Hypermetropia can also be treated by clear lens extraction followed by a high-power IOL implantation. However, risks of intraocular surgery, especially in myopes purely for a refractive goal must be considered when an alternative like LASIK procedure is available.

Indications. The success of RLE with multi-focal or accommodative IOL implant depends mainly on an appropriate patient selection. At present, the best indications for RLE are as follows:

- Refractive errors with associated lens opacities (even early), especially in presbyopic age.
- High refractive error, myopia of >10 D and hyperopia of >5 D in patients older than 40 years are ideal for RLE. Hyperopes in presbyopic age are the best candidates.

Contraindications for RLE are as follows:

- *Retinal diseases* that are potentially vision-impairing (macular degeneration, peripheral degenerations, retinal breaks, etc.) should be considered as a contraindication for RLE, because both multi-focal and accommodative IOLs represent some kind of slight compromise for the patient's vision.
- *Occupational night drivers.*
- Patients with unrealistic expectation or those who seem hypercritical should better be excluded.

Choice of IOL During RLE

Various options available with their advantages and disadvantages are as follows:

Traditional monofocal IOLs. These lenses, yet very effective in providing the patients with one optimal focusing distance (either at distance, intermediate or near), require additional spectacle correction to correct vision at all other distances.

Multi-focal IOLs. These provide a good uncorrected distance and near vision. The multi-focal IOLs are available in diffractive and refractive models.

- *Refractive IOLs* like the AMO Array (Fig. 11.14A) are very pupil-dependent in their distance and near vision performance.
- *Diffractive IOLs* like the AMO Tecnis (Fig. 11.14B) are less pupil-dependent. Disadvantages of multi-focal IOLs are the loss of contrast sensitivity and the inducement of glare and halos from light sources during night vision, which more commonly occur with diffractive IOLs.

Pseudoaccommodative IOLs, e.g. AcrySof ReSTOR (Fig. 11.14C) from Alcon with its apodized diffractive optics, are even less pupil size-dependent and perform better than the refractive and diffractive multi-focal IOLs as regards night vision, but like them they do not provide excellent intermediate computer distance vision.

Accommodative IOLs which move anteriorly during near vision include:

- Eyeonics Crystalens (Fig. 11.14D) and
- Human Optics, Akkommodative IOL.

The unpredictability in terms of amplitude of accommodation, incidence of PCO and long-term centration are issues which need to be settled before the accommodative IOLs gain widespread popularity.

Important Considerations for RLE

RLE, being a refractive procedure, cannot be compared to conventional cataract surgery with IOL implantation. Certain important considerations for RLE are as follows:

1. ***Thorough preoperative ocular examination.*** Whenever surgery on the clear lens is contemplated, the eye is examined thoroughly for any other abnormality, like raised IOP, vitreous degeneration and retinal degeneration. In myopes, these precautions are especially important. It is common to find abnormalities in the peripheral retina, like lattice degeneration

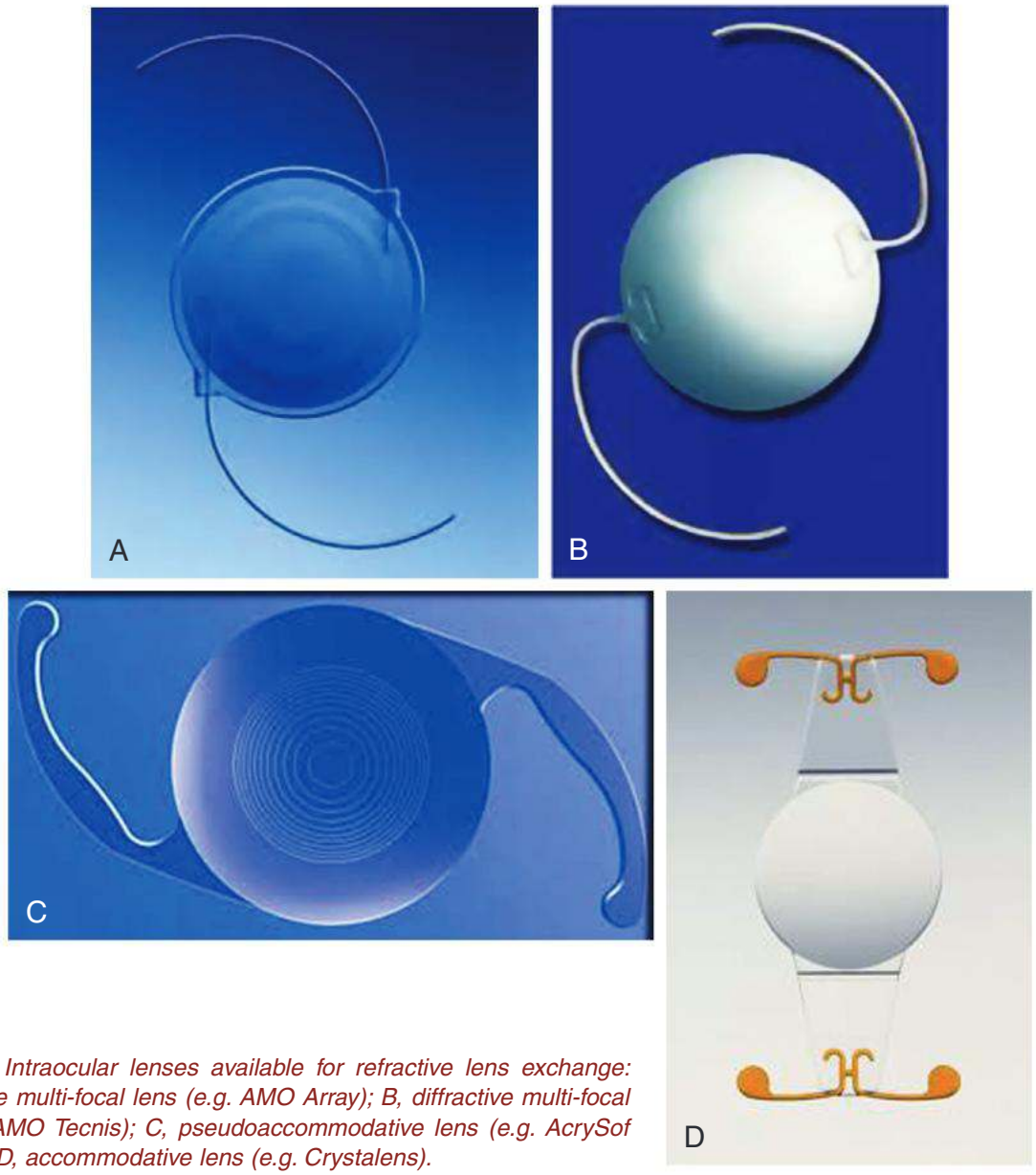


Fig. 11.14 *Intraocular lenses available for refractive lens exchange: A, refractive multi-focal lens (e.g. AMO Array); B, diffractive multi-focal lens (e.g. AMO Tecnis); C, pseudoaccommodative lens (e.g. AcrySof ReSTOR); D, accommodative lens (e.g. Crystalens).*

with or without hole formation. Before any kind of refractive surgery is done, these dangerous lesions are treated by sealing with argon laser or diode laser. In the absence of the lasers, these lesions can be treated by the application of cryoprobe. The important point is that the retina is to be treated by a specialist who is trained for retina work. The presence of macular degeneration rules out good visual acuity after any kind of refractive surgery. However, the patient is likely to get good field of vision.

2. ***IOL power calculation*** should be very-very accurate. Points to be considered:
   - Immersion biometry is better than contact biometry.
   - Optical interferometry-based biometry (Zeiss IOL Master) provides most accurate reading.
   - The best formula to calculate IOL power for myopia is SRKt and that for hyperopia is the Holladay-II.

3. ***Surgical techniques*** need to be very meticulous and flawless. Capsulorrhexis has to be

round, regular and slightly smaller than the IOL optics to allow better centration. Being the refractive surgery, special emphasis should be on the control of surgically induced astigmatism.

Femtosecond Laser-Assisted Cataract Surgery

Femtosecond Laser-Assisted Cataract Surgery (FLACS) technique is technologically more advanced than the conventional phacoemulsification and microincision cataract extraction (MICS), and so should be preferred for RLE procedure.

Commercially available femtosecond laser-based cataract surgery systems include:

- LenSx (Alcon),
- LenSar (Winter Park, Florida, USA),
- Catalys (Optimedica) and
- Victus Technolas (Femtec Technology Perfect Vision, Bausch & Lomb).

Conclusion. The immediate and late postoperative problems are the same as for the cataract cases. While this surgical approach has the potential to correct a wide range of refractive errors, technical complications and a higher incidence of postoperative retinal detachments has minimized its acceptance in non-cataract patients. However, recent advances in the microsurgical technique, IOL power calculations and IOL designs may make RLE a well sought-for refractive procedure.

PHAKIC REFRACTIVE LENSES

PRLs were thought of by Strampelli in 1954. However, it is recently that they are being considered as a refractive procedure. In this refractive surgery, an IOL of appropriate power is implanted inside the eye, without touching the normal crystalline lens, thus without disturbing the accommodation. ***Both myopia and hypermetropia*** can be corrected by this technique. Phakic lens implantation is a job of great responsibility. With advances in the field of microsurgical technique, phakic lens implantation is becoming very popular for correction of refractive errors, especially of higher degree, e.g. myopia >8 D and hypermetropia >6 D.

Types of Phakic IOLs

The following types of IOLs are used for correcting refractive errors as phakic IOLs.

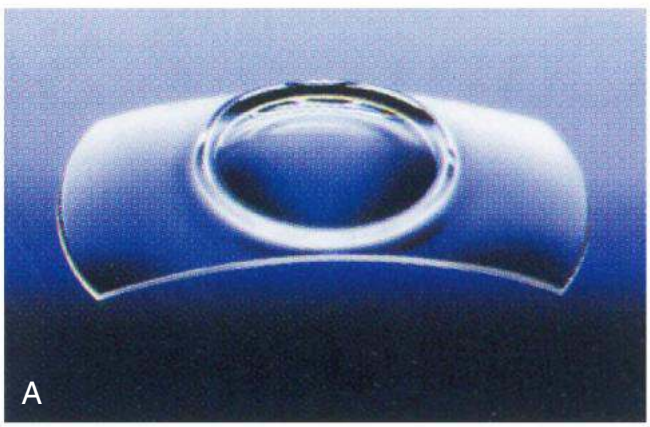
1. ***Posterior chamber lens*** (thin and soft) of plus or minus power is implanted between the back of the iris and the front of the crystalline lens. It is being miscalled as 'implantable contact lens'. The posterior chamber lens is designed to vault the crystalline lens to decrease the likelihood of contact with the crystalline lens and to reduce the potential for cataract formation. An iridectomy/iridotomy must be performed to reduce the potential for postoperative pupillary block. As phakic IOLs and surgeons' skill levels continue to improve, it seems likely that posterior chamber phakic lens implants will become more prevalent in the future. Intraocular inflammation and late cataract formation are important considerations. Adhesion formation makes it difficult to remove, if need be.

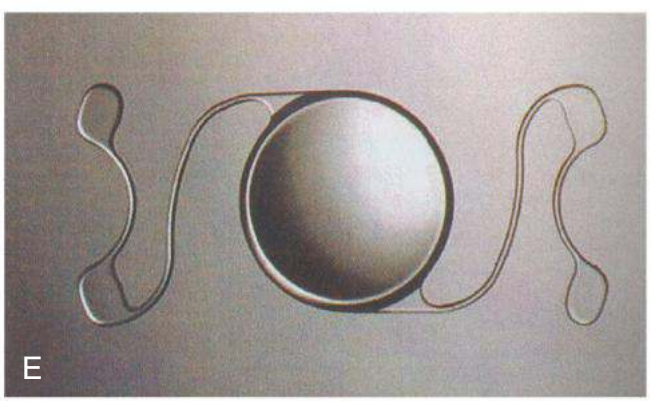
Posterior chamber PRLs best known as of today are as follows:

i. *ICL by Staar Surgical AG, Nidan, Switzerland*
   - Made of hydrogel–collagen copolymer (Collamer), a UV-absorbing material
   - Plate haptic design with a forward vault to minimize IOL-crystalline lens touch
   - A foldable lens which can be implanted through a 3 mm or smaller incision
   - Available from –3.0 to –20.0 D for myopia and +3 to +20 D for hyperopia

ii. *PRL by IVI-Medennium, Irvine, CA* (Fig. 11.15A)
   - A foldable lens made of silicone
   - Available from –4.0 to –22 D for myopia and from +3.0 to +16.0 D for hyperopia

iii. *EVO ICL is available in two forms:*
   - *EVO ICL* surgery correct myopia –3.0 D to –15.0 D, and partially correct myopia up to -20.0 D in eyes with up to 2.5 D of astigmatism.
   - EVO TICL surgery can safely correct myopia between –3.0 D and –15.0 D and astigmatism between 1.0 D and 4.0 D, and partially correct myopia greater than –15.0 D up to –20.0 D, and astigmatism between 1.0 D and 4.0 D.





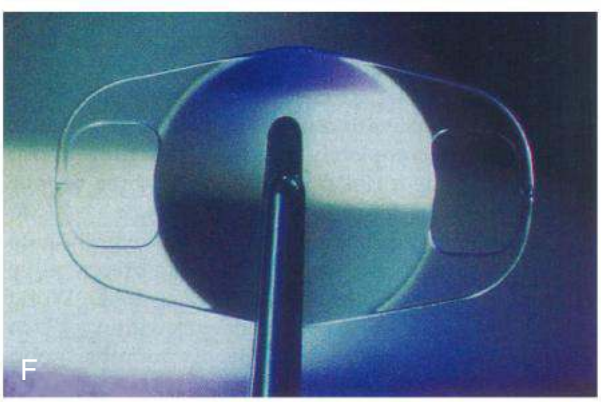


Fig. 11.15 *Phakic Refractive lenses: A, PRL by IVI-Medennium, Irvine, CA; B, IPCL V2.0; C, Eyecryl Phakic IOL; D, RIL Phakic IOL; E, Angle Supported Anterior Chamber PRL, NUVITA MA20; F, Iris Supported PRL (Artisan); G, Iris Claw Lens (Artiflex).*

These lenses have strategically placed holes in the implant to reduce the risk of increased IOP and glaucoma.

iv. *Implantable phakic contact lens (IPCL) (Care Group Sight Solutions Ltd*)

IPCL V2.0 is like a soft contact lens, single piece posterior chamber phakic IOL (aspheric optic), which can be inserted into the eye through sub 2.8 mm incision. IT is made from reinforced hybrid hydrophilic acrylic material to ensure long-term performance (Fig. 11.15B).

IPCL V2.0 portfolio offers the widest range on the market, customizing to as high as +15 D and –30 D. Astigmatic correction +0.50 D to +10.00 D (in 0.5 D Steps) with option for addition for near +1.00 D to +4.00 D (in 0.5 D Steps).

The lens is customized according to the shape and size of each eye.

v. ***Eyecryl phakic and eyecryl phakic toric IOLs***

- *Eyecryl Phakic Intraocular Lens (IOL)* is a monofocal hydrophilic acrylic foldable single-piece posterior chamber intraocular lens for implantation in ciliary sulcus. It is available in dioptric range of +10 to –25 D (Fig. 11.15C).
- *Eyecryl Phakic TORIC Intraocular Lens (IOL)* is a monofocal hydrophilic acrylic foldable single-piece posterior chamber intraocular lens for implantation in the ciliary sulcus for correction or reduction of myopia/hyperopia with astigmatism with a dioptric range of +8 to –25 with cylindrical power range of +0.5 D to +5 D.

vi. *RIL Spherical and Toric Lens*

- Refractive Implantable Lens (RIL), manufactured by Appasamy Associates, is a single-piece foldable phakic IOL, placed in sulcus of the eye in front of natural lens to correct myopia, hypermetropia and astigmatism. It is made up of Biocompatible Acrylic Hydrophilic (26%) material to ensure long-term performance. Refractive Implantable Lens has power range from –1 D to –23 D for myopic correction and 0–10 D for hypermetropic correction (Fig. 11.15D).

2. ***Angle-supported anterior chamber PRL,*** best known as of today is the NUVITA MA 20 (third-generation Baikoff lens design from Bausch & Lomb surgical, Lyon, France) (Fig. 11.15E).

- It is a derivative of the Kelmanaphakic anterior chamber IOL with a four-point support in the anterior chamber angle.
- Optic portion is 5 mm in diameter with effective optical zone of 4.5 mm.
- Available to treat myopia between –7 and –20 D.

This lens has long legs (haptics) that engage in the angle of the anterior chamber, while the optic stays in front of the pupil. This lens has undergone three modifications in the past 7 years to overcome the corneal endothelial damage and shrinkage of the iris periphery, which later leads to a continued elongation of the pupil in over 10% of the cases. Intraocular inflammation and glaucoma are other long-term worries with this kind of lens. *Because of higher incidence of postoperative complications, these lenses are currently not implanted.*

3. ***Iris claw lens.*** Iris-supported PRL, best known as of today is under the trade name *Artisan lens* (Ophtec BV, Groningen, the Netherlands) (Fig. 11.15F).

- Made of UV-absorbing PMMA.
- Total length 8.5 mm, optic zone diameter of 5 and 6 mm.
- Available from –0.5 to –20 D for myopia and from +3 to +12 D for hyperopia with other PRLs.

It is a lens in which there are small haptics on two opposite sides of the optic, fashioned as claws. These claws catch the iris tissue on both sides of the pupil. This lens had the longest trials for phakic eyes in Europe and India for over 18 years before it was introduced in the USA in 1997 as a lens for the phakic eyes. The surgical technique of implantation of this lens is not too difficult, provided it has been learnt from an expert. The lens does not produce angle-related or crystalline lens-related complications.

ARTIFLEX (OPHTEC) is a foldable iris claw fixated phakic intraocular lens, meant for the

correction of refractive errors (Fig. 11.15G). It is designed to be far away from the natural lens to avoid cataract formation. It offers great flow dynamics for the aqueous humor helping to prevent high intraocular pressure. Optic material is Polysiloxane and Haptic material is PMMA. It is available as:

- ARTIFLEX Myopia –14.5 to –2.0 D, and
- ARTIFLEX Toric –13.5 to –1.0 D (Sphere) 5.0 to –1.0 D (Cylinder).

Advantages and Disadvantages

Advantages of PRLs:

- Safe
- Predictable
- Reversible
- Inexpensive equipment
- LASIK can be performed for residual refractive error (*bioptics*)

Disadvantages include risk of potential complications such as corneal endothelial decompensation, chronic uveitis, cataract formation, retinal detachment and endophthalmitis.

Conclusion. Despite potential complications, the preliminary results of the three leading PRL are quite promising. Nonetheless, the notation of a built-in lens to correct refractive error is quite exciting when compared to subtractive procedures such as excimer laser photoablation for higher correction.

C. COMBINED LENS-BASED AND CORNEA-BASED REFRACTIVE PROCEDURES

Rarely, in the presence of very high refractive error, when one refractive procedure alone is not sufficient, a combination of two *(bioptics)* or three procedures *(trioptics)* is required for optimum results.

BIOPTICS

Bioptics options include:

- RLE with LRI to correct astigmatism,
- RLE with post-op LASIK to correct residual refractive error and
- Phakic IOL followed by LASIK to correct residual refractive error.

TRIOPTICS

Trioptics options include:

- Toric IOL in the bag, multi-focal IOL in the sulcus followed by LASIK for residual refractive error and
- Piggyback IOL followed by LASIK for residual refractive error.

SUMMARY

As of today, the refractive procedures of choice for myopia are as follows:

Low to moderate myopia: –1 to –8 D

- LASIK/C-LASIK: –1 to –8 D
- Epi-LASIK: Thin corneas (1–6 D) and normal cornea (–1 to –10 D)
- Intacs: –1 to –3 D
- Orthokeratology: –1 to –3 D below 18 years of age

High myopia: >8 D

- PRL (preferred under 40 years of age)
- RLE (preferred after 40 years of age)

Combined lens-based and cornea-based refractive surgery as per indication as mentioned above.

REFRACTIVE SURGERY FOR ASTIGMATISM

Refractive surgical techniques employed for myopia can be adapted to correct astigmatism alone or simultaneously with myopia as follows.

INCISIONAL REFRACTIVE PROCEDURES

ASTIGMATIC KERATOTOMY

AK refers to making transverse or arcuate cuts in the mid periphery perpendicular to the steepest corneal meridian (Fig. 11.16A). The AK can be performed alone for astigmatism only.

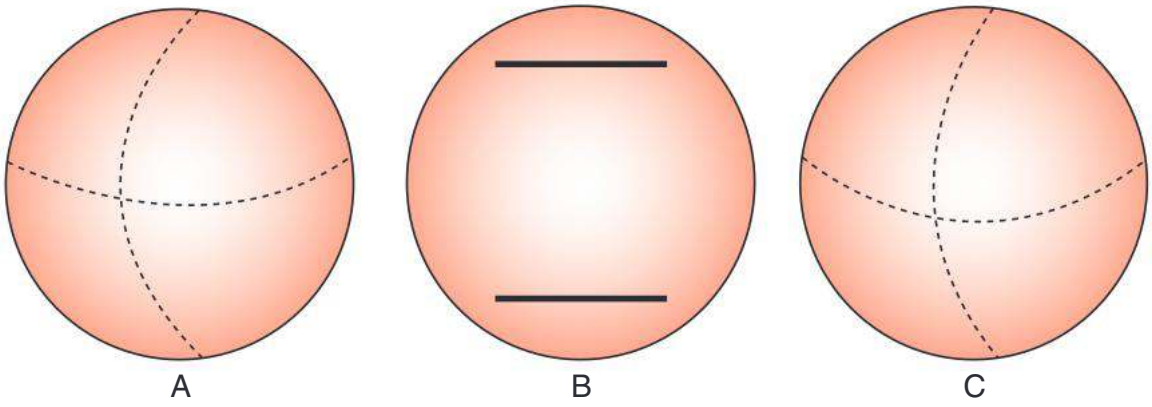


Fig. 11.16 *Astigmatic keratotomy: A, showing flat and deep meridians of cornea; B, paired transverse incisions to flatten the steep meridian; C, showing correction of astigmatism after astigmatic keratotomy.*

This procedure is commonly used in conjunction with cataract surgery.

Mechanism of AK. The incised meridian flattens while the meridian 90 degrees away steepens by nearly the same amount. The AK can correct astigmatism up to 4–6 D. The deeper, longer and more centrally located incisions give greater effect but increase the risk of irregular astigmatism, microperforations and overcorrection.

Technique of AK. Incisions are ideally between 5 and 7 mm from the centre of pupil. Nomograms exist to adjust surgery for patient's age and amount of astigmatism. AK can be performed using transverse or arcuate incisions as given:

1. *Transverse incisions* (Fig. 11.16B). These are usually done in pairs along the steepest meridian and extend for 3 mm. Sometimes a second pair may be added to the same meridian for greater effect. Since the transverse incisions are tangential to a given optical zone size, incremental flattening power decreases accordingly as the incision is lengthened.
2. *Arcuate incisions* (Fig. 11.17), i.e. the clear corneal incisions (CCI) remain at a constant distance from the centre of pupil at any length and may be more effective than transverse cuts at a given optical zone size. The flattening effect increases with the length of incision up to a maximum length of 90 degrees.

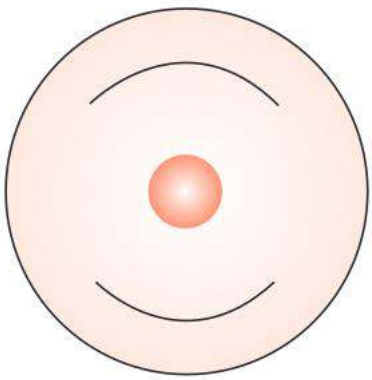


Fig. 11.17 *Paired arcuate incisions, i.e. clear corneal incisions (CCI) to flatten the steep meridian.*

■ LIMBAL RELAXING INCISION

LRI is a procedure used to correct mild (–1.00 to –2.00) astigmatism. This procedure produces less glare and discomfort than AK. The incisions heal faster and optical quality of the cornea is preserved by making incisions at the limbus. The procedure is more safe and easy to incorporate with cataract extraction.

LASER ABLATION CORNEAL REFRACTIVE PROCEDURES

Photoastigmatic Refractive Keratotomy

Photoastigmatic refractive keratotomy uses a cylindrical rather than a spherical ablation pattern to remove a tissue in a chosen meridian (Fig. 11.18). The axis of astigmatism should be marked with the patient seated, because it may shift when the patient reclines. If compound

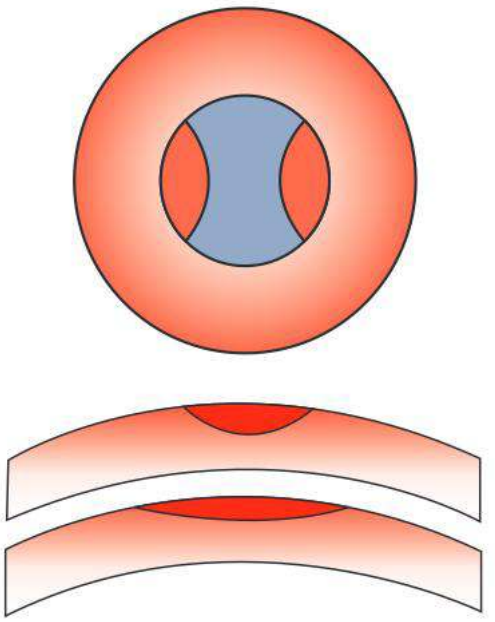


Fig. 11.18 *Photoastigmatic refractive keratotomy to correct astigmatism.*

myopic astigmatism is present, an elliptical PRK ablation (a combination of spherical and cylindrical patterns) results in correction of both myopia and astigmatism.

Astigmatic Epi-LASIK

Presently, astigmatic epi-LASIK is preferred to astigmatic PRK because of its advantages described earlier (see page 417).

Astigmatic LASIK

Like PRK, the LASIK procedure can also be adopted to correct astigmatism. Presently astigmatism of 0.5–10.0 D is amenable to correction with LASIK.

Astigmatic C-LASIK

Wavefront-guided C-LASIK is presently the best technique to treat corneal astigmatism. (For details see page 418.)

MANAGEMENT OF POST-KERATOPLASTY ASTIGMATISM

1. Suture Removal

- Selective suture removal in steep meridians may improve a varying degree of both regular and irregular astigmatism.
- Interrupted sutures may be removed 3 months onwards depending upon the amount of astigmatism.
- Continuous sutures should preferably be removed after 1 year of surgery.
- By measuring the central cornea with the keratometer and examining the central and the peripheral graft with keratoscope, one can often determine exactly which sutures need to be removed. Near a tight suture, the keratoscopic mires are closer together and may demonstrate a 'V' indentation vector (Fig. 11.19).

Note. Suture removal should be tried first of all and all other procedures mentioned below should be performed only after all the sutures are out and refraction is stable with a significant astigmatism.

2. Relaxing Incisions

- Arcuate relaxing incisions along the steeper meridian in the donor cornea 0.5 mm central to host–graft junction are reported to correct astigmatism of 3.5–8.5 D (average 4.25 D).
- Relaxing incisions may be made under topical anaesthesia, using a sharp razor blade fragment or a bearer blade or a diamond knife.
- Two relaxing incisions involving 60%–70% corneal depth are made 180 degrees apart. Depending upon the amount of astigmatism, the incisions may extend 60–100 degree area.

3. Astigmatic LASIK.

LASIK procedure can also be adopted to correct astigmatism of about 6–8 D. Wavefront-guided C-LASIK is presently the best technique to take care of the post-keratoplasty astigmatism.

4. Relaxing Incisions With Compression Sutures

- Relaxing incisions with compression sutures are reported to correct astigmatism of 8.5–16.0 D (average 10.0 D).
- After making relaxing incisions as described above, two or three 10–0 nylon sutures are applied at the host–graft junction 90 degrees away from the steepest meridian on each side (Fig. 11.20).

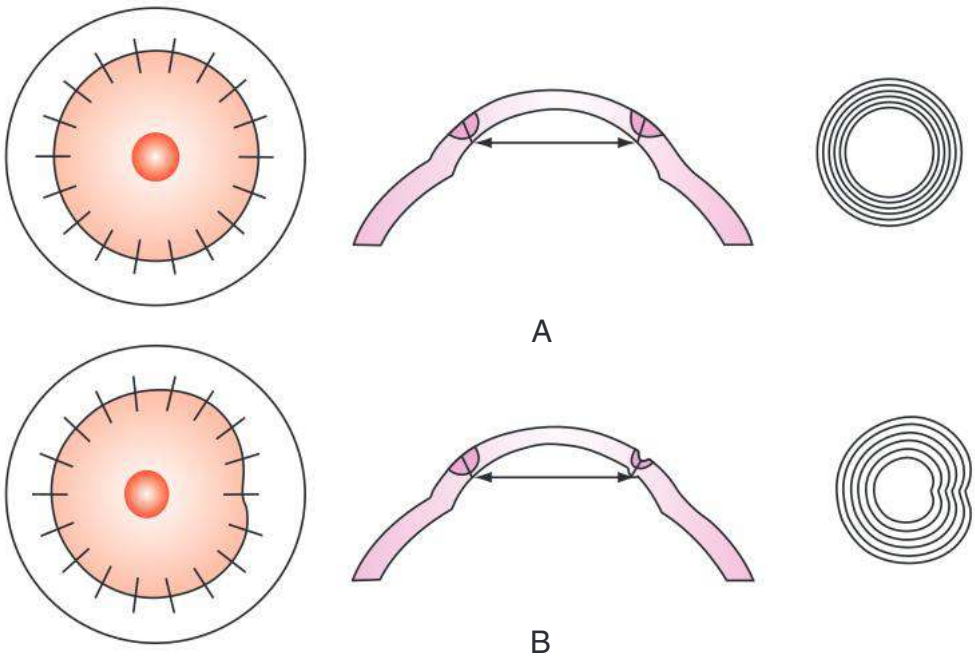


Fig. 11.19 *Effect of suture on keratoscopic picture after penetrating keratoplasty: A, no astigmatism is induced; B, astigmatism induced by a light suture.*

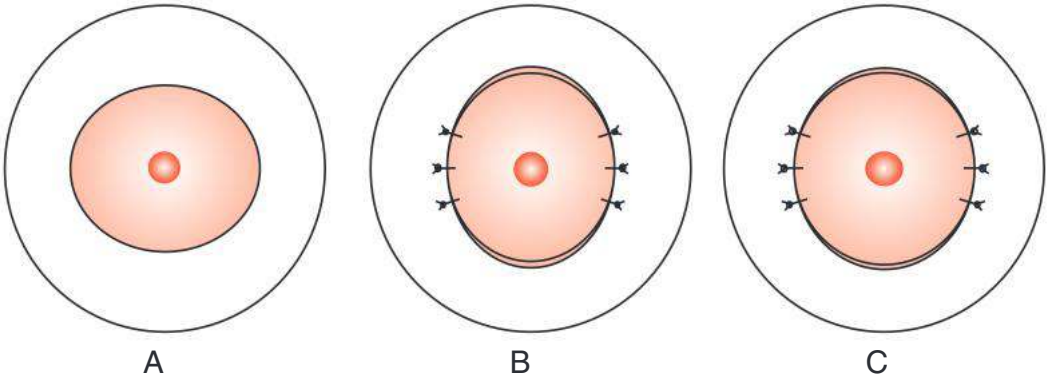


Fig. 11.20 *Relaxing incisions (RI) with compression sutures (CS) to correct astigmatism: A, pre-relaxing incision; B, immediately following RI with sutures; C, 1 month after RI and CS.*

5. Corneal Wedge Resection

This procedure may be tried to correct astigmatism of 10–20 D before repeating the penetrating keratoplasty. Under peribulbar block, a corneal wedge of 1.0- to 1.5-mm-wide base and 90 degree in extent is removed from the recipient cornea adjacent to host–graft junction in the flattest meridian. The gap created is sutured (Fig. 11.21) by five to seven, deep interrupted 10–0 nylon or prolene sutures. The sutures are tightened enough to achieve an overcorrection of about one-third of the existing astigmatism.

6. Ruiz Procedure

If a wedge resection fails or if the patient has a highly myopic spherical equivalent or if significant anisometropia exists such as post-keratoplasty eye with more myopic eye, the Ruiz procedure can be attempted. This may be effective in correcting up to 10 D of corneal astigmatism while changing the spherical equivalent towards hyperopia.

In Ruiz procedure, deep horizontal keratotomy incisions are made with a guarded diamond blade in a 'step-ladder' configuration,

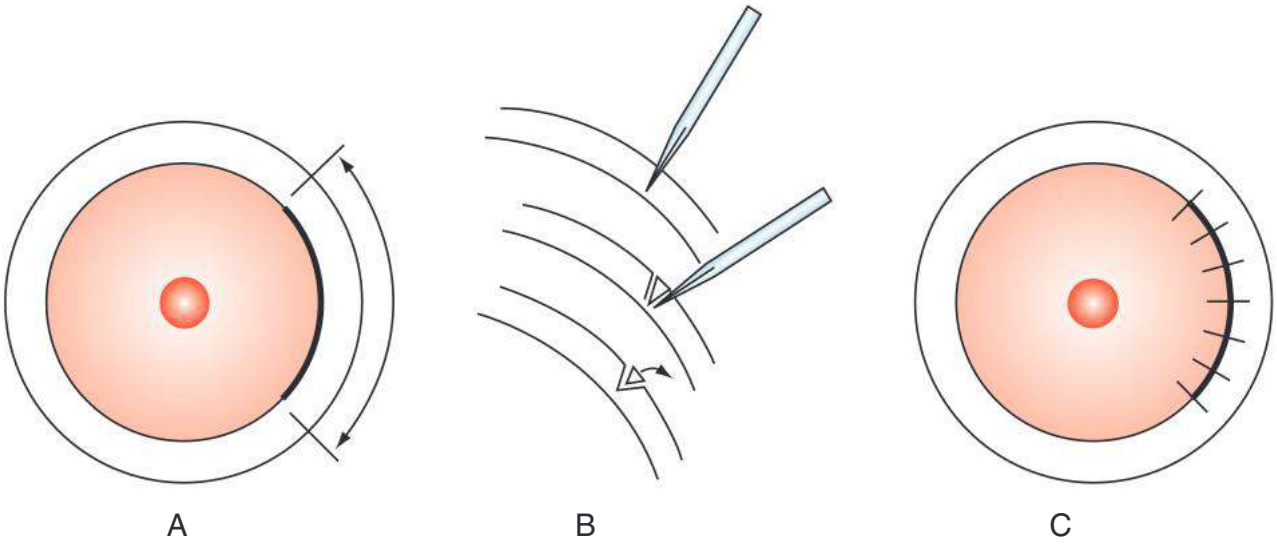


Fig. 11.21 *Corneal wedge resection: A, wedge is removed up to 90 degrees extent in the flattest meridian; B, technique of resecting wedge; C, gap is sutured.*

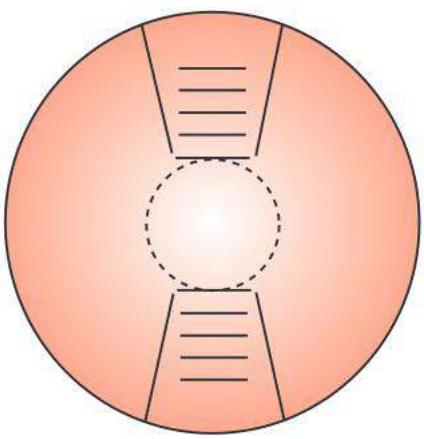


Fig. 11.22 *Ruiz procedure.*

along the axis of the steepest corneal meridian. Each set of horizontal incisions is flanked by two adjacent radial incisions (Fig. 11.22). It is important to ensure that the horizontal and radial incisions do not intersect as this causes gaping and poor wound healing.

Although this procedure may be effective in reducing post-keratoplasty astigmatism, the results are highly variable.

7. Repeat Penetrating Keratoplasty

Repeat penetrating keratoplasty is recommended in patients having astigmatism of more than 20 D or when the corneal wedge resection and/or Ruiz procedure fail to correct the astigmatism.

REFRACTIVE SURGERY FOR HYPERMETROPIA

In general, refractive surgery for hypermetropia is not as effective or reliable as for myopia. However, the general principles of patient selection and preoperative evaluation are the same as for myopia. The following surgical procedures are being tried for hypermetropia.

A. KERATOREFRACTIVE PROCEDURES

I. INCISIONAL REFRACTIVE PROCEDURE

Hexagonal Keratotomy

Hexagonal keratotomy has been reported to correct low to moderate degrees of hypermetropia. The risk/benefit ratio of hexagonal keratotomy is not low enough to warrant its continued use.

II. LAMELLAR CORNEAL REFRACTIVE PROCEDURES FOR HYPERMETROPIA

HKM and its modifications have been tried in the past but never became popular and are ***obsolete***. It is just mentioned as a tribute to pioneer workers who formed the basis of present successful procedures.

III. LASER ABLATION CORNEAL REFRACTIVE PROCEDURES FOR HYPEROPIA

The laser-based corneal refractive procedures for hyperopia include:

- Hyperopic PRK
- Hyperopic LASEK and epi-LASIK
- Hyperopic LASIK
- Hyperopic C-LASIK

Hyperopic PRK

Hyperopic PRK (Fig. 11.23) using excimer laser has also been tried. The laser is used to create a large, doughnut-shaped ablation that requires a large epithelial defect (usually 9 mm or even more). A 3 D hypermetrope requires three times as many laser spots as a 3 D myope. Thus, the procedure becomes lengthy and may lead to dehydration and decentration. Also, the epithelial healing time is prolonged postoperatively.

Although initial results are encouraging, regression effect is often frustrating.

Hyperopic epi-LASIK

Presently hyperopic epi-LASIK is preferred to PRK because of its advantages described earlier (see page 417).

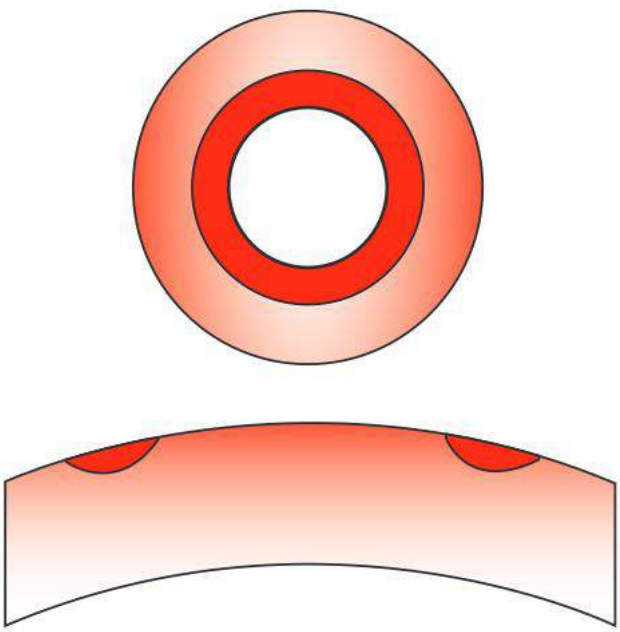


Fig. 11.23 *Hyperopic photorefractive keratectomy.*

Hyperopic LASIK

The LASIK surgeons now claim to correct a hypermetropia of 1–8 D. Principles of LASIK surgery have been described in myopic LASIK.

Hyperopic C-LASIK

Hyperopic C-LASIK is being considered better than conventional hyperopic LASIK.

IV. CORNEAL SHRINKAGE REFRACTIVE PROCEDURES FOR HYPEROPIA

Thermal Laser Keratoplasty

TLK is a non-destructive laser-based modality for the correction of hyperopia and presbyopia. TLK projects the mid-infrared coherent energy on the Thallium–Holmium–Chromium (THC): YAG laser in eight simultaneous emissions by means of a conventional non-contact slit-lamp delivery system.

These eight spots incident upon the cornea at optical zones of 6 and 7 mm result in thermal contraction of the collagen matrix in the mid-stroma, forming a constrictive band. It is this mechanical constriction that results in a steepening of the front surface radius, correcting the hyperopia. The current study is based on treatment of patients over the age of 40 years with hyperopia of 0.75–2.5 D.

Some 30% of the patients treated by this method have retained functional near vision in the correction of presbyopia as well. The entire procedure requires approximately 2.8 s and the effect is immediate. Recent evaluations of the FDA-monitored studies have indicated an 84% success rate in restoring 20/40 or better vision in hyperopic patients. No complications or adverse events have been reported.

Conductive Keratoplasty

CK discovered by Mendez is a non-laser refractive procedure to correct hyperopia and presbyopia. It uses radiofrequency energy to gently heat and shrink corneal collagen tissue at specific treatment points to create a band of tightening. This band reshapes and steepens the cornea to correct hyperopia and/or presbyopia. It is a revolutionary procedure that presents convincing advantages over hyperopic LASIK

and hyperopic correction via laser thermal keratoplasty (LTK).

Indications. CK is recommended in the following conditions in patients who are ≥40 years of age and have a stable refraction:

1. Hyperopia from +0.75 to +3.25 D with –0.75 D or less of astigmatism
2. Presbyopia

CK equipment. Equipment required to perform CK include the following:

1. *ViewPoint CK device* (Fig. 11.24) is a radiofrequency energy-generating system comprising:
   - Console.
   - Handpiece is a reusable, pen-shaped structure that is attached with console by a removable cable and connector.
   - *Keratoplast tip* is a single-use, disposable stainless steel needle which is attached to the handpiece (probe). It is 90 μm in diameter and 450 μm long and delivers the current directly to the corneal stroma. A cuff on it ensures correct depth of penetration.
   - *Foot pedal* controls the release of energy.
2. *Corneal marker* to define treatment spots in a ring pattern.
3. *Lid speculum* to properly expose the cornea.

Fig. 11.24 *ViewPoint conductive keratoplasty system.*

Preoperative work-up for CK includes:

- Slit-lamp biomicroscopy,
- Keratometry,
- Pachymetry,
- Corneal topography,
- Dominance assessment,
- Near and distance vision,
- Refraction, far and near and
- Monovision tolerance assessment.

Procedure of CK performed under operating microscope involves the following steps:

- *Topical anaesthesia* is achieved with proparacaine, a drop instilled three times at 5 min intervals.
- *Corneal exposure* is obtained with a lid speculum which also provides an electrical return path.
- *Marking of cornea* is done with a corneal marker using gentian-violet ink. The corneal marker should be centred carefully on the cornea to avoid induction of astigmatism.
- *Application of radiofrequency energy* to the cornea is then done by inserting the keratoplast tip into the stoma at defined spots in a ring pattern around the peripheral cornea as per nomogram depicted in Table 11.3 and Figure 11.25.

Table 11.3 *Application nomogram for conductive keratoplasty*

Spherical equivalent (D)	Number of treatment spots			
	First ring of 6 mm diameter	Second ring of 7 mm diameter	Third ring of 8 mm diameter	Total
0.75–0.875	—	8	—	8
1.00–1.625	8	8	—	16
1.75–2.25	8	8	8	24
2.375–3.00	8	16	8	32

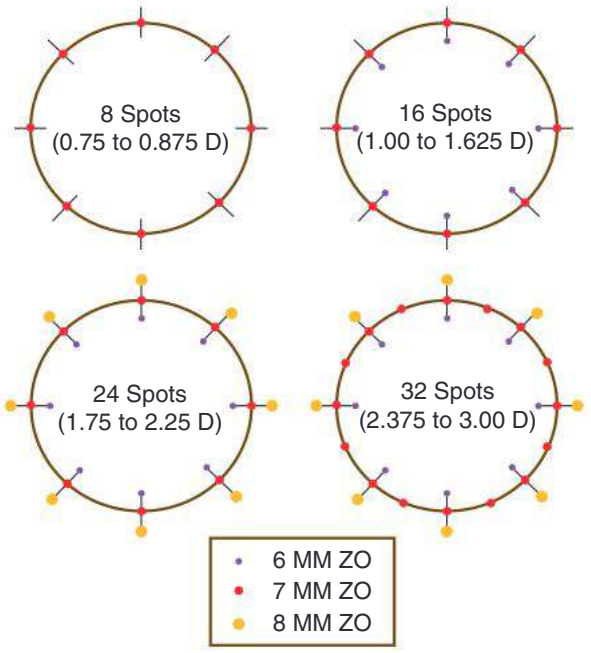


Fig. 11.25 *Diagrammatic depiction of conductive keratoplasty nomogram.*

Important considerations during application of energy are as follows:

- Keratoplast tip should be perpendicular to the corneal surface to ensure full depth penetration.
- Minimal pressure should be applied to cornea while delivery of energy (Light touch technique as shown in Fig. 11.26).
- Spots should be applied smoothly and evenly.
- Treatment application of 0.6 s per spot is required.
- Begin treatment at a 12 o'clock position and continue following the sequence as shown in Figure 11.27, until the full ring of spots has been completed for that optical zone.
- Treatment spots of second and third ring should be aligned precisely with those of first ring in such a way that the spots in each ring just barely touch each other.

Footprint after CK is cylindrical (cf. conical after LTK) and extends deep into the stroma to approximately 80% depth (Fig. 11.28). This is because in CK the corneal tissue is exposed to same temperature at the bottom of the probe as well as at the corneal surface.

Postoperative treatment and follow-up schedule is as follows:

- Antibiotic/steroid eyedrops four times a day for 10–15 days.
- Artificial tears to be used four to five times per day for about a month.
- Patients are seen postoperatively on day 1; week 1, 3, 6 and 12.

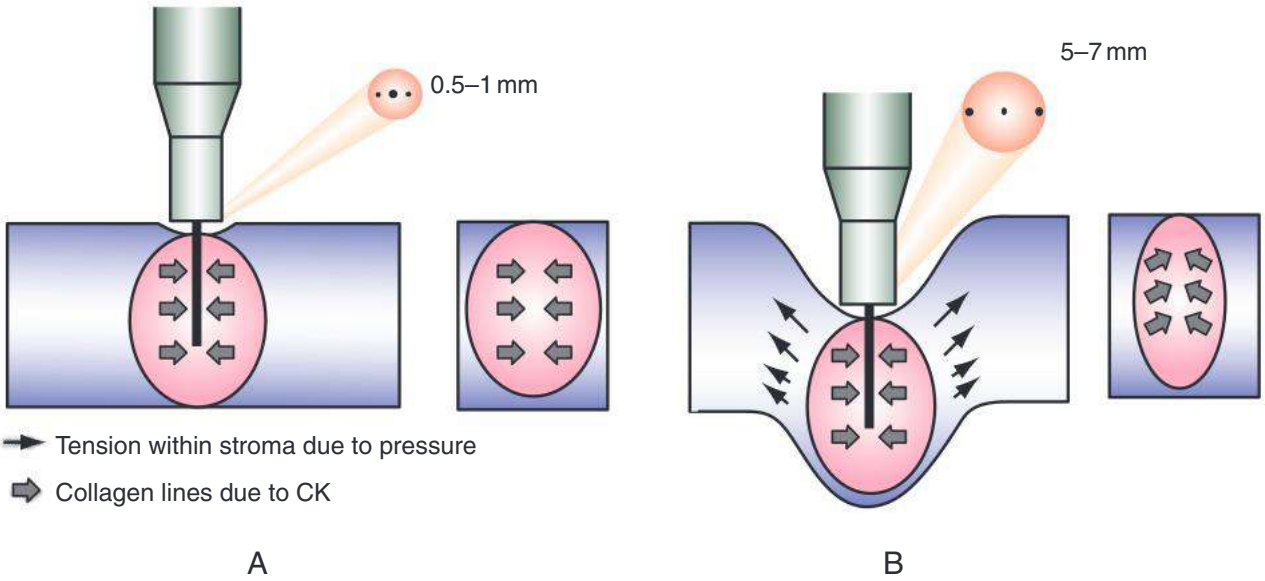


Fig. 11.26 *Ideal light touch technique (A) and wrong heavy touch technique (B) for delivering energy in conductive keratoplasty.*

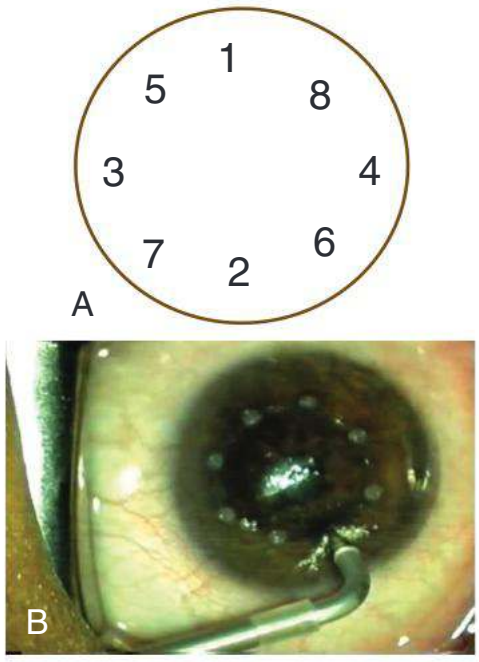


Fig. 11.27 *Sequence of spots for delivering energy in conductive keratoplasty: A, diagrammatic; B, clinical photograph.*

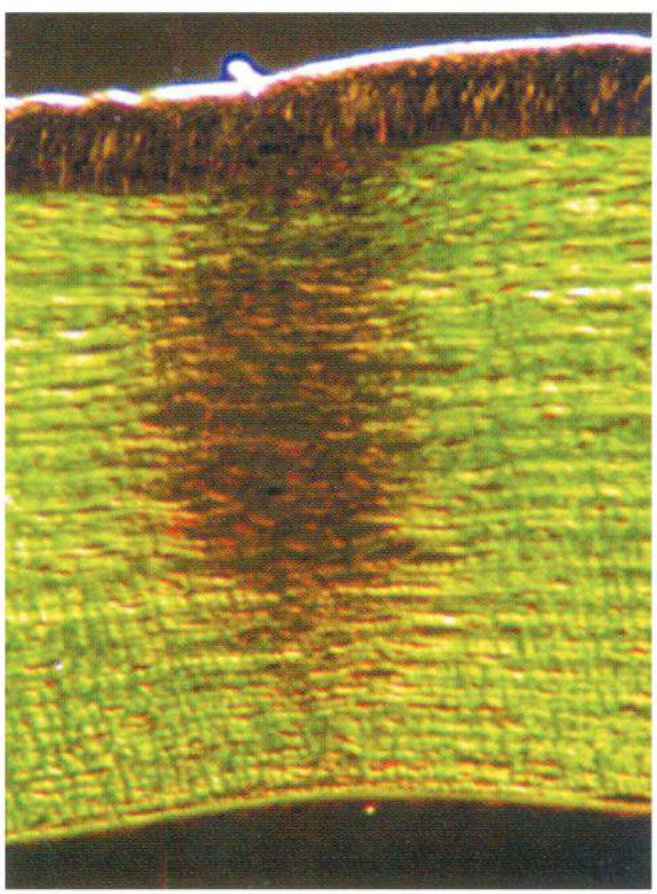


Fig. 11.28 *Footprint of conductive keratoplasty.*

Note. Vision begins to improve within a week's time.

Advantages:

- Minimally invasive, safe and effective for hyperopia and presbyopia of up to 3 D.
- Disadvantages typically associated with monovision do not occur with presbyopic CK, i.e. depth perception is maintained, binocular corrected distance acuity is usually better than preoperative levels, contrast sensitivity is not lost from preoperative levels.

Disadvantages:

- *Not effective* in hyperopia of >4.0 D and >0.75 D of astigmatism.
- *Regression* may occur at a rate of about 1.0 D every 2–3 years after the 6 months' initial healing period. Most patients may need to be re-treated every 2–3 years or about the same frequency that they would have changed their reading glasses.
- *Not reversible* per se, though regression occurs with time.
- Safety and effectiveness of CK has yet not been established in eyes with diseases of cornea, previous surgery or injury to the cornea, intraocular surgery and history of glaucoma.
- *Complications*, such as recurrent corneal erosions, corneal perforation, mild iritis, decrease of best corrected visual acuity of >2 lines, though rare but do occur.

■ V. HYPEROPIC SMILE

Although attempts have been made to provide hyperopic SMILE treatments in the form of endokeratophakia, these treatment modalities have yet to be standardized and made widely available

B. INTRAOCULAR REFRACTIVE PROCEDURES FOR HYPEROPIA

Phakic refractive lenses (PRL).

PRLs are also being considered for correction of hyperopia. (For details see page 430.)

Refractive lens exchange (RLE).

This is a very good option for high hypermetropia in presbyopic age. (For details see page 427.)

SUMMARY

Presently, the following refractive procedures are being considered to treat hyperopia:

- CK: +1 to +4 D
- LASIK/C-LASIK/epi-LASIK: +1 to 5 D
- PRLs: +4 to 10 D
- RLE: >10 D

REFRACTIVE SURGERY FOR PRESBYOPIA

A. CORNEAL PROCEDURES

I. NON-ABLATIVE CORNEAL PROCEDURES

1. ***Monovision CK*** is being considered a safe and effective non-incisional and non-ablative corneal procedure performed on non-dominant eye for treatment of presbyopia. (For details see page 438.)
2. ***Laser thermal keratoplasty or LTK*** has been discarded in favour of CK.

II. LASER ABLATION CORNEAL PROCEDURES

1. ***Monovision hyperopic or myopic LASIK/C-LASIK/epi-LASIK,*** i.e. one eye is corrected for distance vision and other for near vision depending upon the associated refractive error. (For details see page 324.)
2. ***Presbyopic bifocal LASIK or LASIK-PARM,*** i.e. LASIK for presbyopia by Avalos Rozakis method. It is a technique in which the shape of cornea is altered to have two concentric vision zones that help the presbyopic patient to focus on near and distant objects.

Main steps of bifocal presbyopic LASIK are as follows:

- *Corneal flap* of between 8.5 and 9.5 mm is made (Fig. 11.29A).
- *Hyperopic ablation* is done to make cornea myopic, prolate that allows the eye to focus in a range that includes near vision but excludes far vision (Fig. 11.29B).
- *Myopic ablation* is then performed with a 4 mm optical zone (Fig. 11.29C). This results in a central oblate cornea for distance vision with a ring of prolate cornea that allows the eye to focus on near objects (Fig. 11.30).

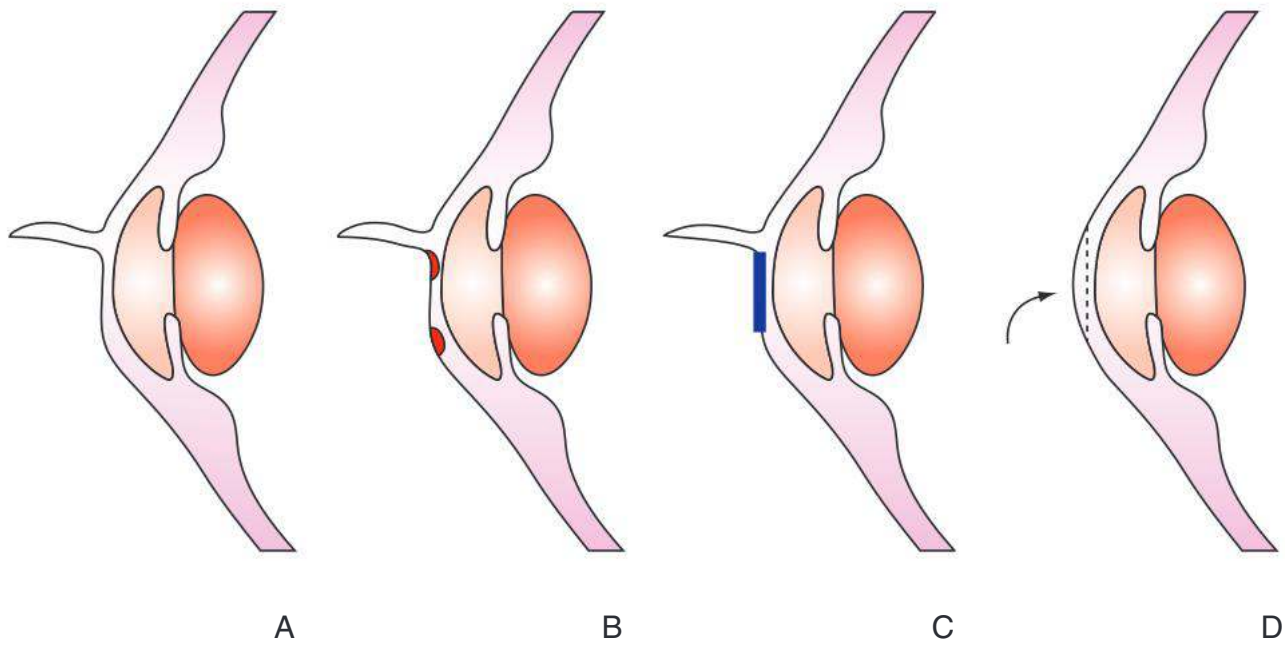


Fig. 11.29 *Procedure of presbyopic bifocal LASIK: A, creation of corneal flap; B, hyperopic ablation; C, myopic ablation; D, reposition of corneal flap.*

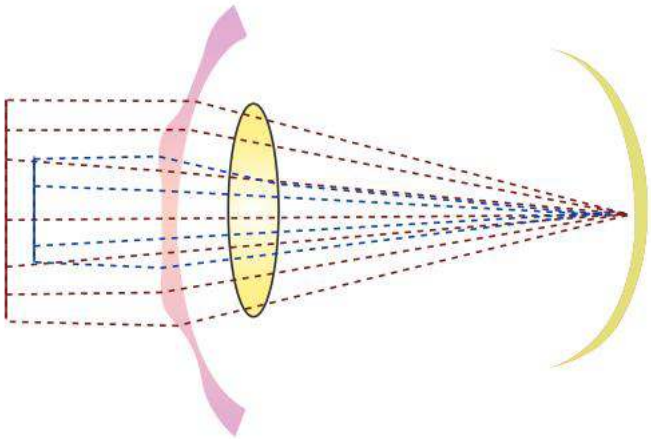


Fig. 11.30 *Schematic diagram to depict central oblate cornea for distance focusing and a ring peripheral prolate cornea for near focusing achieved after presbyopic LASIK.*

- *Reposition of flap* is done after cleaning and drying the stromal bed (Fig. 11.29D).

3. *Presbyopic multi-focal LASIK (PML) C*. This procedure can be performed on presbyopicmyopes, hyperopes, astigmatics and emmetropes.

Principle. Multi-focality on the cornea is created using a multi-step treatment in which several independently calculated ablations are performed at various optical zones.

Main steps of presbyopic multi-focal LASIK (PML) C:

- *Corneal flap* of between 8.5 and 9.5 mm is made.
- *Astigmatic ablation* is first performed in the classic manner.
- *Central corneal ablation* is performed next to treat the distance defect.
- *Multiple paracentral zonal ablations* are then performed at various optical zones to correct near vision and intermediate-vision defects.

4. *PRESBYOND Laser Blended Vision* is similar to monovision in which the dominant eye is corrected for distance vision and the non-dominant eye is corrected to be slightly near sighted for near vision. Both eyes are treated to ensure the best possible balance of vision. To be precise, in this the laser is used not only to make the non-dominant eye near sighted as in monovision but also to create a positive spherical aberration in the centre of the eye (Fig. 11.31). This micro-monovision strategy makes the image disparity from the two eyes smaller and the brain easily blends the images together. Therefore, the patient is less likely to

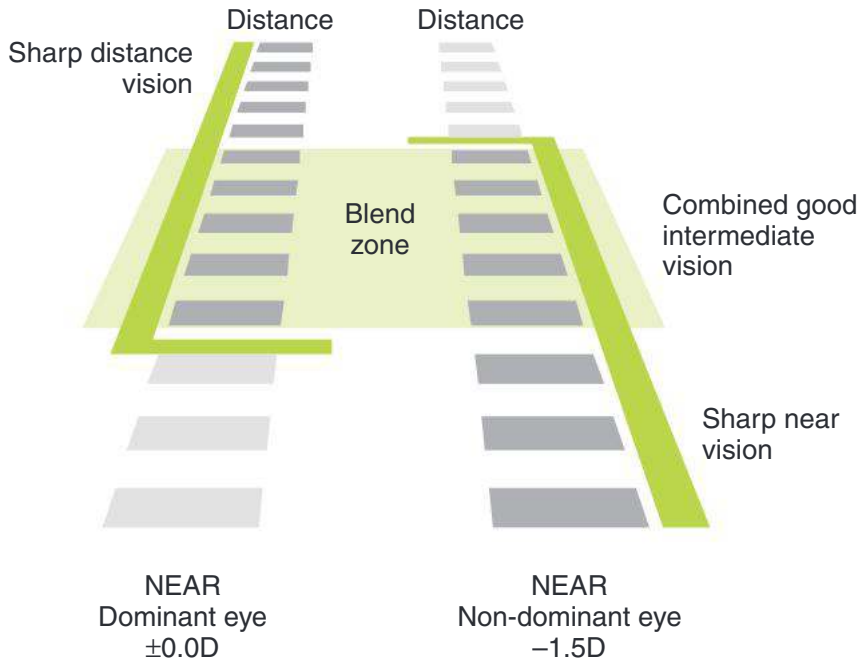


Fig. 11.31 *Concept of blend zone in PRESBYOND Laser Blended Vision technique.*

notice which eye he/she is looking through for distance or near. A customized fusion of the two images for near and distance vision is created for each patient – the so-called 'Blend Zone'.

Essentially, the *Blend Zone* makes it easy for the brain to merge the images of both eyes, thereby achieving true binocular vision. In addition to excellent near and far vision, with PRESBYOND Laser Blended Vision, the patient also experiences very good visual acuity and contrast sensitivity in the intermediate range. Most patients adapt quickly.

III. CORNEAL INLAY

Corneal inlay for presbyopia correction has been tried in the past without much success. Corneal inlay can be used after making a corneal flap. Recently, Intralase femtosecond laser is being used to dissect a corneal pocket for the inlays.

Advantage of femtosecond corneal pocket

- Precise and safe dissection
- Computerized parameters programming
- Inlay movements are not there
- Inlay does not produce corneal topographic changes
- No astigmatism induction
- Avoid dry eye related to flap
- Prevents neurotrophic keratopathy

Types of inlay. Presently, the following corneal inlays are being used in clinical trials for treatment of presbyopia:

- Acufocus inlay
- Biovision
- Presbylens
- Refractive annular and lenticule
- Multi-focal refractive inlay
- Presbyopic allogenic refractive lenticule (PEARL)
- Rain drop near vision inlay

Acufocus Corneal Inlay

Acufocus corneal inlay (ACI) is presently being used in clinical trials only.

Principle. ACI works using the same principle as used in camera lenses to increase range of vision (Fig. 11.32A).

Features. ACI is 5 μm thin, has a 3.8 mm outer diameter and a 1.6 mm pinhole in the centre (Fig. 11.32B). The central small aperture created by the ACI reduces the blur when viewing near objects.

Surgical technique. ACI is implanted in one eye either below the LASIK type flap or injected with an injector in a corneal pocket fashioned with femtosecond laser (Fig. 11.32).

Biovision Invue Inlay

Features. Invue inlay is a hydrogel lens having 3.6–3.8 mm diameter and 10 μm thickness at the peripheral edge. The central thickness varies with the power add. In its centre is a small clear zone and power is incorporated in an annular ring around the central clear zone.

Working principle. Invue corneal inlay is a microlens which creates a multi-focal cornea, out of an emmetropic cornea by adding plus power to the cornea. The multi-focal optics of the Invue inlay works in conjunction with the constriction and dilatation of the pupil that occurs during accommodative and disaccommodative effort, respectively. That is when a patient focuses on a distant object, the resultant pupil dilation delivers more light through the distance component of the reshaped corneal surface. Conversely, constriction of pupil during focusing on near objects delivers more light through the reshaped corneal surface's near component.

Surgical technique of implantation. The corneal pocket is fashioned with a femtosecond or the special Invue's Visitome 20–10 microkeratome. The inlay is inserted in the centre of cornea with the help of specially designed Invue forceps (Fig. 11.32C).

Presbylens Corneal Inlay

Principle. The presbylens corneal inlay is designed to correct presbyopia by changing the

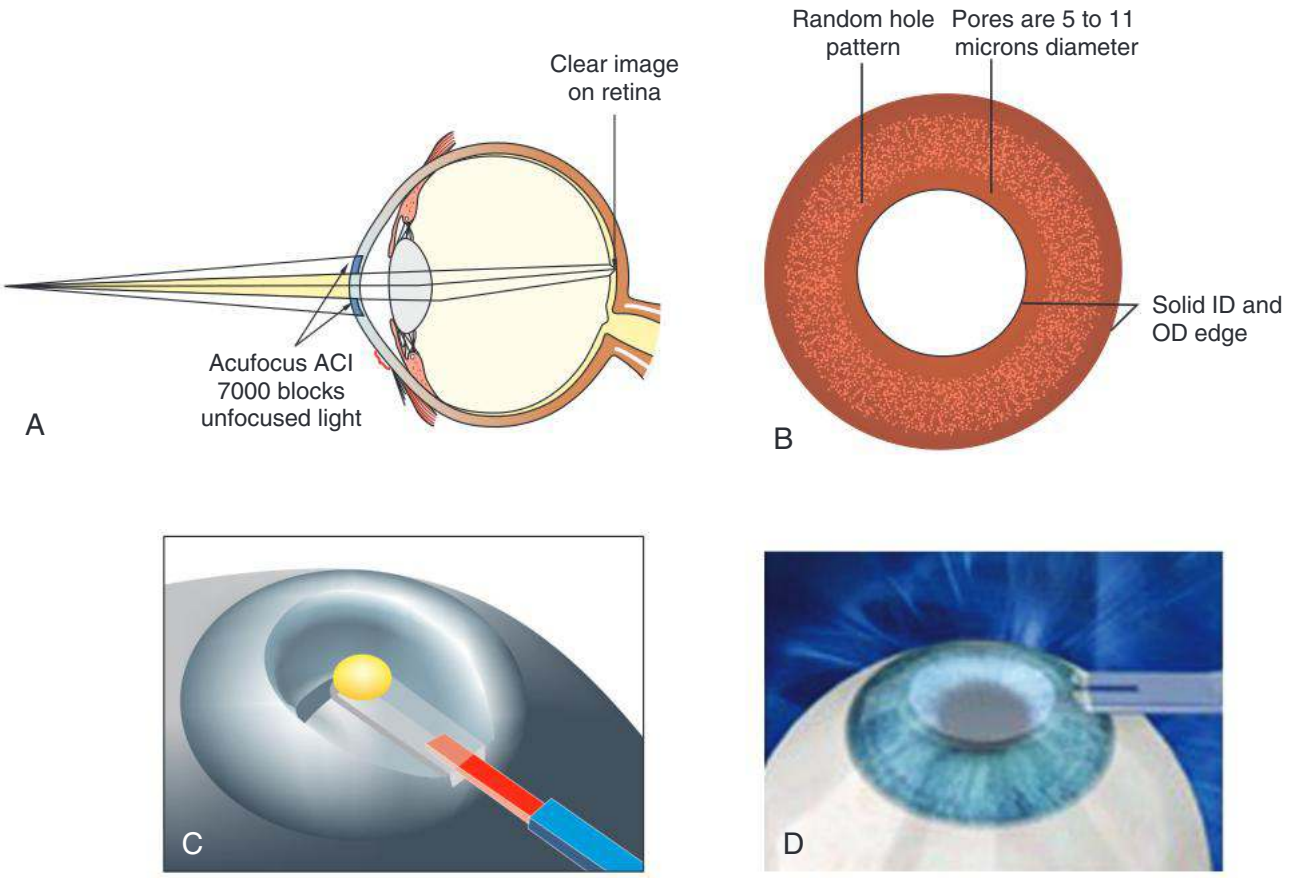


Fig. 11.32 *Corneal inlays for presbyopia: A, optical principle of Acufocus corneal inlay (ACI); B, features of ACI; C, Invue inlay is being inserted with Invue forceps; D, placement of presbylens corneal inlay.*

shape of the corneal surface, i.e. it changes the topography and reproduces a multi-focal system.

Features. Presbylens inlay is made of a piece of proprietary polymer, 1.5 mm in diameter, and is ultrathin (approximately half the thickness of a sheet of paper).

Surgical technique. Presbylens is placed under the 120–130 μm thick corneal flap which is fashioned with either a femtosecond laser or a microkeratome and is centred over the pupil of the eye (Fig. 11.32D).

Refractive Annular Add Lenticule

The Flexivue Microlens (Presbia, Amsterdam, the Netherlands) is the only corneal inlay in development utilizing refractive add power. The Microlens is composed of a hydrophilic acrylic polymer, measuring 3 mm in diameter with an edge thickness of 20 mm. This bifocal optical inlay has separate distance and near focal points. The central zone is free of refractive power and the peripheral zone has a standard refractive power with an index of refraction higher than that of the cornea generating +1.25 to +3.00 D of add power.

Multi-focal Refractive Inlay

The Icolens (Neoptics AG, Hunenburg, Switzerland) is the most recent corneal inlay in development. This hydrophilic acrylic hydrogel lens combines a neutral central zone with a peripheral optical zone of 3 D. This bifocal design delivers two images on the retina simultaneously, like a multi-focal IOL.

Presbyopic Allogenic Refractive Lenticule

PrEsbyopic Allogenic Refractive Lenticule (PEARL) technique is developed by Soosan Jacob from India in 2016.

Principle: PEARL functions as a shape-changing corneal inlay, but it makes use of a lenticule of human corneal tissue rather than artificial material. The tissue is obtained from a patient undergoing SMILE refractive procedure for correction of –2.5 to –3.5 D of myopia, and the lenticule is implanted in the recipient's cornea. The PEARL procedure improves depth of focus by increasing the central radius of curvature and creating an area of hyperprolateness on the cornea, surrounded by normal topography.

Advantages include:

- Easy lenticule implantation and
- Lenticule is biocompatible which allows passage of oxygen and nutrients through the cornea, prevents inflammation and decreases risk of corneal necrosis and melt.

Potential challenges and complications include:

- Manual cutting and obtaining suitable sized lenticules and
- Potential risk of stromal rejection is there because PEARL makes use of donor corneal tissue

Raindrop Near Vision Inlay

Raindrop Near Vision Inlay (ReVision Optics, Inc., Southern California) is a corneal inlay that creates a prolate-shaped cornea and is easily placed under a femtosecond laser flap. It is made of a soft, biocompatible material called hydrogel, which has similar properties and water content as the cornea. It is 2 mm in diameter and 32 μm in thickness (Fig. 11.33). One Raindrop Near Vision Inlay is placed in the cornea of the nondominate eye. It improves both near and intermediate vision while slightly affecting distance vision in the treated eye.

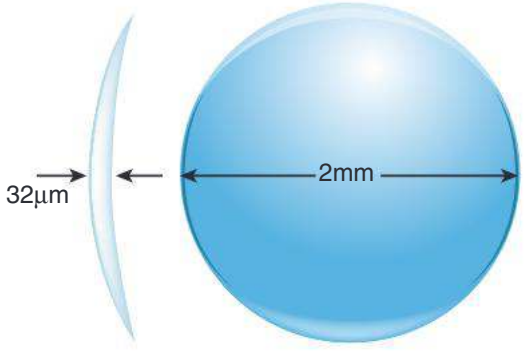


Fig. 11.33 *Raindrop near vision inlay.*

Raindrop near vision inlay is as follows:

- As transparent as natural tears, so there are zero cosmetic issues.
- Well suited for dim light, offering good performance.
- Raindrop resembles a tiny water droplet.
- Bio-engineered to facilitate the transport of nutrients and fluid to the eye.
- Extensive trials and usage show that Raindrop is safe.

Advantages of corneal inlays for presbyopia over CK, presby LASIK and accommodating IOLs.

The procedure of corneal inlays for presbyopia:

- Minimally invasive
- Produces minimum side effects
- Easily reversible

Final Results and Recommendations for Inlays

The corneal inlays, described above, work on different principles and are still under clinical trials. The final results and recommendations are still awaited. It seems promising results are in pipeline.

IV. INTRACOR TREATMENT

IntraCor surgery is a new technique that utilizes the femtosecond laser technology to correct presbyopia by selectively changing the topographic and refractive characteristics of the central portion of the cornea.

The technique involves the creation of several concentric intrastromal rings (5–8), using a femtosecond laser, at different corneal depths (between the Bowman's and Descemet's boundaries) in the central portion of the cornea.

It is applicable to emotropic or low-degree hyperopic eyes (+0.5 to +1.5 D); however, recent modifications suggest that this technique may be applicable in low myopic eye as well.

B. LENS-BASED PROCEDURES OR INTRAOCULAR REFRACTIVE PROCEDURES

1. ***RLE*** is being considered increasingly in presbyopic patients with associated high refractive error. Of course it is the treatment of choice in patients with cataract. (For details see page 427.)
2. ***PRLs*** are also an alternative procedure, but not convincing in comparison to RLE. (For details see page 430.)
3. ***Monovision with IOLs***, i.e. correction of one eye for distant vision and other for near vision with conventional monofocal IOLs after bilateral clear lens extraction (in presbyopic patients with high refractive errors) or after cataract extraction also serves as a solution for far and near correction.

C. SCLERA-BASED PROCEDURES

Scleral spacing is based on the theory that the lens is under increased equatorial zonular tension during accommodation; thus, any procedure that increases the distance between the lens equator and the ciliary muscle (thereby increasing tension) should reverse presbyopia.

1. ***Anterior ciliary sclerotomy with tissue barriers*** is currently under trial, with initial encouraging results; multi-site clinical trials are planned for the USA and Europe to evaluate this technique.
2. ***Scleral spacing procedure*** using PresView Scleral Implants is another technique under trial with promising results. The PresView Scleral Implant is inserted in a scleral tunnel created posterior to the lens equator. The effect of the implant is that it allows the lens greater movement for accommodation.
3. ***Scleral ablation with Erbium (Er):YAG laser*** is also being studied in clinical trials as an alternative to anterior ciliary sclerotomy for the treatment of presbyopia. ***The laser ACE procedure*** utilizes the Visiolite Erbium:YAG laser to ablate 600 μm laser spots in the sclera which are presumed to free the ciliary muscle to contract normally. The spots are delivered in a diamond matrix pattern of nine laser spots into each oblique quadrant. This effectively increases focal power and focal depth. Currently, this procedure is in the preliminary stage of an 18-site formal study being carried out in seven countries.

FUTURE REFRACTIVE SURGERIES

LASER-INDUCED REFRACTIVE INDEX CHANGE

Developed at the University of Rochester, laser-induced refractive index change (LIRIC), (Clerio Vision), is a novel refractive correction technology that changes the refractive index of the cornea without cutting or removing tissue using Femtosecond LASER. The technology will be commercially available in the next 3–5 years.

Principle: The stroma is a mixture of collagen and water. The stromal refractive index is roughly 1.38. Femto energy that is applied is below the damage threshold. Once the Femto energy (performed using a blue, 405 nm wavelength laser system) is applied, the collagen matrix gets more densely packed at the spot leading to a change in refractive index and the spot is scanned across the optical zone. All corneas are clear post-treatment and there are no signs of haze, scarring, endothelial damage or opacity.

Advantages include:

- A variety of optical wavefronts can be inscribed within the cornea (e.g. sphere, cylinder, higher-order aberrations and multi-focal)
- By avoiding ablation, LIRIC preserves the cornea's original curvature and avoids epithelial remodelling and the subsequent regression.
- It also preserves the corneal nerves and reduces the rate of postoperative dry eye.
- As there is no tissue removal, there is no corneal ectasia.
- It may be done as an in office procedure and obviate the fear in patients hesitant of getting refractive surgery as it is incision free procedure.

- Patient recovery is faster (within 24 h).
- No need for topical steroid or antibiotics.

REFRACTIVE LENTICULAR IMPLANTATION

Refractive lenticular implantation (RELIMP), popularized by Dr Osama Ibraham from Egypt, is an additive refractive surgery, used for refractive correction, stromal volume expansion and biomechanical strengthening of the cornea.

The lenticule generated after SMILE surgery is usually discarded. With advent of better lenticule preservation techniques including serotyping and infection screening and storage at –198, studies are underway for customizing them by: (1) excimer laser reshaping, (2) ultraviolet A-riboflavin cross-linking (CXL) and (3) decellularization by sodium dodecyl sulphate (SDS).

The lenticules can be utilized for correcting various refractive errors and corneal conditions such as hyperopia, presbyopia and keratoconus by implanting donor stroma under corneal flaps or in pockets:

- *To treat keratoconus*, inserting a planar or donut-shaped lenticule into a pocket to thicken and centrally flatten the cornea.
- *Presbyopia is treated by adding* a centrally placed 1.0 to 2.0 mm lenticule, improving near vision while maintaining distance correction with no haze or inflammatory response.
- *Excimer lasers correct hyperopia* by tissue subtraction. However, the donut-shaped tissue removed leaves the cornea with an uneven surface, which tends to regress as the epithelium thickens to fill in the curves and creates an extreme hyperprolate corneal shape profile that distorts vision at higher corrections.

LENTICULAR IMPLANTATION KERATOPLASTY

Lenticular implantation keratoplasty (LIKE) is a technique popularized by Dr Theo Seiler. This involves shaping donor corneal tissue with Bowman's layer using a lenticule cavity unit, which defines the precise shape profile and power. The implanted lenticule power is targeted to be greater and placed under the large LASIK flap of moderate to high hyperopia eyes, making it possible to later lift the flap for a myopic or customized ablation enhancement.

- LIKE-shaped lenticules are also being shaped for treating keratoconus by placing the lenticule in a corneal stromal pocket.

12 Optical Instruments and Techniques

Chapter Outline

INTRODUCTION

Modern ophthalmology has reached a stage where more and more optical instruments and techniques are being evolved day by day. This chapter is devoted to the principles of operation of some selected ophthalmic instruments, devices and techniques which include the following:

Optical instruments and techniques for anterior segment evaluation

- Slit-lamp biomicroscopy
- Gonioscopy

- Keratometry (see page 175)
- Corneal topography (see page 184)
- Aberrometry (see page 213)
- Biometry and intraocular lens (IOL) master (see pages 345 and 348)
- Pachymetry
- Specular microscope
- Comprehensive anterior segment analyser (Pentacam)
- Confocal microscopy of cornea.

Optical instruments and techniques for posterior segment evaluation

- Ophthalmoscopy
- Slit-lamp biomicroscopic examination of the fundus
- Fundus camera
- Wide-field imaging system (retinal camera)
- Scanning laser imaging techniques
  Scanning laser ophthalmoscopy (SLO)
  Confocal scanning laser ophthalmoscopy (CSLO)
  Retinal thickness analyser (RTA)
  Scanning laser polarimetry (SLP) (retinal nerve fibre analyser)
- Optical coherence tomography (OCT)
- OCT ophthalmoscopy

Optical instruments used for ocular surgery

- Operating microscope
- Vitreoretinal surgical lenses and lens rings

Optical instruments used for refractions

- Retinoscopes (see page 133)
- Auto refractometer (see page 146)
- Lensmeter

OPTICAL INSTRUMENTS AND TECHNIQUES FOR ANTERIOR SEGMENT EVALUATION

SLIT-LAMP BIOMICROSCOPY

INTRODUCTION

Slit-lamp is the most important piece of equipment in the present-day ophthalmologist's armamentarium. Modern slit-lamp with its auxiliary devices not only provides magnified views of every part of the eye from cornea to retina, but also allows quantitative measurements (intraocular pressure, endothelial cell counts, pupil size, corneal thickness, anterior chamber depth, etc.) and photography of every part for documentation.

The term slit-lamp is basically a misnomer, since slit is only one of the various other diaphragmatic openings present in the instrument. Therefore, Mawas in 1925 introduced the term *biomicroscopy* and defined it as examination of the living eye by means of a corneal microscope and a slit-lamp.

HISTORICAL LANDMARKS IN THE DEVELOPMENT AND EVOLUTION OF SLIT-LAMP

These can be summarized as follows:

- *Purkinje*, in 1823, attempted to develop a type of slit-lamp by using one hand-held lamp to magnify another hand-held lens to focus strong oblique illumination. However, it was not until almost 100 years later that a version of the slit-lamp appeared that is recognizable today.
- *De Wecker*, in 1863, devised a portable *ophthalmomicroscope* that combined a small monocular microscope which rested against the face of the patient with an attached condenser lens. It lacked stereoscopic view.
- *Albert* and *Greenough*, in 1891, developed a binocular microscope which provided stereoscopic view.
- *Czapski*, in 1897, modified the binocular corneal microscope, which is still found in many modern slit-lamps.
- *Gullstrand*, in 1911, introduced the illumination system which had for the first time a slit-diaphragm in it. Therefore, Gullstrand is credited with the invention of the slit-lamp.
- *Henker*, in 1916, developed the prototype of the modern biomicroscopy by combining the Gullstrand's slit-illumination system with the Czapski's binocular corneal microscope.

- *Hans Goldmann*, in 1933, improvised the biomicroscope in which all the vertical and horizontal adjustments for both the lamp and the slit-beam were placed on a single mechanical stage. The slit-lamp designed by Goldman was marketed in 1937 as the *Haag–Streit model 360 slit-lamp.*
- *Littmann*, in 1950, introduced the new optical principle for the biomicroscope. He incorporated the rotatory magnification changer based on the principle of Galilean telescope. The slit-lamp designed by Littmann is the forerunner of the current Zeiss slit-lamp series.
- *Modern slit-lamps* have achieved a very high degree of refinement.

PARTS OF A SLIT-LAMP

A slit-lamp (Fig. 12.1) is composed of three basic parts:

1. Observation system (microscope),
2. Illumination system and
3. Mechanical support system.

1. OBSERVATION SYSTEM (MICROSCOPE)

The observation system (Fig. 12.2) is essentially a compound microscope which is composed of two optical elements, an objective and an eyepiece. It presents to the observer an enlarged image of a near object. The slit-lamp microscope is designed to have a long working distance, i.e. the distance between the microscope's objective and the patient's eye.

- Objective lens consists of two plano-convex lenses with their convexities put together, providing a composite power of +22 D.
- Eyepiece has a lens of +10 D. To provide a good stereopsis, the tubes are converged at an angle of 10–15 degrees.
- Prisms. To overcome the problem of inverted image produced by the compound microscope, slit-lamp microscope uses a pair of prisms between the objective and the eyepiece to re-invert the image (Fig. 12.2).

Magnification Systems

Most slit-lamps provide a range of magnification from 6× to 40×. The modern slit-lamps use

Fig. 12.1 *A slit-lamp.*

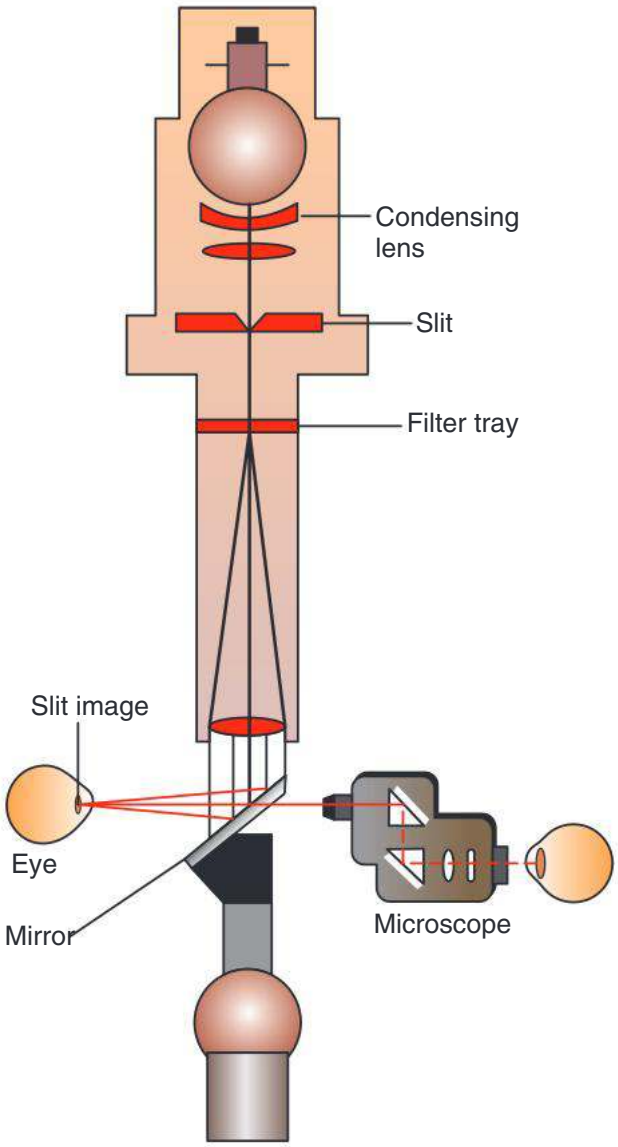


Fig. 12.2 *A cross-section of the observation system of a modern slit-lamp.*

one of the following three systems to produce a range of magnification.

i. ***Czapskiscope with rotating objectives.*** This is one of the oldest and possibly still the most frequently used techniques for obtaining different magnifications. The different objectives are usually placed on a turret type of arrangement that allows them to be fairly rapidly changed during the examination.

The Haag–Streit model, the Bausch and Lomb and the Thorpe are the examples of the slit-lamps using this system.

ii. ***The Littmann–Galilean telescope principle.*** The Galilean magnification changer (G), as developed by Littmann (1950), is a completely separate optical system that sits neatly between the objective and eyepiece lenses and does not require either of them to change. It provides a large range of magnifications, typically five, via a turret arrangement which is completely enclosed within the microscope's body. It is called a Galilean system because it utilizes the Galilean telescopes to alter the magnification. Galilean telescopes have two optical components, a positive lens and a negative lens. It fits within the standard slit-lamp microscope along with a relay lens (R) and the prism erector (P) in the manner shown in Figure 12.3.

The Zeiss, the Rodenstock and the American optical slit-lamps are the examples of slit-lamps using the Littmann–Galilean telescopic system.

iii. ***Zoom system.*** Some slit-lamps (e.g. Nikon photo slit-lamp and Zeiss-75 SL) have been produced with zoom system that allows a continuously variable degree of magnification. The Nikon slit-lamp contains the zoom system within the objective of the microscope and offers a range of magnification from 7× to 35×.

2. ILLUMINATION SYSTEM

The Gullstrand's illumination system is designed to provide a bright, evenly illuminated, finely focused adjustable slit of light at the eye. It comprises following components (Fig. 12.4):

i. ***Light source.*** Originally, a Nernst lamp was used as a light source which was followed by Nitra lamp, arc lamp, mercury vapour lamp and finally halogen lamps. It provides an illumination of 2×10^5 to 4×10^5 lux.

ii. ***Condenser lens system.*** It consists of a couple of plano-convex lenses with their convex surfaces in apposition.

iii. ***Slit and other diaphragms.*** The height and width of the slit can be varied using two knobs provided for this purpose. In addition, there are

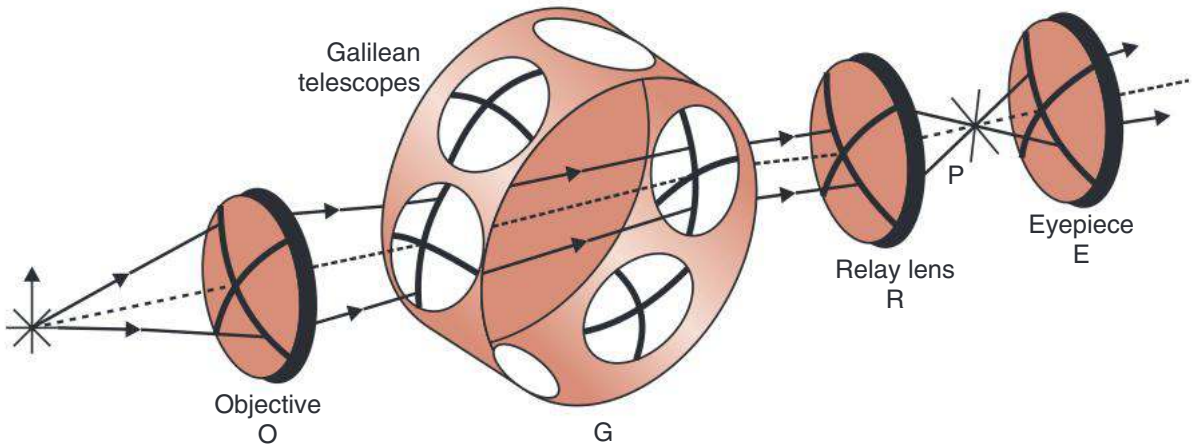


Fig. 12.3 *Galilean magnification changer (G) is placed between the slit-lamp objective (O) and the relay lens (R) which focuses the light through a prism erector (P) into the eyepiece (E).*

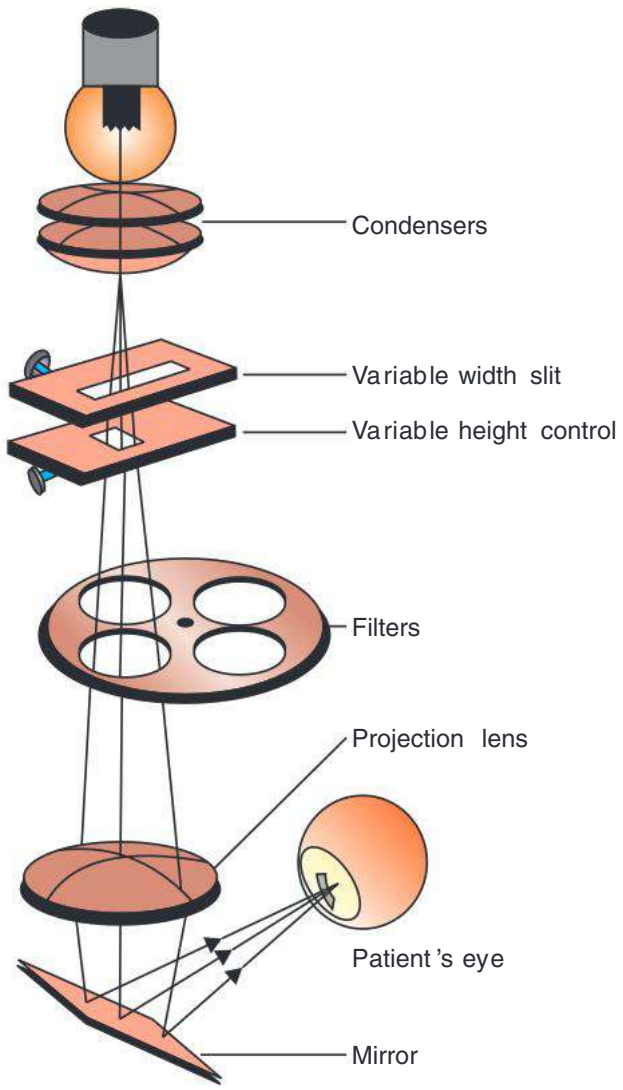


Fig. 12.4 *Typical slit-lamp illumination system.*

some stenopaeic slits of 2.0 and 0.5 mm to provide conical beam of light.

There is a facility to rotate the slit away from the vertical meridian and also the ability to tilt the projection system about a horizontal axis that is provided. These two additional degrees of freedom are included to assist in the examination of the fundus and the angle of anterior chamber.

iv. ***Filters.*** Different filters can be inserted into the illumination beam. Cobalt blue and red-free filters are provided in most of the models.

v. ***Projection lens.*** It forms an image of the slit at the eye. The diameter of the projection lens is usually fairly small. This has two advantages: first, it keeps the aberrations of the lens down, which results in a better quality image; second, it increases the depth of focus of the slit and thereby produces a better optical section of the eye.

vi. ***Reflecting mirror or prism.*** It forms the last component of the illumination system. The illumination system of a slit-lamp has to be able to pass relatively easily from one side of the microscope to the other. To allow this, the projection system is normally arranged along a vertical axis, with either a *mirror* or *prism* finally reflecting the light along a horizontal axis. The use of a narrow prism or mirror means that when necessary, such as in examination of the

fundus, the illumination axis can be made to, without obstructing the field of view, almost coincide with the viewing axis.

Optics of the Illumination System

The Koeller illumination system has been adopted in slit-lamps. Optically, it is identical to that of a 35 mm slide projection with the exception that a variable aperture slit takes the place of the slit and the projection lens has a much shorter focal length. In the Koeller illumination system, as shown in Figure 12.4, the filament of the light source is imaged by the condenser lenses at or close to the projection lens which in turn forms the image of the slit in the patient's eye.

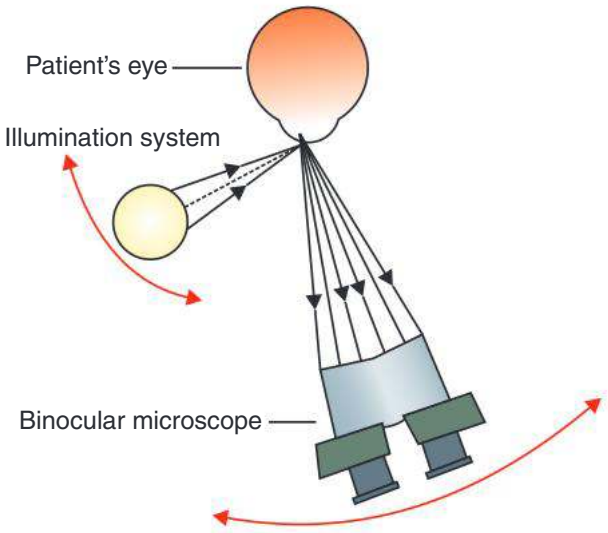


Fig. 12.5 *Mechanical coupling of the microscope and illumination system allows their focusing on the same point.*

3. MECHANICAL SUPPORT SYSTEM

Although mechanical support system is least glamorous, a brief review of the instrument's history reveals that the optical principles upon which the modern slit-lamp is based have changed little over the years, whereas the ease of examination, characteristics of all modern slit-lamps, is due to the indigenous mechanical design.

Salient features of most of the mechanical support systems are as follows:

i. ***Joystick arrangement.*** Movement of the microscope and illumination system towards or away from the eye and from side to side is usually achieved via a joystick arrangement.

ii. ***Up and down movement arrangement.*** The up and down movement is obtained via some sort of screw device that moves the whole illumination and viewing system up and down relative to the chin rest.

iii. ***Patient support arrangement.*** A vertically movable chin rest and the provision to adjust the height of the table have been made to accommodate the persons of all sizes.

iv. ***Fixation target.*** A movable fixation target greatly facilitates the examination under some conditions.

v. ***Mechanical coupling.*** The mechanical system not only provides a support but also a coupling of the microscope and the illumination system along a common axis of rotation that coincides their focal planes. This arrangement ensures that light falls on the point where microscope is focused. It allows either the microscope or the illumination system to be rotated around this axis without changing the focus (Fig. 12.5).

The coupling of the microscope and illumination system in this way has advantages when using the slit-lamp for routine examination of the anterior segment of the eye. However, when certain accessories, such as gonioscope or the three-mirror fundus lens, are used, this can be a disadvantage, since the slit and the microscope optics frequently do not reach a common focal point under those conditions, leaving the observer with the choice of suffering under suboptimal images or refocusing the eyepieces.

TECHNIQUE OF BIOMICROSCOPY

SLIT-LAMP BIOMICROSCOPY ROUTINE

While performing slit-lamp biomicroscopy, following routine may be adopted:

1. ***Patient adjustment.*** The patient should be positioned comfortably in front of the slit-lamp with his or her chin resting on the chin rest and forehead opposed to head rest (Fig. 12.1).
2. ***Instrument adjustment.*** The height of the table housing the slit-lamp should be adjusted according to patient's height. The microscope

and illumination system should be aligned with the patient's eye to be examined. Fixation target should be placed at the required position.

3. ***Beginning slit-lamp examination.*** Some points to be kept in mind are as follows:

i. Examination should be carried out in semi-dark room so that the examiner's eyes are partially dark-adapted to ensure sensitivity to low intensities of light.

ii. Diffuse illumination should be used for as short a time as necessary.

iii. There should be a minimum exposure of retina to light.

iv. Medications like ointments and anaesthetic eyedrops produce corneal surface disturbances which can be mistaken for pathology.

v. Low magnification should be first used to locate the pathology and higher magnification should then be used to examine it.

METHODS OF ILLUMINATION

Berliner described seven basic methods of illumination using the slit-lamp. A few guidelines for the set-up for each method of illumination are described briefly.

1. Diffuse illumination (Fig. 12.6). The *set-up* is as given below:

- The microscope is positioned directly in front of the patient's eye at 0 degree and achromatic lights focused on the anterior of the cornea.
- Angle between microscope and illumination system should be 30–45 degrees.
- Slit width should be widest.
- Filter to be used is diffusing filter.
- Magnification used is low to medium.
- Illumination should be medium to high.

Diffuse illumination is used for the following:

- General view of the anterior eye and the palpebral conjunctiva especially for gross inspection, corneal scars, irregularities of the lids and tear debris.
- Contact lens fitting.
- Cobalt blue filters and fluorescein sodium permits evaluation of corneal and conjunctival epithelium and tear break up time.

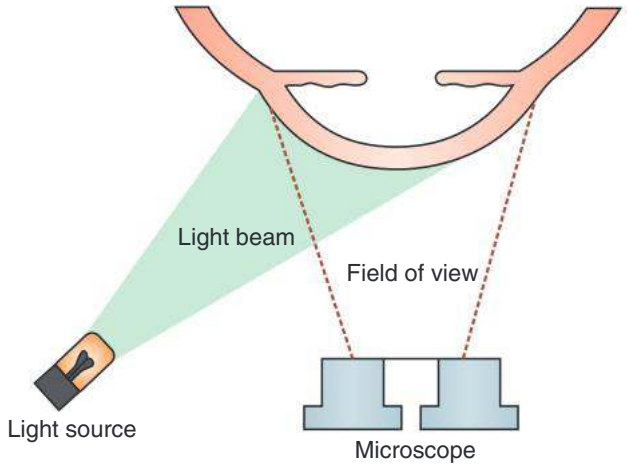


Fig. 12.6 *Set-up for diffuse illumination.*

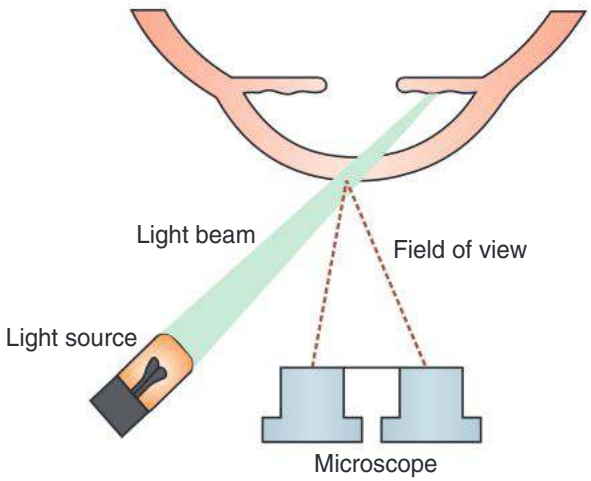


Fig. 12.7 *Set-up for direct illumination.*

- Rose Bengal staining with achromatic light will show pink staining of damaged epithelial cells as in case of keratoconjunctivitis sicca with red-free filter helps to view bulbar conjunctiva (superficial vessels) and episcleral vessels.

2. Direct focal illumination. In this technique, the slit-beam is regulated until it coincides with the exact focus of the microscope (Fig. 12.7). Light is directed as a narrow slit at an oblique angle (30–45 degrees). Heterogenous tissues like cornea and lens disperse light and become visible as bright objects against a dark background.

The direct illumination examination is carried out utilizing three slit-beam effects on the transparent structures of the eye, i.e. optical

section, parallelopiped and a conical beam effect.

i. ***Optical section*** (Fig. 12.8) is produced by a very narrow slit-beam focused obliquely. The angle between the illuminating and viewing path should be kept small to minimize dazzling the patient. The slit should be narrow about 0.1–0.25 mm wide and 7–9 mm high. The magnification is to be kept about 7–10×. The height of the coaxial beam can be adjusted to measure the horizontal and vertical size of the lesion. The optical section produced resembles a knife-like histological section of the tissue focused (cornea, lens and anterior part of vitreous). The whole tissue can be examined by moving the slit-beam and simultaneous focus of the microscope across the surface.

- *Corneal optical section* (Fig. 12.9) consists of a segment of an arc with following concentric zones:
  Tear layer is seen as a bright *anterior most* zone.

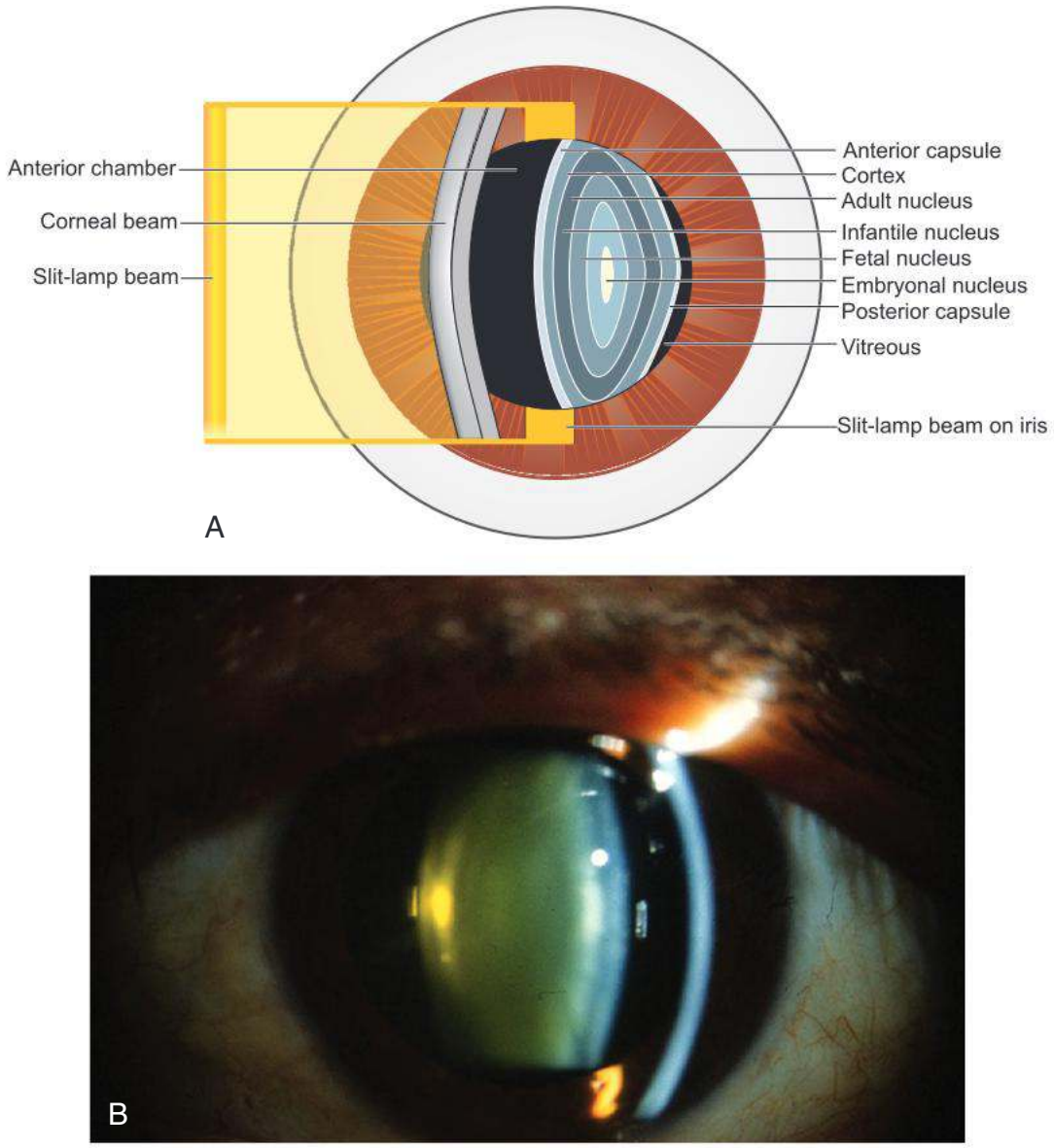


Fig. 12.8 *Optical section of the cornea, lens and anterior vitreous seen on slit-lamp examination: A, diagrammatic and B, clinical photograph.*

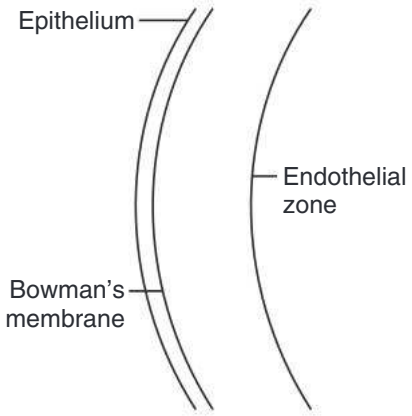


Fig. 12.9 *Corneal optical section.*

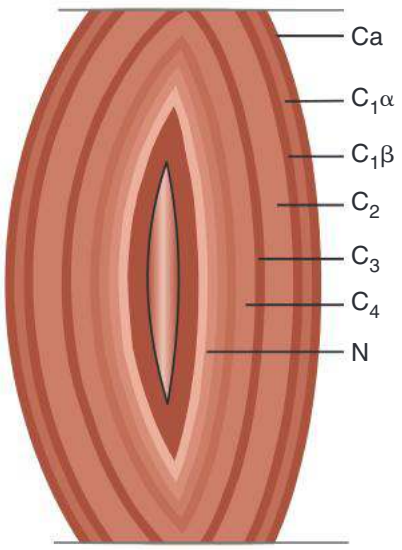


Fig. 12.10 *Optical section of the lens.*

Epithelium is seen as a dark line immediately behind the tear layer.
Bowman's membrane is seen as a bright line.
Stroma is focused as a wider granular and greyer zone.
Descemet's membrane and endothelial layers are seen as *posterior most* bright zone.

- Examination of the optical section of the cornea gives useful information about:
  Changes in corneal curvature,
  Changes in corneal thickness,
  Depth of the corneal pathologies, e.g. location of a foreign body and
  Anterior chamber angle grading by van Herrick method can be done by the use of corneal optical sections at the nasal and temporal periphery.
- *Optical section of the lens* (Fig. 12.10) seen with slit-lamp microscope shows stratification of the lens into following layers (from front to backwards):
  Anterior capsule (Ca),
  Sub-capsular clear zone (first cortical clear zone $C_1\alpha$),
  A bright narrow scattering zone of discontinuity (first zone of disjunction $C_1\beta$),
  Second cortical clear zone (C_2),
  Light scattering zone of deep cortex (C_3),
  Clear zone of deep cortex (C_4) and
  Nucleus (N) which follows the clear zone of cortex represents the prenatal part of the lens. It shows further stratification with a central clear interval which has been termed the embryonic nucleus.
  The entire optical section of the lens cannot be focused in one field and thus the microscope needs to be shifted forward to focus more posterior layer. The location and extent of lenticular opacities can be easily made in the optical section of the lens.
  - *Optical section of the anterior one-third* of the vitreous can be studied with slit-lamp beam.

ii. ***Parallelopiped*** of the cornea (Fig. 12.11) is observed using a 2–3 mm wide focused slit. The light source should be 45–60 degrees temporally and directed onto the pupil. The magnification is to be kept about 7–10×. The room should be darkened.

- Pathologies of epithelium and stroma are better studied under this illumination.
- Corneal scars or infiltrates appear brighter than surroundings because they have more density.
- Water clefts have decreased optical density, and so appear black in optical block.
  The zone between the out of focus cornea and the lens is normally optically empty and appears totally black. Flare makes the normally optically empty zone appear milky or grey. The white blood cells will reflect the light and be seen as white dots floating in the anterior chamber. The flare

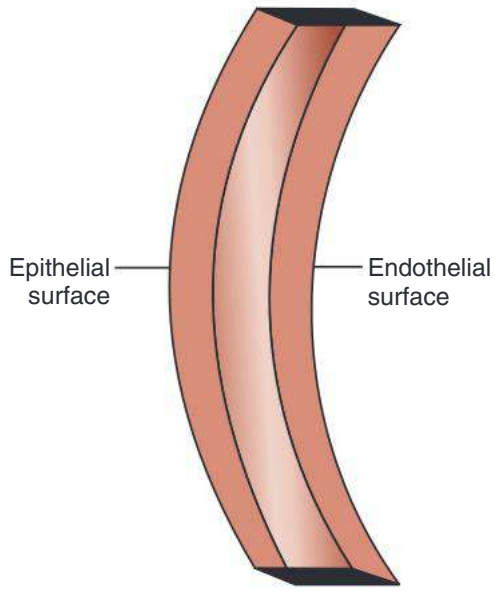


Fig. 12.11 *Parallelopiped of cornea seen on slit-lamp.*

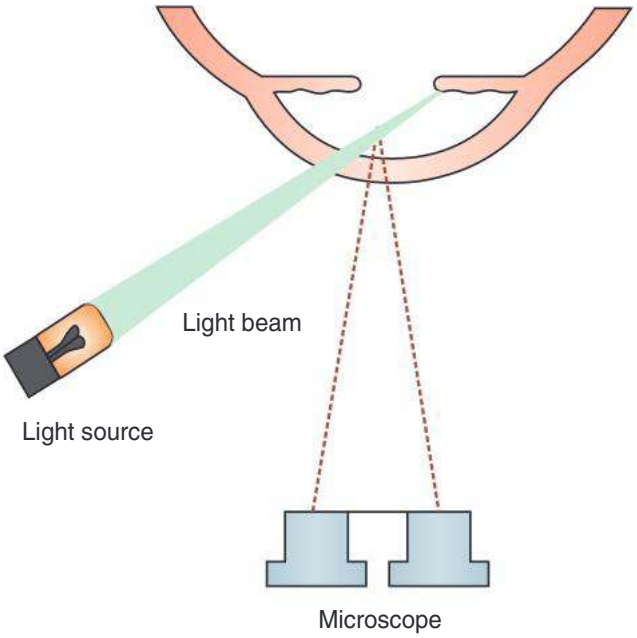


Fig. 12.12 *Conical beam used to examine the presence of aqueous flare.*

can be graded based on the degree of interference in the visualization of the iris, and the number of cells seen during a minute period is counted and the cells are graded accordingly. Cells and flare in the anterior chamber are graded by using a parallelopiped 2 mm wide × 4 mm high.

iii. ***Conical beam*** (Fig. 12.12) is a small circular beam used to examine the presence of aqueous flare. Settings for examination of aqueous flare are as follows:

- Beam: small circular pattern.
- Light source: 45–60 degrees temporally and directed into the pupil.
- Biomicroscope: directly in front of the eye.
- Magnification: high (16–20×).
- Focusing: beam is focused between the cornea and the anterior lens surface, and the dark zone between cornea and lens is observed. This zone is normally optically empty and appears black. Flare appears grey or milky and cells are seen as white dots. Locating the cells may be facilitated by gently oscillating the illuminator.

As per Standardized Uveitis Nomenclature (SUN), the size of beam to be used is:

- 1 mm × 1 mm (for anterior chamber cells and flare grading).
- 1 mm × 0.5 mm (for vitreous cells grading).

3. ***Indirect illumination***. The slit-beam is focused on a position just beside the area to be examined (Fig. 12.13). The *set-up* required is as given below:

- Angle between slit-lamp and microscope should be 30–45 degrees.
- Beam width used is moderate (2–4 mm).
- Illumination used is low, medium or high.
- Slit-lamp can be offset.

Indirect illumination is *useful* to observe the following:

- Corneal infiltrates,
- Corneal microcysts,
- Corneal vacuoles and
- Epithelial cells.

4. Retroillumination. Light is reflected off the iris or fundus, while the microscope is focused on the cornea (Fig. 12.14). Graves divided retroillumination as direct and indirect, depending on the angle between observer and light.

a. ***Direct:*** The slit width is 1–2 mm wide and 4–5 mm high with the biomicroscope and light source placed in direct alignment with each other. Observer is in direct pathway of light reflected from structures. The pathology

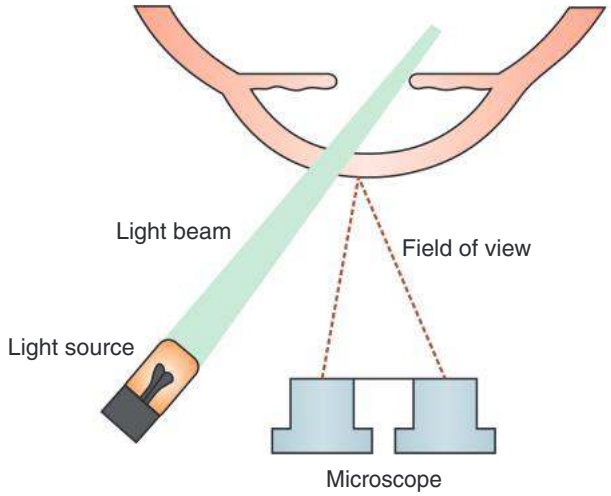


Fig. 12.13 *Set-up for indirect illumination.*

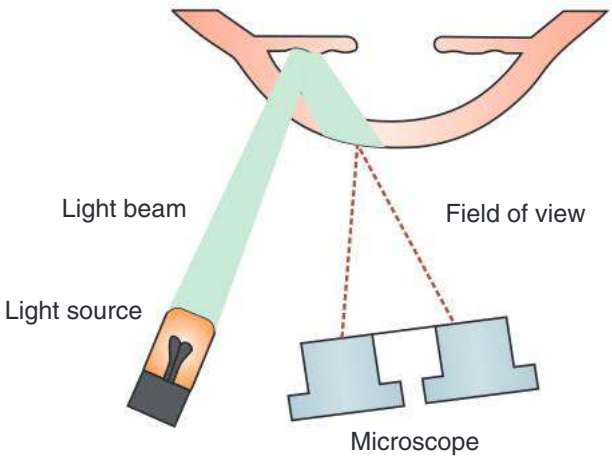


Fig. 12.14 *Set-up for retroillumination.*

is seen against an illuminated background (Fig. 12.15).

b. ***Indirect:*** Observer is at right angle to the observed structure and, therefore, not in line with light, so pathology is seen against a dark, non-illuminated background (Fig. 12.16).

Based on the optical properties, Graves divided the pathologies as follows:

- *Obstructive.* These are opaque to light and seen as dark against a bright background, e.g. pigment or blood-filled vessel.
- *Respersive*. These scatter light but do not obstruct light completely. The pathology is seen brightly against a dark background, e.g. epithelial oedema, precipitates. Infiltrates are relucent in direct focal illumination but respersive in direct retroillumination.
- *Refractile.* These refractile pathologies distort the view of junction of illuminated and dark areas because their refractive index is different from surroundings, e.g. vacuole.

A vacuole is seen as an illuminated area bordered by dark line in direct retroillumination, but in indirect retroillumination, it appears as black area with a bright surface towards the illuminated area (unreversed illumination). A solid or opaque precipitate will be seen as

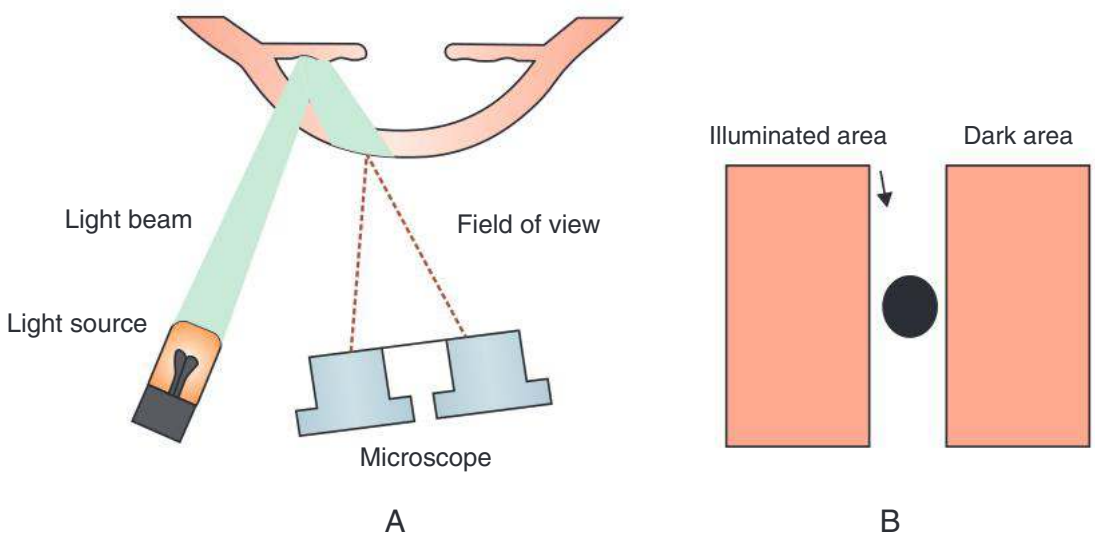


Fig. 12.15 *Direct retroillumination: A, cross-sectional view and B, a keratic precipitate is seen as dark against illuminated background.*

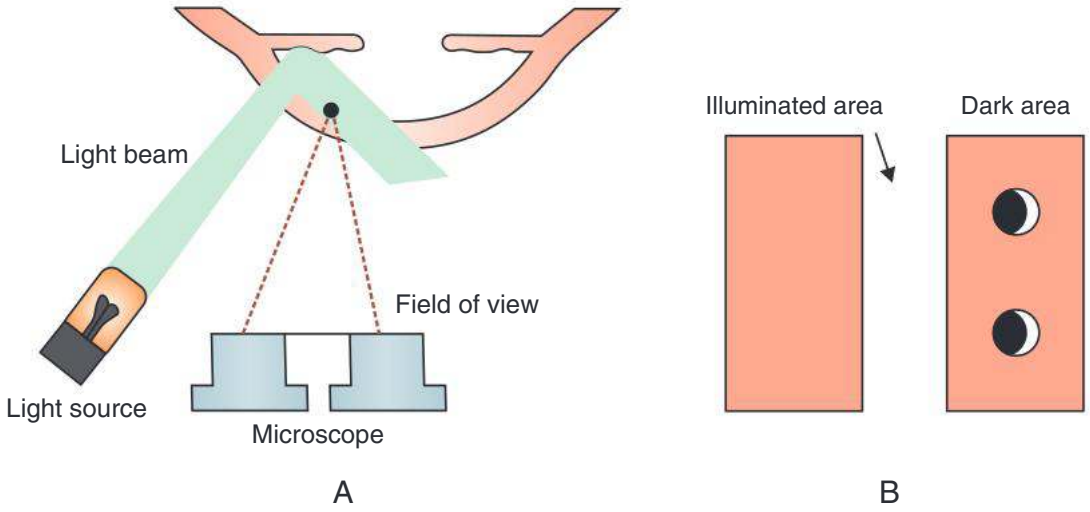


Fig. 12.16 *Indirect retroillumination: A, cross-sectional view and B, a keratic precipitate seen as dark with lighted crescent on the border away from illuminated side (reversed illumination) and seen against a dark background.*

dark area in direct retroillumination, but under indirect retroillumination, it will show reversed illumination; i.e. its side away from the illuminated area will be bright.

Thus, retroillumination can provide information regarding not only the form but also the refractive index and consistency of the pathology.

Retroillumination from the fundus. This technique is used to observe media clarities and opacities. The pupil is dilated and the slit-beam and microscope are made coaxial. The light is directed so that it strikes the fundus and creates a glow behind the opacity in the media. The media opacity creates a shadow in the glow. The microscope is then focused on the pathology directly and 10–16× magnification is used. Cornea, lens and vitreous pathologies are examined by this technique. Retroillumination of crystalline lens is required to classify and grade both cortical and posterior sub-capsular cataracts using LOCS II (lens opacity classifying system II).

5. Specular reflection. Reflection of light occurs when a beam of light is incident on an optical surface, which is called *zone of discontinuity*. Such zones may be found in cornea and lens. When an observer is placed in the pathway of reflected light, a dazzling reflex will be seen which is called specular reflection. The surface from which reflection is obtained is called zone of specular reflection. Surface pathologies will scatter the light irregularly and, therefore, create dark areas in the reflex.

To get specular reflection, the patient is asked to look 30 degrees temporally. Light beam is directed from opposite side. Optical block is focused under high magnification, 3–4 mm from limbus. Towards the side of light source, a shining reflex is seen on the cornea. When the light source is rotated still temporally, the optical block will approach the reflex. When the angle between microscope and slit-beam is about 60 degrees, i.e. when the angle of incidence becomes equal to the angle of reflection (Fig. 12.17) at this point, dazzling reflex which is coming from tear meniscus will show the meniscus irregularities. At the same time, a deeper less luminous glow will be seen which when focused will show the endothelial mosaic. A parallelopiped beam with high illumination and high magnification is used in this technique. Similarly, specular reflection from anterior and posterior capsule of lens can be obtained. Using an eyepiece reticule, endothelial cells can be measured and counted. It can also be used to study tear film details.

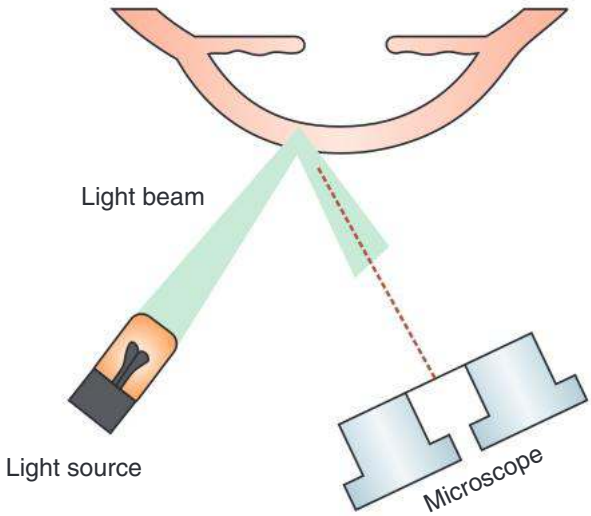


Fig. 12.17 *Set-up for specular reflection.*

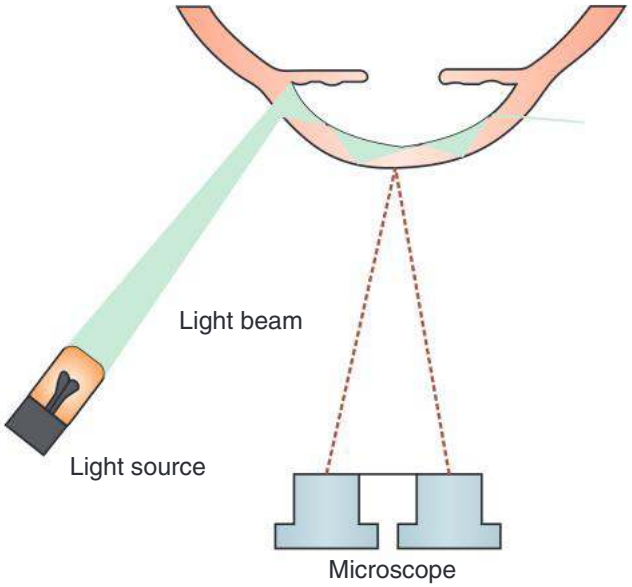


Fig. 12.18 *Set-up for sclerotic scatter.*

6. Sclerotic scatter. It is used to outline even the faintest corneal pathology. Light beam is focused at the limbus. Because of the phenomenon of total internal reflection, rays of light pass through the substance of cornea and illuminate the opposite side of limbus. If there is any pathology like corneal opacity, it becomes visible because it scatters the rays of light. A magnification of 6–10× is used and microscope is directed straight ahead (Fig. 12.18).

7. Oscillating illumination of Koeppe. In this, the slit-beam is given an oscillatory movement by which it is often possible to see minute objects or filaments especially in the aqueous which would otherwise escape detection.

ACCESSORY DEVICES

Specialized examinations that can be accomplished with the help of a slit-lamp biomicroscope utilizing certain accessory devices are given below:

- Gonioscopy
- Fundus examination with focal illumination
- Pachymetry
- Applanation tonometry
- Ophthalmodynamometry
- Slit-lamp photography
- Slit-lamp videography
- Slit-lamp as delivery system for argon, diode and YAG laser
- Laser interferometry
- Potential acuity meter test

GONIOSCOPY

The term gonioscopy was coined by Trantas in 1907. It is a clinical technique that is used to examine structures in the anterior chamber angle. Gonioscopic assessment is essential for diagnosing the type of glaucoma and for planning the appropriate therapy. In fact, without reasonable proficiency in the technique of gonioscopy, anybody should be able to manage glaucomas.

PRINCIPLE OF GONIOSCOPY

A direct view of the angle of anterior chamber is not normally possible with the slit-lamp because of overhanging opaque scleral shelf and the fact that light which emanates from the angle is reflected back into the eye by the cornea owing to phenomenon of total internal reflection.

The total internal reflection at the cornea occurs because the angle of incidence of the rays from the anterior chamber angle structures is greater than the critical angle of the cornea–air interface, which is approximately 46 degrees

Fig. 12.19 *The angle of incidence of light rays originating from the angle structures is greater than the critical angle of the cornea–air interface, resulting in total internal reflection.*

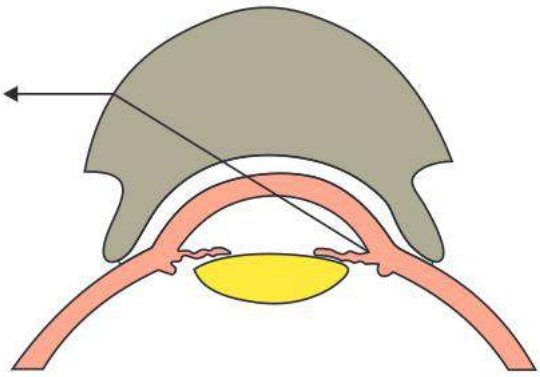


Fig. 12.20 *Schematic drawing of a direct gonioscope.*

(Fig. 12.19). The solution to this problem is to eliminate cornea optically. Gonioscopic contact lenses where refractive index is similar to that of cornea eliminate the optical effect of the front corneal surface. Therefore, light rays from the anterior chamber angle enter the contact lens and are made to pass through the new contact lens–air interface by one of the following two basic designs:

1. **In direct gonioscopes,** the curve of the contact lens (goniolens) is such that the critical angle is not reached and the light rays are refracted at the contact lens–air interface (Fig. 12.20).
2. **In indirect gonioscopes,** the light rays are reflected by a mirror in the contact lens (gonioprism) and leave the lens nearly at right angle to the contact lens–air interface (Fig. 12.21).

DIRECT GONIOSCOPY

It is performed with a steep convex lens, which permits light from the angle to exit the eye closer to the perpendicular at the lens–air interface.

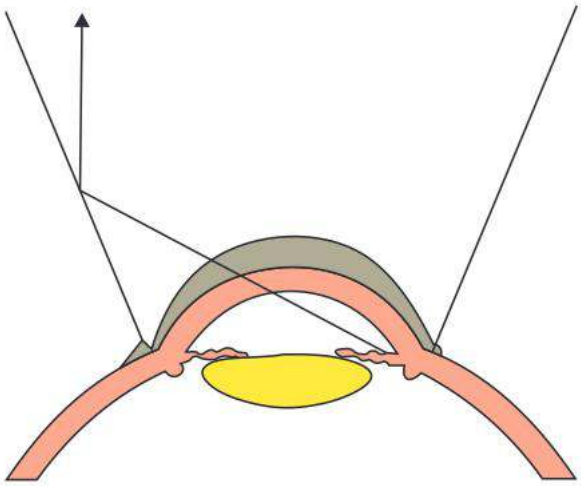


Fig. 12.21 *Schematic drawing of an indirect gonioscope.*

These lenses are used with a portable slit-lamp or an operating microscope. Direct gonioscopy is useful but fairly impractical for routine use. Various types of direct goniolenses are given below:

1. *Koeppegoniolens* 50 D concave lens available in two size for infants (16 mm) and adults (18 mm) is the most commonly used for diagnostic direct gonioscopy.
2. *Huskins Barkan's lens* is a prototype surgical goniolens used for goniotomy. It is available in various sizes and has blunted edges allowing access for goniotomy.
3. *Swan Jacob's lens* is also used for surgical purpose.
4. *Richardson–Shaffer's goniolens* is basically a small Koeppe lens used for infants.
5. *Worth goniolens.* It anchors to cornea by partial vacuum.
6. *Sieback's goniolens.* It is a tiny goniolens which floats on the cornea.
7. Thorpe. Surgical and diagnostic lens.
8. Layden. Diagnostic lens for evaluating neonatal angle.

Technique

Cornea is first anaesthetized with 4% xylocaine instilled topically. The ideal position for direct gonioscopy is the patient lying supine with the examiner sitting on the side of the eye to be examined. With the patient looking up, lower lip of goniolens is inserted below the lower lid. Now the patient is asked to look down

and upper lip is placed beneath upper eyelid. Now with patient's head turned towards the examiner, the nasal lip of goniolens is slightly raised and normal saline drops are used for irrigation. This way all the air bubbles also rise on the top and are removed. Now gonioscopy is performed with the patient looking to the ceiling. A systematic approach is to be followed: nasal angle – superior – temporal than inferior angle.

Advantages

1. Greater flexibility, because position of observer can be changed.
2. Panoramic view is obtained so one part of angle could be compared to the other.
3. Angle becomes deep in supine position so it is easy to see the angle.
4. Detailed examination of minor structures is possible because the observer can change his or her height to look deeper into anterior chamber.
5. Causes lesser distortion of anterior chamber.
6. Can be used in sedated/anaesthetized patients as in infants.
7. Provides a straight view rather than inverted view.
8. Using two lenses, both eyes can be examined simultaneously.
9. Can be used for surgical procedures like goniotomy.

Disadvantages

1. Inconvenient.
2. Annoying light reflexes from cornea.
3. Time-consuming.
4. Benefits of slit-lamp (like variable light and better clarity) are not available.

INDIRECT GONIOSCOPY

Indirect gonioscopy uses mirrors or prisms to overcome the problem of total internal reflection. Gonioprisms have an angled mirror through which light rays from anterior chamber angle are reflected so that they emerge perpendicular to the lens–air interface. Moreover, it uses the slit-lamp's illumination and magnification system to its advantage. And if we are examining all our patients on the slit-lamp – as indeed we should be – it makes sense to use an indirect gonioscope at the same time.

Commercially Available Gonioprisms

I. Gonioprisms Requiring Coupling Agents

1. **Goldmann's three-mirror gonioprism** (Fig. 12.22A). Three mirrors are used as below:
   - The mirror having inclination of 59 degrees and domed upper border is used for gonioscopy. Goldmann's goniomirror has broad area of contact (approximately 12 mm) with cornea, and under pressure may artificially close the angle.
   - The mirror inclined at 67 degrees is used to examine pars plana area of ciliary body.
   - The mirror having inclination of 73 degrees is used to examine ora serrata area of the peripheral fundus.
2. **Goldmann's two-mirror gonioprism** (Fig. 12.22B). Both the mirrors are inclined at 62 degrees. It needs to be rotated once to examine the whole angle.
3. **Goldmann's single-mirror gonioprism** (Fig. 12.22C). The mirror is inclined at 62 degrees. It is a prototype diagnostic gonioprism. It is to be rotated three times to examine the whole angle.

Advantages of Goldmann's gonioprisms

(i) Easy to use, (ii) excellent view, (iii) stabilizes the globe and, therefore, can be used in argon laser trabeculoplasty, (iv) peripheral retina can be seen and (v) Goldmann's two-mirror gives best in situ view of the angle.

Disadvantages of Goldmann's gonioprisms

(i) Curvature of lens is more than that of cornea so a coupling material is required. It blurs vision and fundus; therefore, field charting, direct and indirect ophthalmoscopy cannot be done immediately after its use. (ii) Only one mirror is there for gonioscopy so it needs to be rotated by 360 degrees. (iii) It cannot be used for indentation gonioscopy. (iv) Broad area of contact with cornea is there in case of Goldmann's three-mirror and under pressure it can lead to artefactual closure of angle.

Fig. 12.22 *Various types of gonioscopes: A, Goldmann's three-mirror contact lens; B, Goldmann's two-mirror goniolens; C, Goldmann's single-mirror goniolens; D, Zeiss four-mirror gonioprism; E, Posner gonioprism; F, Sussman lens.*

4. Allen–Thorpe gonioprism. It has got four prisms instead of mirrors and allows examination of the whole angle without rotating the prisms.

II. Gonioprisms Not Requiring Coupling Agents

1. ***Zeiss four-mirror gonioprism*** (Fig. 12.22D) has four identical mirrors angled at 64 degrees which allow examination of the four quadrants without rotation of the lens. By turning only 11 degrees through lens, the smaller areas in between the mirrors can be visualized. Because the lens has small area (9 mm) of contact with the cornea, the angle is deepened by pushing the lens backwards.

Advantages of Zeiss four-mirror gonioprism
(i) Coupling material is not required, (ii) easy to perform when mastered, (iii) all the four quadrants are visible at the same time so no need to rotate the gonioprism; a rotation of just 11 degrees covers the area between the mirrors, (iv) indentation gonioscopy can be performed and (v) as coupling material is not used, visualization of fundus and photography is possible.

Disadvantages of Zeiss four-mirror gonioprism
(i) Difficult to master, (ii) does not stabilize the globe and (iii) may open the angle artefactually, if pressure is applied.

2. ***Posner gonioprism*** (Fig. 12.22E). It is similar to Zeiss gonioprism but is made of plastic instead

of glass and also has fixed rather than detachable handle.

3. ***Sussman lens*** (Fig. 12.22F). It is also similar to Zeiss lens except that it has no handle.
4. ***Tokelgonioprism.*** It is a single-mirror gonioprism and has got a wider field of view.
5. ***Ritch Trabeculoplasty Lens.*** Four-mirrored lens with pairs inclined at 59 and 62 degrees. One of each set has a convex lens over it providing magnification – both diagnostic and therapeutic.

Technique of Indirect Gonioscopy

(1) The eye is anaesthetized with the topical anaesthetic agent. Coupling fluid is poured into the well of the gonioscope. (2) The patient who is sitting on the slit-lamp is asked to look down. (3) The thumb of one hand is used to retract the upper lid. (4) The lower edge of the gonioscope is placed on the lower lid and the gonioscope is tipped on to the cornea in one smooth manoeuvre. In the event of difficulty in keeping the gonioscope in place, a solution like hydroxypropyl methylcellulose 2.5% may be used. This is thick and a little messy, so once one is more experienced, one can use the less viscous hydroxypropyl methylcellulose 0.7%. (5) Slit-lamp beam is focused on the mirror that shows the angle diametrically opposite to it. Image in indirect goniomirrors is inverted but not laterally reversed. Three types of illuminations are used: diffuse, sclerotic scatter and direct focal illumination. By using all these, various subtle findings can be elicited.

Advantages and Disadvantages

Advantages

1. Easier to learn.
2. Faster to perform.
3. Requires less instrumentation and space.
4. Slit-lamp provides better optics and lighting.
5. Corneal wedge can be used to localize angle structures.
6. Indentation gonioscopy can also be done.
7. Magnified stereoscopic view of optic disc can also be obtained.

Disadvantages

1. Comparison is not possible.
2. Limited positioning of light rays.
3. Difficult to perform in horizontal meridian.
4. Mirror image seen, so confusing.
5. Excessive pressure may open or close the angle artefactually.
6. Exaggerates the degree of angle closure.

DISINFECTION OF GONIOSCOPIC LENSES

The American Academy of Ophthalmology issued guidelines for cleaning gonioscopic lens – keeping in mind the presence of HIV and other infectious agents in tears.

- Concave contact area should be wiped with alcohol sponge.
- A 1:10 household bleach (sodium hypochlorite) solution should be filled in the contact area, left for 5 min and then rinsed with water.
- Lenses can be cleaned with 2% glutaraldehyde.
- Glass lenses can be autoclaved.
- Gas sterilization can also be followed out.
- Formalin and phenol have been found to damage lenses.

AIMS AND INDICATIONS AND TYPES OF GONIOSCOPY

Aims and Indications

Gonioscopy is performed on a patient in order to answer at least two questions:

1. Is the angle occludable?
2. Are there any abnormalities in the angle?

There are other questions, such as grading, but they can wait till later.

Techniques of Gonioscopy

To answer the above questions, gonioscopy is done by three techniques:

- Gonioscopy in situ,
- Manipulative gonioscopy and
- Indentation gonioscopy.

Gonioscopy In Situ

To answer the first question, the testing conditions must be appropriate; what we want is an in situ view of the angle. The act of placing any lens on the eye disturbs the angle, but we can routinely use a two-mirror lens to obtain as much of an in situ view as possible. The patient is asked to look straight ahead with the lens on the eye. The room lights are then dimmed; the illumination and the height of the slit-beam are decreased so that it does not impinge on the pupil and cause pupillary constriction (with attendant artefactual opening of the angle). The angle is then observed in situ to assess its occludability.

When no angle structure is directly visible on routine gonioscopy in situ, the closure of the angle can be due to three reasons:

- Optical or apparent closure (due to steep iris configuration),
- Appositional closure and
- Synechial closure.

Having assessed occludability, we look for any other abnormality in the angle. To do this, we increase the room and slit-lamp illumination and allow the light to impinge on the pupil, thereby opening up the angle.

Manipulative Gonioscopy

On routine gonioscopy in situ, the angle structures may not be identified in eyes with a steep iris configuration and a narrow angle. To visualize the angle in eyes with a steep iris configuration, the examiner has to use a special manoeuvre to look over the iris. This technique of manipulating the goniolens to visualize over a steep iris (over the hill view) is known as dynamic or manipulative gonioscopy. This can be achieved in Goldmann's type of lenses by simply asking the patient to look in the direction of the mirror or moving the mirror towards the angle being viewed (Fig. 12.23A–D). This procedure is called *manipulation* (as opposed to

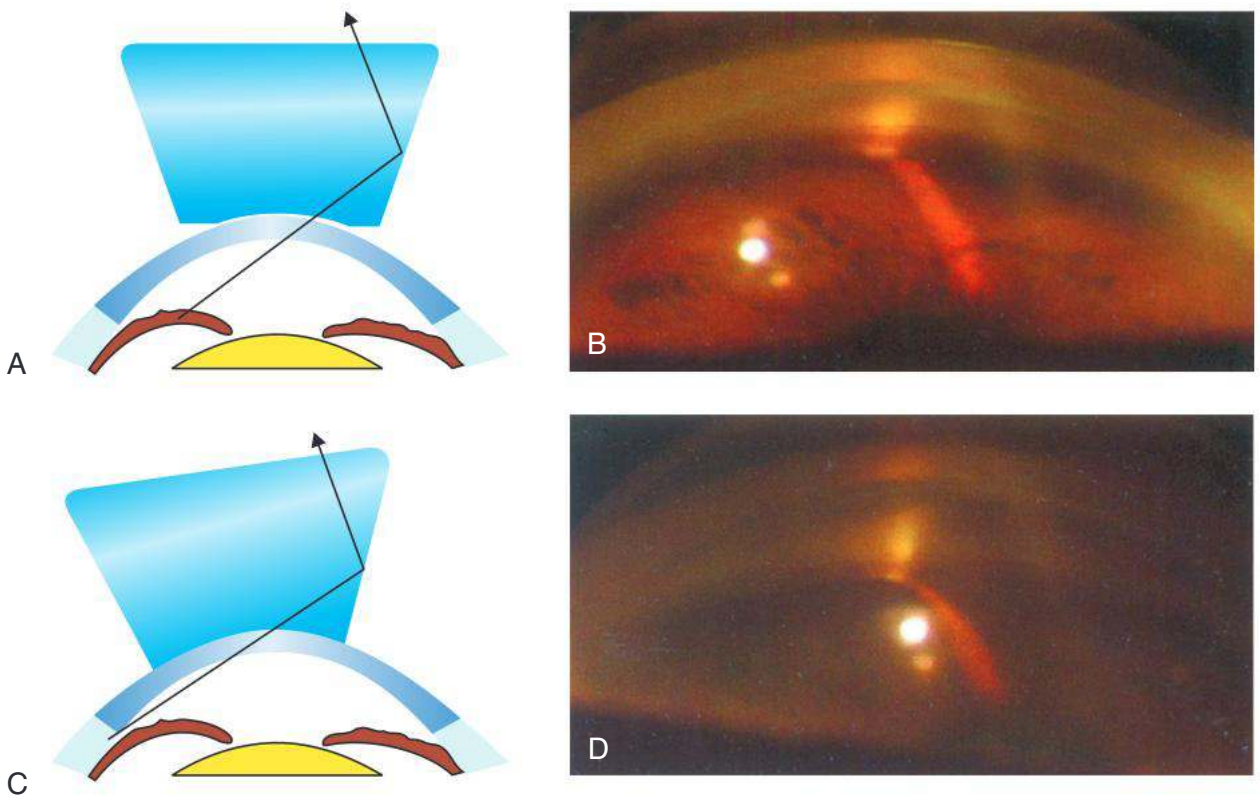


Fig. 12.23 *Gonioscopy in situ versus manipulative gonioscopy in steep iris configuration: A, a schematic diagram to show how steep iris does not allow view of the angle on gonioscopy in situ and gonioscopy view; B, narrow angle recess; C, a schematic diagram to show how manipulation of the gonioscope allows the view of angle recess and the gonioscopic view; and D, open-angle recess.*

indentation). This allows us to look for peripheral anterior synechiae.

Indentation Gonioscopy

If manipulation does not reveal the angle, it can be achieved by *indentation* using an indentation lens. Sussman four-mirror lens is preferred for indentation, since it is held in the hand while Zeiss four-mirror and Posner lenses have to be held by handle. Indentation gonioscopy requires more of patient's cooperation. The indentation lens has to be continuously held just in opposition to the cornea without any pressure. It helps us to differentiate between angle closure due to synechiae from appositional closure. Indentation deepens appositionally closed angle because of aqueous being pushed in the angle (Fig. 12.24).

Besides specific indentation lenses, Goldmann's two-mirror lens can also be used. Another reason for using Goldmann's two-mirror lens is that it is about half the price of an indentation lens. Although it would be nice to have both, but if one can afford only one lens, one can certainly manage very well with a two-mirror lens alone, which is useful 95% of the time.

GONIOSCOPIC VIEW OF ANGLE STRUCTURES

While performing gonioscopy, one can identify the structures from anterior to posterior or vice versa. *Angle structures* seen from anterior to posterior are (Fig. 12.25A):

1. **Schwalbe's line.** It is the peripheral termination of the cornea where the Descemet's membrane ends. It is marked only by a slight change

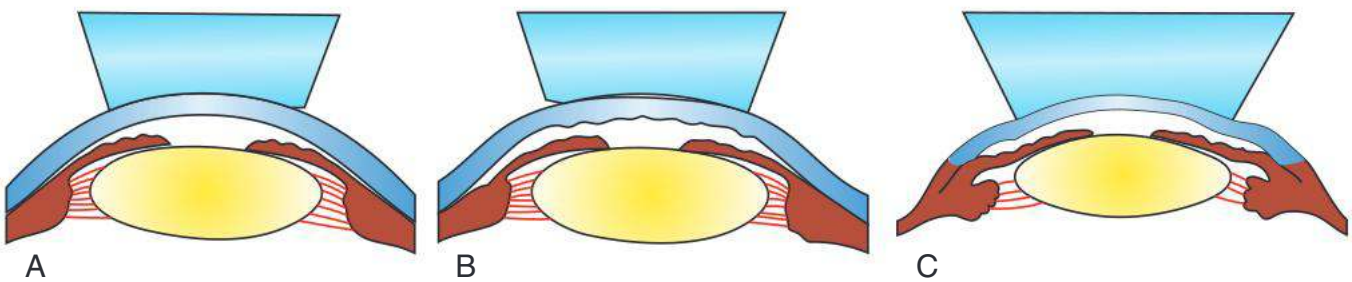


Fig. 12.24 *Schematic diagram to depict how indentation opens the angle recess: A, closed angle without indentation; B, on indentation, the aqueous is pushed into the angle and the angle recess is opened in oppositional closure; C, in synechial angle closure, the angle recess is not opened on indentation.*

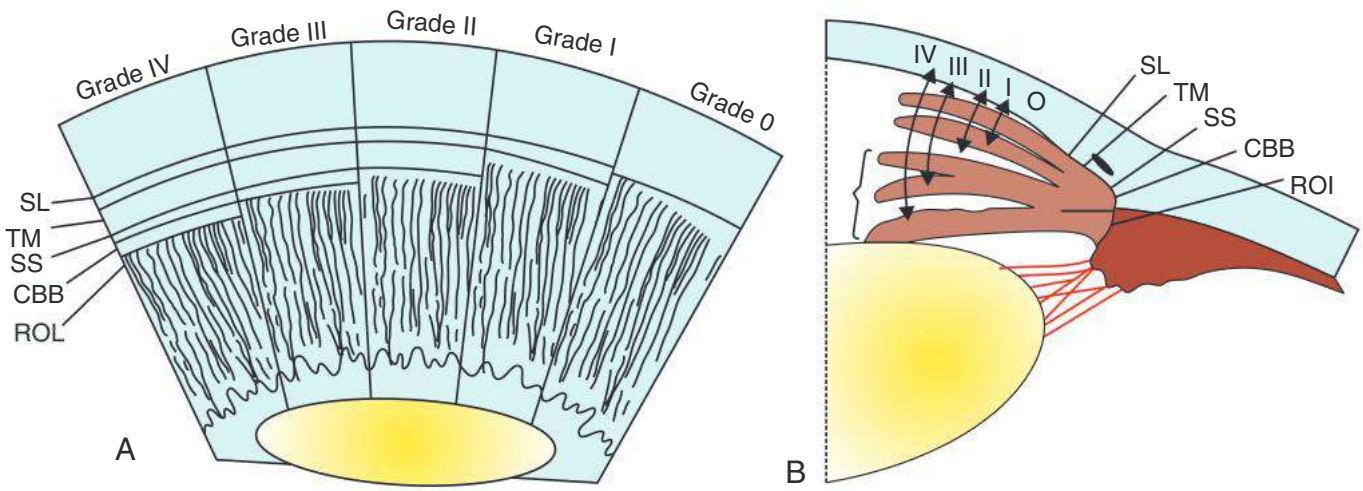


Fig. 12.25 *Diagrammatic depiction of various angle structures (SL, Schwalbe's line; TM, trabecular meshwork; SS, scleral spur; CBB, ciliary body band; ROI, root of iris) as seen in different grades of angle width (Shaffer's grading system): A, gonioscopic view and B, configuration of the angle in cross-section of the anterior chamber.*

in colour from trabecular meshwork or by a faint white line. It can be best identified by locating the *corneal wedge*. A thin slit of light slightly inclined from the oculars is projected on to the cornea. In the angle, two separate corneal reflections are perceived; one illuminates the inner and the other illuminates outer aspect of the cornea. In addition to the inner and outer parts of the cornea, the lines also illuminate the opaque scleral face. The portion between the two lines is called the corneal wedge; the corneal wedge intersects at and identifies Schwalbe's line.

Schwalbe's line is an important landmark in identifying the gonioscopic anatomy in confusing angles. It is easy to make a mistake while doing gonioscopy in eyes with closed angles, hazy corneas and pigmentation anterior to Schwalbe's line. Such a false angle can be mistaken for an open angle. Therefore, one should stress on identifying the Schwalbe's line first and then identifying the structures from anterior to posterior.

2. Trabecular meshwork. It lies between the scleral spur and Schwalbe's line. It has an anterior non-pigmented trabecular meshwork and a posterior pigmented trabecular meshwork. It is non-pigmented and smooth in infants but becomes coarse and pigmented with age.

3. Scleral spur. It appears as thin, white or light grey band (yellowish in elderly) just below the trabeculum. It is a fairly consistent landmark. Argon laser burns, if applied posterior to it, may have increased inflammatory response with concomitant increased intraocular pressure and peripheral anterior synechiae.

4. Ciliary body band. It is light grey or dark brown, just posterior to the scleral spur. Width of the ciliary body band varies (narrow in hypermetropes, wide in myopes or aphakics).

5. Root of iris. Iris contour is slightly convex or flat. Colour varies in different individuals. Radial markings and crypts are present. Peripherally, concentric contraction rolls are present.

6. Other structures that may be visible are as follows:

- *Iris processes*. These are normal variants that should have disappeared in the normal course of development. They appear as fine strands extending from iris to the scleral spur. Unlike peripheral anterior synechiae, iris processes follow the concavity of the angle, do not inhibit the movement of iris during indentation gonioscopy and do not obstruct the flow of aqueous.
- *Blood vessels*. Blood vessels may be present normally and are branches of the major circle of iris. Unlike neovascularization, they are either arranged radially or form loops.
- *Schlemm's canal*. It lies deep in the posterior portion of trabecular meshwork and, therefore, is not visible generally. It can be made visible by filling it with blood. This could be done either by compressing ipsilateral jugular vein or by pressure from Goldmann's lens.

GRADING SYSTEMS FOR THE ANGLE OF ANTERIOR CHAMBER

Several grading systems have been devised to quantify the findings and for future reference:

I. Scheie's Grading

Scheie gave his gonioscopic classification of the anterior chamber angle, based on the extent of visible angle structures as follows:

- *Wide open*. All structures visible.
- *Grade I narrow*. Hard to see over iris root into recess.
- *Grade II narrow*. Ciliary body band obscured.
- *Grade III narrow*. Posterior trabeculum obscured.
- *Grade IV narrow* (closed). Only Schwalbe's line visible.

II. Shaffer's Grading

In this system, an estimation of the angle width is achieved by observing the amount of separation between the two imaginary lines, constructed tangential to the inner surface of the trabeculum and the anterior iris surface. This grading system also provides a method of comparing the widths of the different chamber angles. The system assigns a numerical grade (0–4) to each angle with associated

Table 12.1 *Shaffer's system of grading the angle width*

Grade	Angle width	Configuration closure	Chances of gonioscopy	Structures visible
IV	35–45 degrees	Wide open	Nil	From Schwalbe's line to ciliary body
III	20–35 degrees	Open angle	Nil	From Schwalbe's line to scleral spur
II	20 degrees	Moderately narrow	Possible	From Schwalbe's line to trabecular meshwork
I	10 degrees	Very narrow	High	Schwalbe's line only
0	0 degrees	Closed	Closed	None of the angle structures visible

anatomical description, the angle width in degrees and implied clinical interpretation is as below (Table 12.1 and Fig. 12.25).

1. *Grade 4* (35–45 degrees) is the widest angle characteristic of myopia and aphakia in which the ciliary body can be visualized with ease. It is incapable of closure.
2. *Grade 3* (20–35 degrees) is an open angle in which at least the scleral spur can be identified. It is incapable of closure.
3. *Grade 2* (20 degrees) is a moderately narrow angle in which only the trabeculum can be identified. Angle closure is possible but unlikely.
4. *Grade 1* (10 degrees) is a very narrow angle in which only Schwalbe's line and perhaps also the top of the trabeculum can be identified. Angle closure is not inevitable, although the risk is high.
5. *A slit angle* is one in which there is no obvious iridocorneal contact, but no angle structures can be identified. This angle has the greatest danger of imminent closure.
6. *Grade 0* (0 degree) is a closed angle resulting from iridocorneal contact; it is recognized by the inability to identify the apex of the corneal wedge (Fig. 12.26).

III. RP Centre Gonioscopic Grading

It has been described by Dr Rajendra Prasad Centre for Ophthalmic Sciences, AIIMS, New Delhi, and is based on indirect gonioscopic findings. There is a good inter observer agreement of this system:

Grade 0: No dipping of the beam
Grade 1: Dipping of the beam

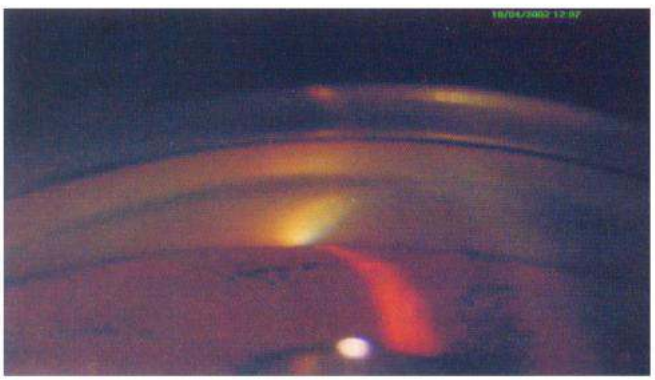


Fig. 12.26 *Gonioscopic photograph revealing grade 0 – angle closure.*

Grade 2: Schwalbe's line and anterior one-third of the trabecular meshwork visualized
Grade 3: Middle one-third of trabecular meshwork visualized
Grade 4: Posterior one-third of trabecular meshwork visualized
Grade 5: Scleral spur visualized
Grade 6: Ciliary body band visualized.

Grades 3 and less are considered narrow. Grades 2 and less are considered closed. The above classification can easily be modified to state the structure seen. This has the advantage that it does not have to be committed to memory; the angle is graded according to the structure seen without converting it into a numerical representation, thus decreasing the chance of inter-observer variability.

IV. Modified Gonioscopic Grading

N: No dipping of the beam
D: Dipping of the beam

SL: Schwalbe's line and anterior one-third of trabecular meshwork seen
TM: Middle one-third of trabecular meshwork visualized
SC: Posterior one-third of trabecular meshwork (location of Schlemm's canal) visualized
SS: Scleral spur visualized
CB: Ciliary body band visualized

Whatever the classification used (or not used), in addition to the grading, the ophthalmologist should make a forced choice decision as to whether the angles are occludable or not, based on the type of entry into the angle (narrow or wide) and the angle structures visible.

SCHEMATIC DRAWING OF GONIOSCOPIC FINDINGS

Gonioscopy involves various systems of classifying the anterior chamber angle, but they stop short of giving information about other pathologies seen. Becker came out with a scheme of representing the gonioscopic findings which involves (Fig. 12.27):

- Drawing a dark circle, depicting scleral spur.
- Drawing three lighter circles outside that for the trabecular meshwork.
- Drawing three circles inside it, depicting various levels of insertion of the iris.

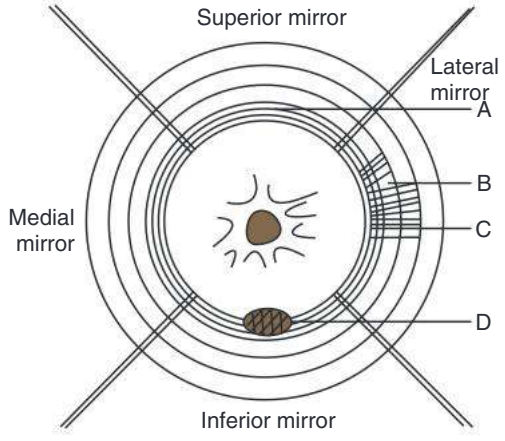


Fig. 12.27 *Schematic drawing of gonioscopic findings: A, neovascularization; B, peripheral anterior synechiae; C, level of insertion of iris; D, peripheral iridectomy.*

- Drawing the pupil in the centre.
- Each eye is examined quadrant-wise – going clockwise, starting from the inferior angle because it usually is the widest and helps in orientation. Colour coding of findings simplifies the interpretation and provides all the information at one glance. For colour coding of gonioscopic findings, refer to Table 12.2.

Gonioscopic findings could be simplified to drawing only three circles as shown in Figure 12.28.

Table 12.2 *Colour codes for gonioscopic findings*

Findings	Colour
Iris	Drawn in colour of the eye, e.g. blue, brown
Iris pathology, e.g.:	
Iridectomy	Black, cross-hatched
Blood vessels	Red
Synechiae	Orange
Membranes	Yellow
Pigment	Black
Depigmentation	Purple
Angle recession	Brown, cross-hatched

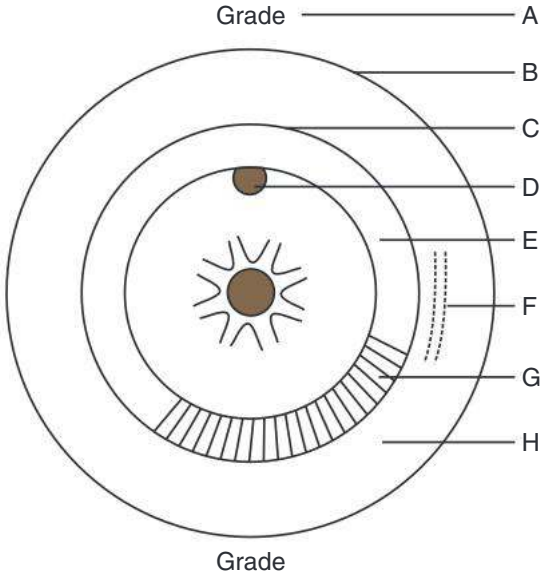


Fig. 12.28 *Modified method of representing gonioscopic findings: A, grading of angle; B, Schwalbe's line; C, scleral spur; D, peripheral iridectomy; E, angle recess; F, position of Schlemm's canal; G, peripheral anterior synechiae; H, trabecular meshwork.*

These methods of standardized representation reduce the need for writing down every finding. They also help in better communication of facts between ophthalmologists. They also make follow-up quicker because the ophthalmologist does not have to refer to voluminous notes each time the patient comes for follow-up.

BIOMETRIC GONIOSCOPY

This is a new method for objective measurement of the anterior chamber angle, proposed by Congdon et al. (*Ophthalmology* 1999; 106:2161–7). In this method, gonioscopic measurements are performed with the help of a special reticule. The anterior chamber angle is viewed under the following conditions on a Haag–Streit 900 BM slit-lamp: ambient lighting from a small side lamp is used to provide only an indirect illumination with a total magnification of 16×, power of 6 W, middle filter setting and a slit-lamp beam of 4 mm length and 1 mm width. The reticule is mounted on a slit-lamp 10× ocular and ruled in 0.1 mm units, which is used to measure the distance between the insertion of the iris and the Schwalbe's line. Measurements are recorded separately in the superior, inferior, nasal and temporal quadrants. If the angle is closed, a measurement of 0 is recorded while an occludable angle is defined as one with an average measurement of 0.25 mm or less for the four quadrants.

This method correlates well with other measures of the anterior chamber angle like conventional gonioscopy and Scheimpflug photography, shows a much higher degree of inter-observer reliability than conventional gonioscopy and can be readily learned and performed by an inexperienced observer. Hence, it offers a definite advantage over conventional gonioscopy, which is purely a subjective technique and has a long learning curve.

AUTOMATED GONIOSCOPY

GS-1, Gonioscope (Nidek Co., Gamagori, Japan) is the first automated gonioscopy enabling degree corneal angle imaging. It allows more clinicians to reliably perform gonioscopy in daily practice.

It captures the entire 360 degrees of the angle using a unique 16 surface multi-mirrored prism lens. Each area is automatically captured in 17 different loci, enabling versatile approaches to the angle.

The acquired images are automatically stitched together, and linear and circular montages of the entire 360 degrees are presented for examination.

This innovative 'Stitching function' provides a view of entire angle to support angle assessment and clinical findings.

CLINICAL USES OF GONIOSCOPY

Some of the many uses of gonioscopy are listed below:

1. To make the crucial differentiation between primary open angle glaucoma and primary angle closure glaucoma.
2. To diagnose and provide a prognosis for the congenital glaucomas.
3. To diagnose secondary glaucomas, especially subtle angle recession, uveitic glaucoma and that due to early neovascularization, and iridocorneal endothelial syndromes. The black pigment balls are quite characteristic of the resolved hyphema. This sign may be the only indicator of past trauma.
4. To diagnose conditions like tumours of the anterior segment, ciliary body cysts, intraocular foreign body and for early detection of Kayser–Fleischer ring.
5. To diagnose unusual causes of glaucoma, e.g. a haptic of a posterior chamber lens protruding through the peripheral iridectomy and resting in the angle of anterior chamber. The resultant pseudophakic pigmentary glaucoma can only be diagnosed by gonioscopy.
6. Gonioscopy for treatment. To perform argon laser trabeculoplasty, laser iridoplasty, laser cyclophotocoagulation. Gonioscopy is also necessary for follow-up on patients who have undergone peripheral iridotomy, trabeculectomy. It now becomes obvious that in addition to the patient care and academic purposes, learning gonioscopy has the potential to more than pay for the cost of gonioscopes.

7. Indentation gonioscopy can be used to break an attack of acute angle closure glaucoma.

■ LIMITATIONS ARTEFACTS OF GONIOSCOPY

Limitations

1. Cannot be performed in painful inflamed eyes.
2. Difficult to perform in cases of acute glaucoma where eyes are painful, congested and have oedematous cornea.
3. Mydriatic drugs obscure angle by bunching up iris; therefore, it is not possible to perform gonioscopy in such cases.

Artefacts

1. Excessive pressure artefactually opens an angle while using Goldmann's four mirrors or closes the angle while using Goldmann's single mirror.
2. Residues on lens because of oily secretion or methylcellulose may give rise to artefacts.
3. Mirror in Goldmann's goniomirrors is closer to the centre of cornea; therefore, angle recess is better seen, which could give erroneous impression of open angle in case of narrow angle glaucoma.

OPTICAL PACHYMETER

Pachymetry refers to the measurement of corneal thickness. This measurement gained importance for planning refractive corneal surgeries.

Methods of pachymetry include:

I. Ultrasonic techniques
- Conventional ultrasonic pachymetry
- Ultrasound biomicroscopy (UBM)

II. Optical techniques
- Manual optical pachymetry
- Specular microscopy
- Scanning slit technology
- Optical coherence tomography
- Optical low coherence interferometry
- Confocal microscopy
- Laser Doppler interferometry

III. Optical pachymetry with corneal types
- Orbscan
- Pentacam
- Pachycam

IV. Pachymetry with ocular response analyser (ORA)

Functioning of the manual optical pachymeter is discussed here briefly.

■ INSTRUMENT DESCRIPTION

Optical pachymeter is used with the slit-lamp. It hangs over the objectives of the microscope from a part attached to the microscope body. The left objective is occluded by the pachymeter, while the right one has two glass plates with parallel sides placed in front of it. These plates rest one on top of the other, with the junction between them situated so as to horizontally bisect the objective. The upper plate can be rotated while the lower plate is fixed and positioned so that its faces are normal to the axis of microscope.

■ OPTICAL PRINCIPLE

The optical pachymeter utilizes the principle of optical image doubling and is designed to measure the distance between the Purkinje–Sanson images formed by the anterior and posterior corneal surfaces, a value that represents the corneal thickness.

■ OPTICS

Working optics of the optical doubling pachymeter depicted in Figure 12.29 is described below:

- The slit-beam (a in Fig. 12.29) illuminates the patient's cornea.
- The image is viewed through a biomicroscope, half through a glass plate orthogonal to the path of light (b in Fig. 12.29) and half through another glass plate rotated through an angle (c in Fig. 12.29).
- The beam path through glass plate is displaced laterally for a distance (d in Fig. 12.29) that varies depending upon the angle of rotation.
- Through the eyepiece (e in Fig. 12.29), the observer views a split image. The half of the image (f_1 in Fig. 12.29) comes from the fixed plate and the other half (f_2 in Fig. 12.29) from the rotatable plate.

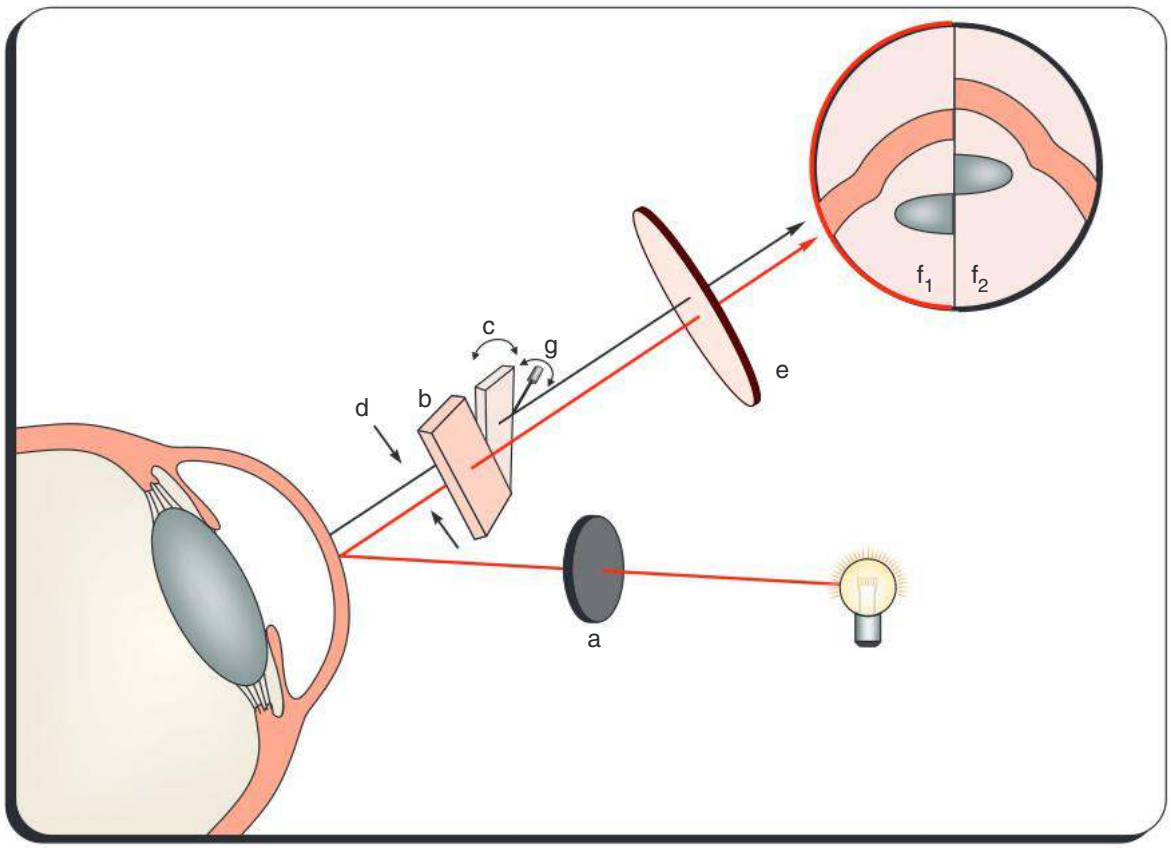


Fig. 12.29 *Optics of the optical pachymeter (for explanation see text).*

Measurement of Corneal Thickness

- To measure the corneal thickness (as shown in Fig. 12.30), the observer aligns the endothelial surface of one image with epithelial surface of the other image by carefully adjusting the rotatable plate (d in Fig. 12.29).
- Value of corneal thickness is read off the calibrated scale (g in Fig. 12.29).
- As the apparent thickness of the cornea varies with the angle between the slit-lamp and the microscope, it is essential to set this at some predetermined value before a measurement is made. With the Haag–Streit slit-lamp, this angle should be 40 degrees (Fig. 12.29).

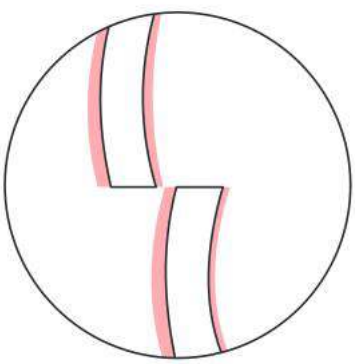


Fig. 12.30 *Showing end point of pachymetry.*

SPECULAR MICROSCOPY

Specular microscopy is a procedure that provides the clinical and morphological study of corneal endothelial cells in vivo without disturbing their function. Efforts were made by Vogt, more than 75 years ago, to examine the endothelial cell morphology in the reflected light of the slit-lamp biomicroscope. However, fine rapid movements of the eye and limited magnification preclude the use of this technique for systematic studies of the endothelium. Maurice (1968) introduced the

'specular microscope' for examination of the corneal endothelial cells at high magnification (400×). This instrument used Vogt's reflection principle but separated illuminating and viewing light paths at a fixed angle in a split microscope objective. Laing (1975) adopted specular microscope for clinical use. He replaced the original water immersion lens with a dipping case objective to applanate the cornea. Baurne et al. (1976) simplified the specular microscope for rapid endothelial examination and photography at 200×.

OPTICS

The specular microscope is a reflected light microscope which projects a slit of light on to the cornea and utilizes the light reflected from an optical interface of tissue for image formation (rather than light transmitted through the tissue sample). It is the difference in refractive indices between the endothelial cells and aqueous humour which gives rise to this specular or mirror-like reflection at the flat posterior surface. The reflected light is estimated to be about 0.02% of the incident light. Figure 12.31 shows a drawing of the optics of the visualization of the endothelial mosaic produced by slit-lamp biomicroscopy. Reflected light from the epithelium and stroma obscures the view of the endothelium unless a narrow slit of light is used for illumination. Laing described that specular microscopy yields an image with three or four distinct zones (Fig. 12.32), depending upon the width of the illuminating slit as:

- Zone 1. Epithelium/lens-coupling fluid
- Zone 2. Corneal stroma
- Zone 3. Corneal endothelium
- Zone 4. Aqueous humour

The boundary between endothelial region (zone 3) and aqueous region (zone 4) is almost dark and is termed the *dark boundary*. The boundary between endothelium region (zone 3) and stroma (zone 2) is usually bright and is termed the *bright boundary*.

TYPES OF SPECULAR MICROSCOPES

There are two basic types of clinical specular microscopes:

1. CONTACT SPECULAR MICROSCOPES

Commercially available contact specular microscopes include:

- Keller-Konan, SP-580 (Konan Medical USA, Torrance, CA, USA)
- EM-1000 (Tomey, Erlangen, Germany)
- HAI Labs; HAI CL-1000.

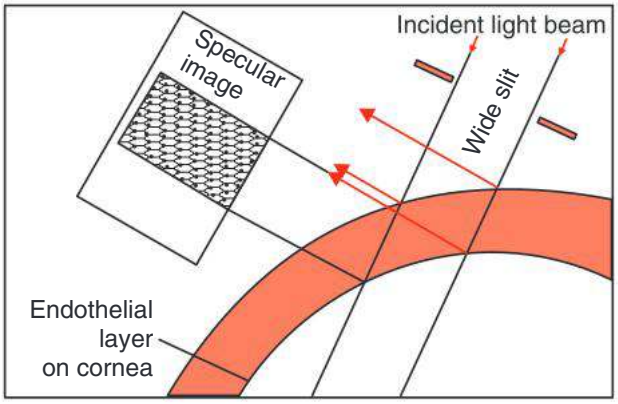


Fig. 12.31 *Schematic drawing of the endothelial layers as seen with slit-lamp microscopy. Note the wide angle between the illuminating beam and the observation path needed to remove the annoying surface reflection and stroma scatter from view of the endothelial mosaic.*

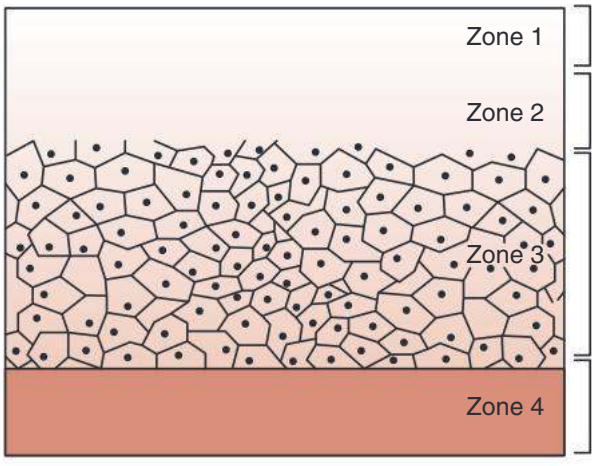


Fig. 12.32 *Specular micrograph of endothelial cells showing four distinct zones.*

In such types of specular microscopes, a contact lens with a coupling fluid of index of refraction similar to that of cornea is used to eliminate the corneal surface reflection. The corneal thickness in such an arrangement can be thought to also include the contact lens thickness. The reflection from the surface of contact lens replaces that of the corneal surface. However, because of the thickness of contact lens, the surface reflection is moved well over to side (Fig. 12.33).

Such specular microscopes provide good resolution and magnification. But the patients are less comfortable and there is a risk of spread of infection, if strict sterile precautions are not taken. Further, manipulating the cornea with this technique may cause *artefacts*, especially in fragile, diseased cornea.

2. NON-CONTACT SPECULAR MICROSCOPES

Commercially available non-contact specular microscope includes the following:

- Automated SM is SP-3000p (Topcon Medical Systems Inc., Paramus, NJ, USA)
- Biooptics: LMS-12000
- Konan ROBO Pachy/CASP.

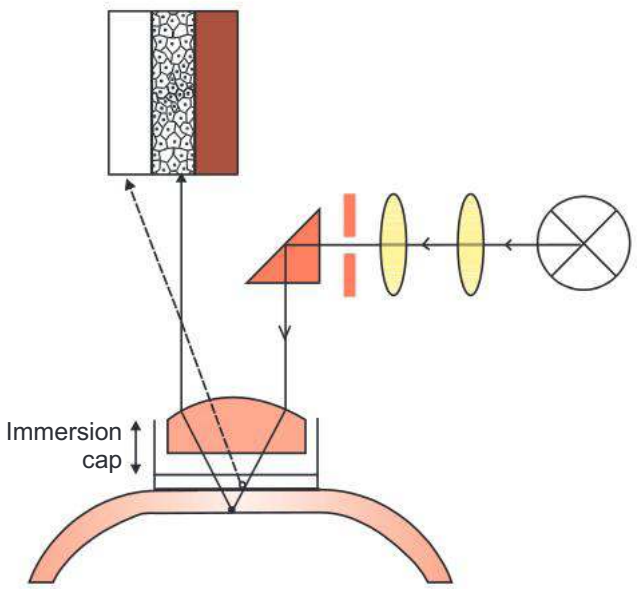


Fig. 12.33 *Optics of contact lens-assisted endothelial specular microscope.*

In non-contact specular microscopes, the bothersome reflection from the front corneal surface is eliminated by increasing the angle of incidence. As shown in Fig. 12.31, by increasing the angle of incidence, the anterior reflection is moved to the side, covering less of specular reflection from the endothelium. These microscopes have the advantages of greater patient tolerance and acceptability, and there is no risk of trauma to the cornea. However, a broader view is obtained at the expense of resolution and magnification due to uncontrolled eye movements.

WIDE-FIELD SPECULAR MICROSCOPES

A modification to the standard specular microscope has been described with the use of a scanning mirror. In this way, fields of 800 μm in diameter have been achieved with no loss in contrast. The technique allows continuous viewing of the 800 μm diameter area because of the high speed of mirror oscillation.

Advantages

The wide-field specular microscopes combine the advantages of both the above microscopes.

- Field of view is 10–15 times larger, the resolution is high and image quality is less susceptible to eye movements.
- Endothelial layer topography is more readily evaluated. The relocation of a specified region of the endothelium is relatively easy and the larger field provides more accurate cell counts.
- *Resolution of endothelium* has been further improved by the addition of highly sensitive video cameras and recording systems, as well as a variety of optic improvements such as scanning mirror system.
- Annoying reflections from the incident light have been minimized by the improvements in optics.

PROCEDURE

Currently available contact and non-contact wide-field specular microscopes are easy to use

with little patient discomfort. The procedure is first explained to the patient to relieve any anxiety. The contact specular microscopy procedure is very similar to that of Goldmann's applanation tonometry (Fig. 12.34A). The whole cornea should be systematically scanned to ensure complete evaluation of the endothelial mosaic – centrally, superiorly, inferiorly, nasally and temporally (Fig. 12.34B).

METHODS OF ANALYSIS

For cell analysis, a minimum of 75 cells should be counted. The early processing methods were tedious and time consuming. The introduction of large-field microscopes has made the process a bit simplified.

Methods of endothelial cell analysis are as follows:

1. ***Cell density.*** The number of cells in a photographic field is counted to obtain the cell density. The cell count is calculated per square millimetre. The cell density of endothelium is around 3500 cells/mm^2 in young adults, which decreases with the advancing age (2000 cells/mm^2). There is a considerable functional reserve for the endothelium. Corneas with cell count <1000 cells/mm^2 poorly tolerate intraocular surgery.
2. ***Fixed frame analysis.*** In this method, the photograph of endothelial cells is compared to the drawings of endothelial mosaic of known size. It provides quantitative assessment of the cell density by counting the number of cells within a frame.
3. ***Tracing analysis.*** The tracing of the individual cell outlines can be made and subsequently analysed for individual cell areas and other parameters.
4. ***Analysis of digested cells.*** The cells may be digested after tracing their outlines, using a digesting tablet. The analysis can then be made using a photograph – a negative image on a television screen or a videotaped recording.
5. ***Computerized image analysis.*** The computerized cell analysis provides the mean cell density, i.e. cells per square millimetre, and frequency distribution of the individual cell sizes, and analyses the polygonality.

QUANTITATIVE AND QUALITATIVE ANALYSIS BY SPECULAR MICROSCOPY

Calculation of Cell Density (Quantitative Analysis)

To calculate the cell density, a rectangular area can be determined manually. All the cells completely within the border of the rectangle as well as those touching two adjacent borders are marked. However, this technique gives only the

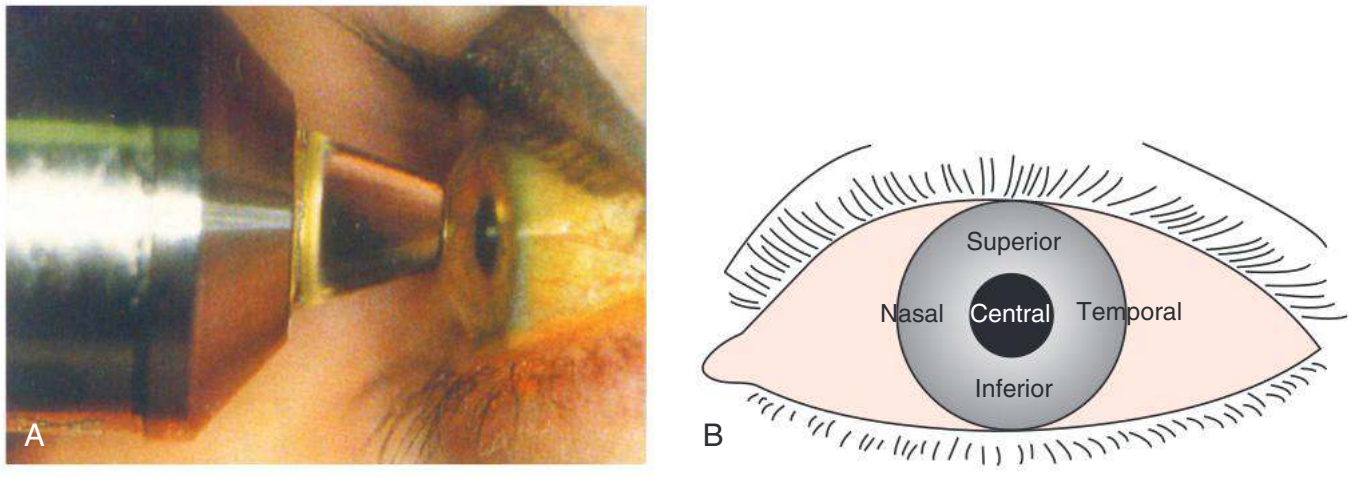


Fig. 12.34 *Procedure of specular microscopy: A, placement of applanation cone in the centre of cornea with the light shining through the pupil and B, areas of cornea for systematic scanning of endothelium.*

cell density in cells per square millimetre. The other method is to mark the centre of adjacent cells. This allows automated computation of the mean cell area, maximum cell area (MAX), minimum cell area (MIN), number of cells actually analysed (NUM), mean cell density (CD) and standard deviation of the mean cell area (SD).

Study of Cell Morphology (Qualitative Analysis)

Alterations in morphology – such as variations in cell size, i.e. polymegathism and cell shape, i.e. pleomorphism – and asymmetry of the cell population may be more reliable indices of endothelial stress than mean cell density alone.

- *Coefficient of variation*. The degree of uniformity of cell size is determined by measuring the areas of a population of cells and calculating the coefficient of variance, which is the standard deviation of mean cell area divided by the mean cell area, i.e. SD/AVE. The normal endothelium has a coefficient of variance of 0.25. An increase in this value means that the cell size is variable and is known as polymegathism. Cell size varies over a wide range in a number of disorders, and endothelial cells may assume shapes that are substantially different from their usual hexagonal appearance.
- *Percentage of hexagonal cells*. Cell boundaries normally intersect in a manner that results in three angles of intersection, each approximately 60 degrees. The endothelial mosaic in healthy young corneas consists of 70%–80% hexagonal cells. A decrease in hexagonality with a concomitant increase in the number of cells with more or fewer than six sides is known as pleomorphism.

COMMERCIALLY AVAILABLE SPECULAR MICROSCOPES

KONAN NONCON ROBOCA SP 8000 SPECULAR MICROSCOPE

It is a computerized non-contact type of specular microscope. It includes an autofocus device to record the specular images readily. There is also an incorporated semi-automated image analysing program. The software program has got two analysing modalities for cell density and cell morphology. With Konan Noncon Roboca Sp 8000, it is possible (i) to calculate the individual cell area, with which the coefficient of variance can be deduced as a degree of polymegathism and (ii) to analyse the polygonality, i.e. percentage of hexagonality.

KEELER–KONAN SPECULAR MICROSCOPE

It is a contact type wide-field specular microscope. Its advantages over the non-contact type wide-field specular microscope are follows:

- It allows more detailed study of corneal endothelium. Different magnification cones can be used to study the endothelial morphology.
- It also allows the study of corneal epithelium, corneal stroma, the crystalline lens epithelial surface, the surface of IOL and the posterior capsule. The entire cornea can be examined by moving the cone manually over the corneal surface.

CLINICAL USES OF SPECULAR MICROSCOPY

1. Assessment of changes in the endothelium:
   - With ageing.
   - *Following surgical procedures* such as:
     - Corneal grafting,
     - Cataract surgery with or without IOL implantation and
     - Newer procedures like excimer laser and LASIK.
   - *With associated conditions* such as:
     - Glaucoma,
     - Uveitis,
     - Contact lens wear and
     - Trauma – blunt or penetrating.
   - With use of intra-cameral drugs, irrigating solutions and topical medications.
2. Assessment of endothelium in donor corneas and the effect of preservation.
3. Assessment of naturally occurring diseases, degenerations and dystrophies.

4. Assessment of longitudinal effect of surgical procedures.
5. Measurement of corneal thickness, i.e. pachymetry (with contact type only).
6. Assessment of the epithelium of the cornea and the crystalline lens.

COMPREHENSIVE ANTERIOR SEGMENT ANALYSER

PENTACAM

Pentacam is the trade name of 'Comprehensive Anterior Segment Analyser' – which originally was a five-in-one innovation from the Oculus, Germany. The latest model, 'Pentacam AXL', is an upgraded version of 'Pentacam HR'. It is now equipped to measure axial length, and this also allows the surgeons to make IOL calculations. Basically, it is three-dimensional (3D) rotating Scheimpflug camera. Pentacam (Fig. 12.35) is a diagnostic unit able to perform following functions in 2 s:

- Scheimpflug image of anterior segment
- 3D anterior chamber analyser
- Pachymetry
- Corneal tomography
- Cataract analyser
- Measurement of axial length of eyeball

Fig. 12.35 *Pentacam – a five-in-one 3D rotating Scheimpflug camera.*

Technical Data

Technically, the Pentacam system uses the following:

- *Blue light* (UV-free), 475 nm, to illuminate the eye.
- *Rotating Scheimpflug camera* for taking images. It is a custom-designed digital charge-coupled device (CCD) camera with synchronous pixel sampling.
- *Processor* – an ultrafast DSP (digital signal processor) with 400 million operations per second.

Working Principle

The newer version, Pentacam AXL is a dual Scheimpflug and Placido ring imaging system.

Principle of measurement. The Scheimpflug law says, 'To get a higher depth of focus, move the three planes, provided that the picture plane, the objective plane and the film plane has to cut each other in one line or one point of intersection' (Fig. 12.36).

The Pentacam captures Scheimpflug images of the anterior segment through a rotating measurement (Fig. 12.37). This rotating measuring process supplies picture in three dimensions. It obtains 50 scans in 2 s with 500 true elevation points per scan surface, i.e. about 25,000 measured and analysed true elevation points. It calculates a 3D model of the anterior segment of the eyeball, based on the measured elevation data. All further information is deducted from this 3D model.

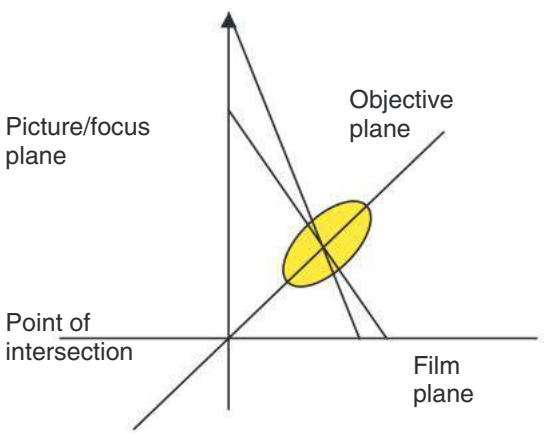


Fig. 12.36 *Schematic diagram of Scheimpflug principle.*

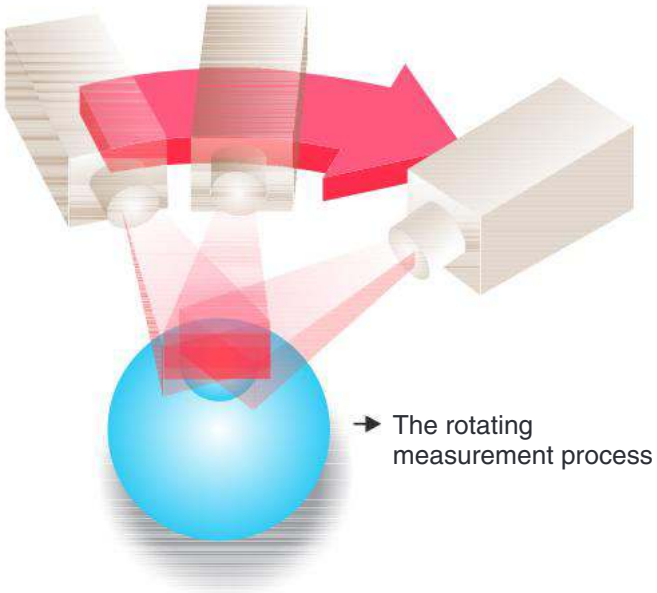


Fig. 12.37 *The rotating measuring process with Pentacam.*

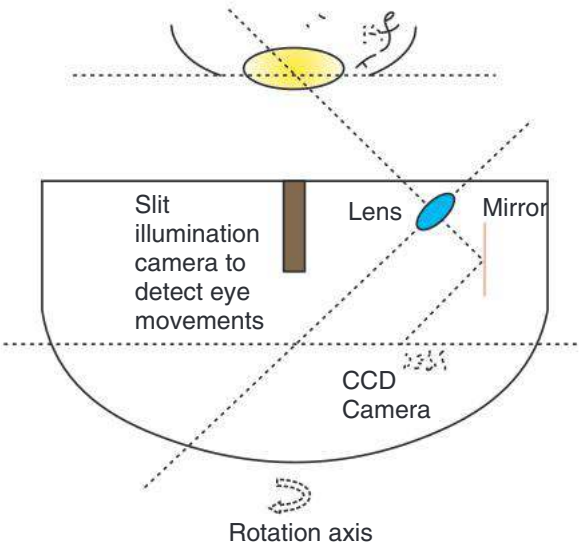


Fig. 12.38 *Schematic assembly of the Pentacam.*

Procedures

Pentacam scanning is a non-contact procedure and takes less than 2 s to complete. During the scan, fixation control is achieved via a second camera focused on the pupil that monitors size and orientation (Fig. 12.38). The detected eye movements are corrected for automatically after the scan is completed. Thus, the examination process is very comfortable, rapid and accurate.

Functions (Outputs)

Pentacam is a five-in-one device that generates following outputs:

1. ***Scheimpflug image***. It obtains a clear, sharp Scheimpflug image depicting the entire anterior segment from the cornea to the posterior lens surface, including the angle area to the most distal 100–150 microns (Fig. 12.39). This image can also be reviewed with 3D animation.
2. ***Corneal topography***. It provides topography maps of the anterior and posterior surfaces of the cornea based on the measurement of approximately 25,000 true elevation points (Fig. 12.40). Through the rotating measurement, the centre of the cornea is fine meshed.

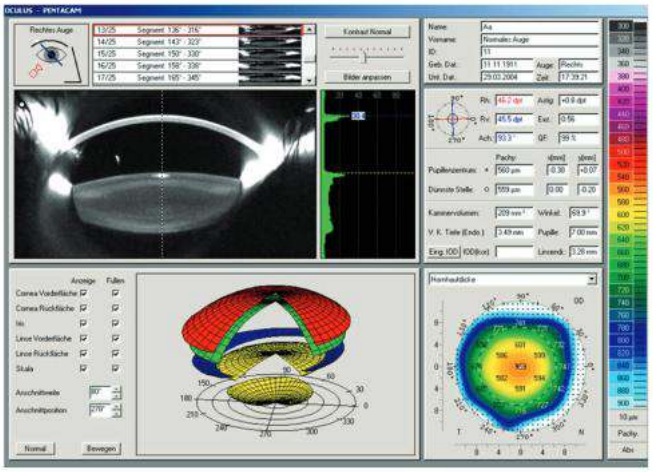


Fig. 12.39 *Pentacam: Scheimpflug image of anterior segment.*

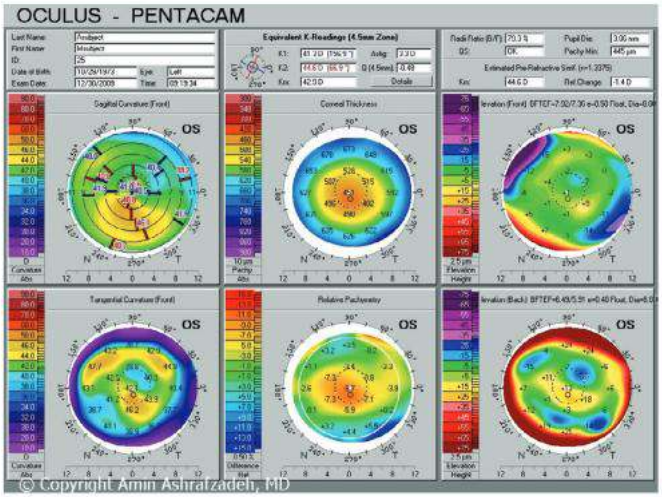


Fig. 12.40 *Pentacam: corneal topography map.*

The topographic analysis of the anterior and posterior corneal surfaces is based on the true elevation measurement. It includes the following:

- Various topographic maps.
- Elevation maps with free multiple reference shapes.
- True net power map which considers the influence of the posterior corneal refractive power.
- Keratometric power deviation map which shows the difference between sagittal power and true net power.
- Several standard and user-selectable four-map printouts.
- Various comparison and difference screens.
- Keratoconus detection and quantification based on topography and pachymetry data.
- Corneal wavefront of the anterior and posterior corneal surfaces using Zernike polynomials (Fig. 12.41).

Applications include:

- Keratoconus detection,
- Pre-operative planning for any corneal refractive surgery,
- Progression control after corneal surgery and
- Improved IOL calculation for post-LASIK patients.

3. *Pachymetry.* The corneal thickness is displayed as a colour image over its entire area from limbus to limbus (Fig. 12.42). The actual thickness can be evaluated individually by a mouse click at any location or by using the numerical function.

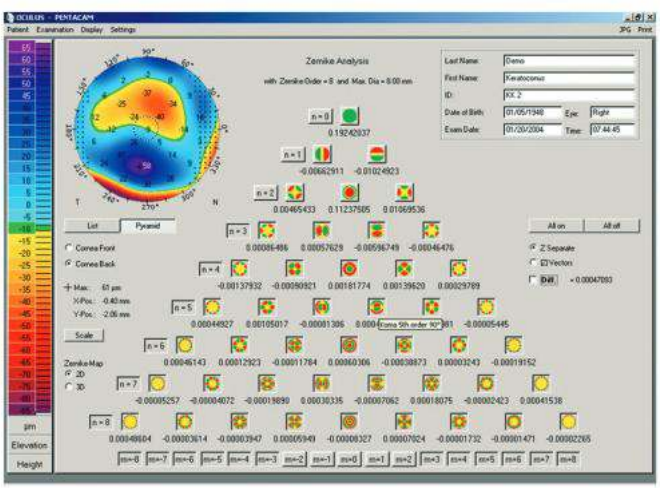


Fig. 12.41 *Pentacam: corneal wavefront.*

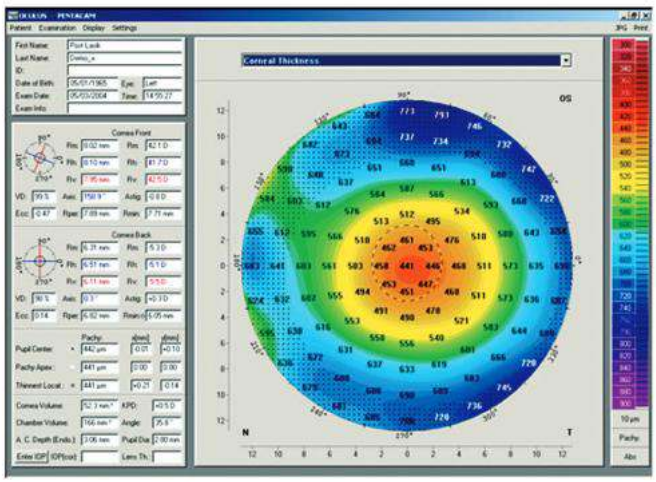


Fig. 12.42 *Pentacam: pachymetry map.*

The most important points are displayed in values and location, such as:

- Thickness in the pupil centre,
- Thickness in the apex,
- Thinnest location and
- Corneal volume.

Applications include:

- Pre-operative planning for corneal refractive surgery,
- Glaucoma screening,
- Intraocular pressure modification with regard to corneal thickness and
- Keratoconus detection and quantification.

4. *3D anterior chamber analyser*. It provides:

- Coloured map of the anterior chamber allowing evaluation for chamber angle, chamber volume, chamber depth and chamber height,
- Tomography tool and a virtual 3D model of the anterior chamber and
- Manual measurement function in the Scheimpflug images.

Applications include:

- Allows improved pre-operative planning for implanting phakic lenses as well as post-operative control and
- Glaucoma screening.

5. ***Densitometry of the lens***. Pentacam's densitometry of the human lens provides the ophthalmologist with an analysis of the lens thickness and of structural alterations like radial opacities and early or advanced calcification of the lens core. In other words, the Pentacam also works as 'cataract analyser' (Fig. 12.43). Densitometry comes with following advantages:

- The evolution of a cataract can be made visible even at an early stage.
- It makes classification of the cataract easy.
- Long-term controls of cataracts are possible.
- The extension of the cataract can be measured.
- Knowing the thickness of the lens is helpful for the ophthalmic surgeon in deciding which type of IOL to use for implantation.

6. ***Improved IOL calculations in post-LASIK patients*** (Fig. 12.44). Patients who have previously undergone corneal surgery and subsequently develop cataracts have frequently posed a significant problem, as the calculations for the power of the lens to implant have frequently been inaccurate. This problem is well-known and several methods have been tried to get proper k-readings for the calculation of the IOL, but no method has been precise enough. In fact, all the methods which have been in use so far are based entirely upon assumptions and approximations. The Pentacam system provides the surgeon with an accurate program, developed in conjunction with Dr Jack T. Holladay, to improve the calculation of IOLs for patients who have undergone corneal surgery.

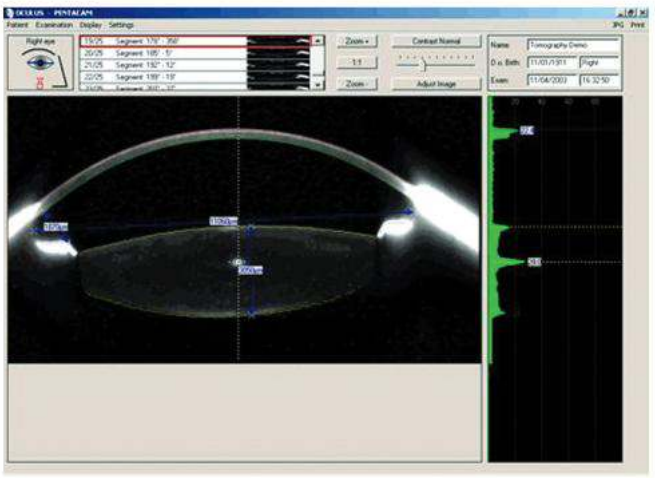


Fig. 12.43 *Pentacam: cataract analyser.*

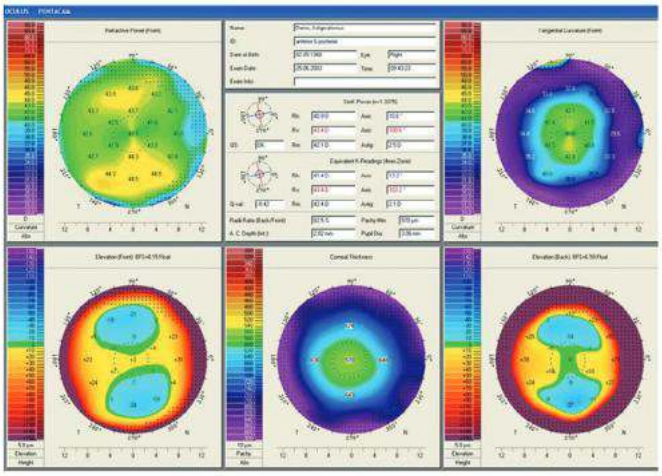


Fig. 12.44 *Intraocular lens (IOL) calculation map of Pentacam.*

7. ***Measurement of axial length***, with great accuracy is now possible with latest upgraded version, the Pentacam AXL.

Advantages of Pentacam

The most important features of this examination are as follows:

- Automatic initiation of the measurement
- High reproducibility
- Non-contact measuring
- Less than 2 s required
- Pentacam's pachymetry provides an accurate data from one limbus to the other
- Examination is easy, efficient and time-saving (surgeon's friend)

CONFOCAL MICROSCOPY OF CORNEA

Clinical confocal microscopy is a new bioimaging technique which enables non-invasive analysis of corneal structure and function. Minsky described the first confocal microscope in 1957. Since then several improvisions have occurred. Bohnke and Masters (1999) have detailed the optical techniques for ocular biomicroscopy and theoretical foundations of confocal microscopy. The most modern confocal

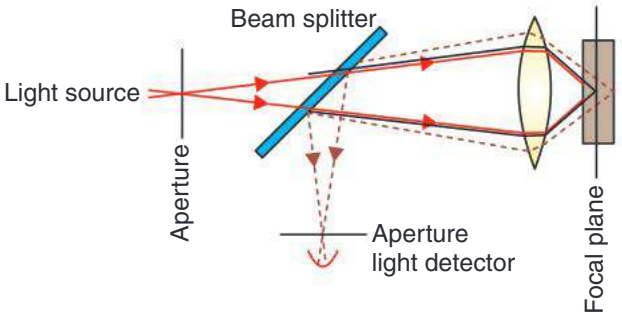


Fig. 12.45 *Diagrammatic representation of the optical principles of the confocal microscope.*

microscopes have light source focused on to a small volume within the specimen tissue, and a confocal detector is used to collect the resulting signal to produce an image with enhanced lateral and axial resolution. This new imaging paradigm and its application in vivo provide insight into the understanding of the structure and function of the eye.

PRINCIPLE

The principle of the confocal microscope was first described by Minsky. He proposed that both the illumination (condenser) and observation (objective) systems be focused on a single point (have common focal points), hence the name 'confocal' microscopy (Fig. 12.45). This dramatically improved the axial (z) and lateral (x, y) resolution of microscopy by eliminating out focus information, bringing lateral resolution to an order of 1–2 µm and axial resolution to 5–10 µm. This allows for possible magnification of up to 600 times, depending on the numerical aperture of the objective lens used. As the field of view of the confocal imaging systems is limited, it is necessary to rapidly scan the focal point across the sample and reconstruct the image to allow a real-time on-screen view.

TYPES OF CONFOCAL MICROSCOPE

Depending on the method of scanning, following types of confocal microscopes are known.

1. ***Tandem scanning confocal microscope***. Optics of tandem scanning confocal microscope is depicted in Figure 12.46. In it, thousands of light beams are moved over the fixed object, generating a high scan rate. These parallel beams are generated by a Nipkow wheel – a disc with thousands of pinholes spinning at high speed. These apertures are arranged in tandem, i.e. as diametrically opposed pairs. Light passes through one pinhole and is then reflected back through the corresponding pinhole situated opposite. The high-speed rotation of the disc enables the light beam to scan the full field of view many times a second, thus producing a real-time image.

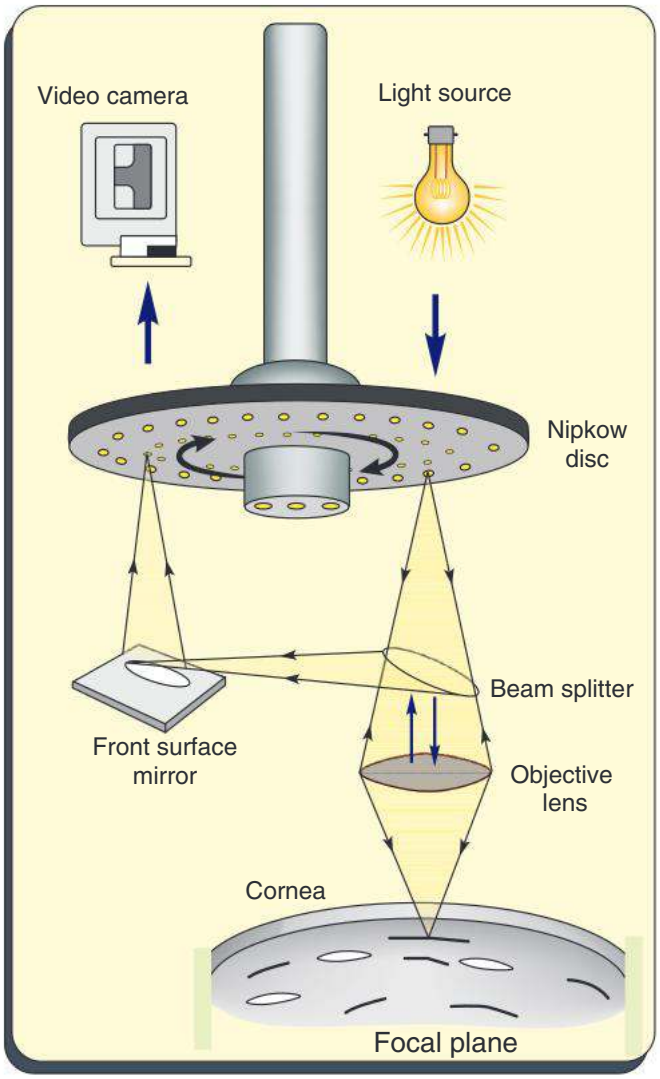


Fig. 12.46 *Optics of tandem scanning confocal microscope.*

2. ***The scanning slit confocal microscope*** uses a light source with 1D spot scanning instead of 2D spot scanning.

3. ***The confocal laser scanning microscope (LSM)*** uses a laser beam and this generates a monochromatic, bright, intense, sharply focused and coherent light. A novel digital confocal LSM, recently developed, is a combination of the Heidelberg retina tomograph (HRT II) and the Rostock cornea module (RCM). LSM has a computer-controlled hydraulic linear scanning device and a water contact objective and diode laser beam of 670 nm wavelength is used as the light source. The Rostock scanning laser confocal microscope provides reproducible images of high resolution with uniform illumination and precise depth measurements.

CONFOCAL MICROSCOPY OF THE NORMAL HUMAN CORNEA

- *Superficial epithelial cells* are seen with clear visible cell borders, bright cytoplasm and black nuclei. These cells are characteristically polygonal, usually hexagonal in shape (Fig. 12.47A).
- *Intermediate layer of wing cells* comprises cells smaller than the superficial cells, with bright cell borders and dark cytoplasm. These cells are fairly uniform in size and shape (Fig. 12.47B).
- *Basal epithelial cells* are located just above the Bowman's membrane and are seen as a distinct mosaic, with light cell boundaries. The basal epithelial cells are the smallest cells in the epithelium (Fig. 12.47C).
- *Bowman's layer* appears as a homogenous acellular layer and nerve fibres of the subepithelial nerve plexus are seen as beaded nerve fibres (Fig. 12.47D).
- *Keratocyte nuclei* are identified as bright reflections in the stroma. The anterior stromal keratocyte nuclei are more abundant and oval compared to the posterior keratocyte nuclei, which were less abundant and more oblong in shape (Fig. 12.47E).
- *Endothelial cells* are visible as bright cell bodies and dark cell boundaries, characteristically hexagonal in shape with fairly uniform appearance in size and shape (Fig. 12.47F).
- *Corneal nerves* enter from periphery, mid-stromal depth and proceed anteriorly terminating between corneal epithelial cells. They are seen as hyper-reflective linear structures with diameter measuring from 0.52 μm to 4.6 μm. It helps in exploring corneal innervation after PRK, LASIK, dry eye and diabetic neuropathy.

CONFOCAL MICROSCOPY IN CORNEAL PATHOLOGIES

Confocal microscopy is useful in following corneal pathologies:

1. ***Keratoconus.*** The characteristic stromal changes seen are multiple 'striae' represented by thin hypo-reflective lines oriented vertically, horizontally and obliquely.

2. ***Corneal dystrophies,*** e.g.

- *Granular dystrophy.* Characteristic changes are highly reflective, bright, dense structures in the anterior and mid-stroma.
- *Limbus,* i.e. junction of conjunctiva and cornea is shown in Figure 12.47G.
- *Palisades of Vogt* is shown in Figure 12.47H.
- *Posterior polymorphous dystrophy* is characterized by multiple round vesicles at the level of Descemet's membrane and endothelium.
- *Fuch's endothelial dystrophy.* The cornea guttata appear dark with a bright central reflex. In advanced stage, endothelial cells are seen distorted.

3. ***Measurement of flap thickness in LASIK*** is obtained by measuring the distance between the high reflective spike from the front surface of the cornea and the low reflective interface.

4. ***Intra-corneal deposits*** that can be seen directly with confocal microscopy include the following:

- *Exogenous deposits,* e.g. acanthamoeba cyst and ova, drug deposits (amiodarone, chloroquine), deposits after contact lens use, refractive surgery and vitreoretinal surgery using silicone oil.
- *Endogenous deposits* as seen in Wilson disease, hyperlipidaemia, Fabry disease and haemosiderosis.

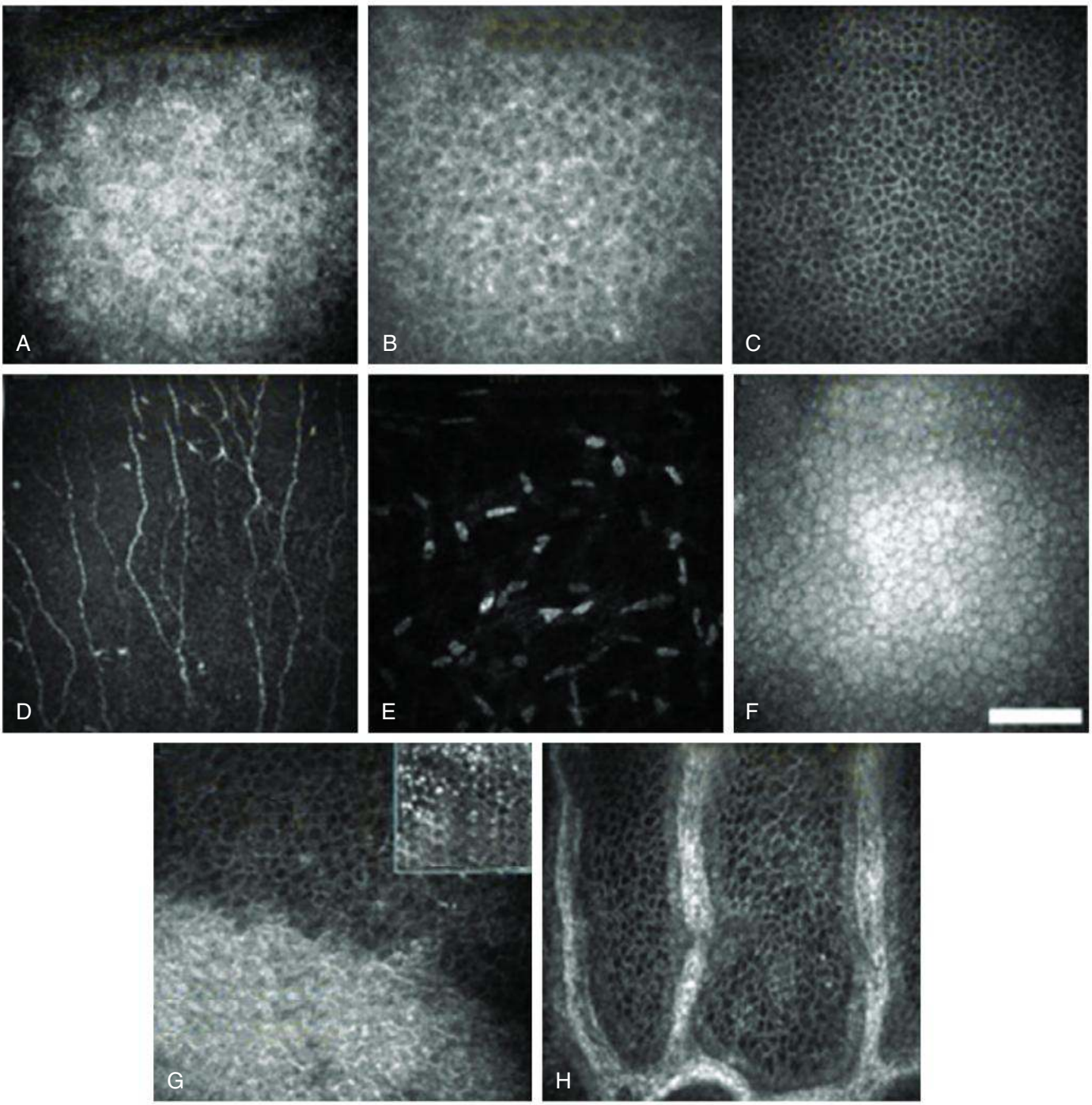


Fig. 12.47 *Confocal microscopy of normal human cornea: A, superficial epithelial cells are seen with prominent nuclei; B, Wing cells; C, basal epithelial cells are seen as small cells with high cell density and well-demarcated cell borders; D, Bowman's layer; E, mid-stroma; F, endothelium; G, limbal epithelium, i.e. junction of conjunctiva and cornea; and H, palisades of Vogt.*

CONFOSCAN

Confoscan 4 (Nidek, Inc.) is a fully automatic, fast (takes less than 12 s) non-contact endothelial microscope with 20× probe. It has a 5-micron accuracy in confocal pachymetry with Z-Ring Optics which improves the image stability. It produces high-quality imaging through opacities.

HEIDELBERG RETINA TOMOGRAPH 3

HRT 3 in conjunction with RCM (Heidelberg Engineering, Germany) is a microscope which has a 1 micron resolution. It scans the entire cornea from epithelium to endothelium layer by laser. It uses 670 nm red wavelength diode laser. It offers 400× magnification with an axial

high resolution. This helps in early accurate and rapid diagnosis, expediting initiation of therapy, follow-ups and hence visual outcomes especially in acanthamoeba keratitis, in fungal keratitis like *Aspergillus* and *Fusarium*. Confocal microscopy helps in examining flap-related complications and images of the particles at the interface. It can also aid in assessment of the wound healing following refractive surgery. It also helps in the study of corneal nerve alterations following corneal surgery and in systemic diseases like diabetic neuropathy.

Limitation. It is difficult to visualize bacteria and virus owing to their size less than 0.5 micron length.

OCULAR RESPONSE ANALYSER

The ORA applies an air puff on the anterior surface of the cornea and cause the cornea to deform. It measures the intensity of the reflected infrared light from the deforming corneal surface and reports several indices for diagnosis. It measures the biomechanical properties of the cornea which is useful in comparing LASIK and surface ablation as well as to evaluate the effect of creating a flap on corneal strength. It utilizes a dynamic, bidirectional applanation process and accurately measures the IOP. It takes into account the corneal hydration, connective tissue composition and bioelasticity and contributes to the response of the corneoscleral shell and to the force applied during the measurement of IOP. It has a built in 20 MHz ultrasound pachymeter that measures central corneal thickness (CCT).

Advantages

- It is a non-contact procedure.
- Superficial anaesthesia is not required.
- The technique is speedy and offers high accuracy and repeatability.
- It can diagnose corneal ectasia earlier than conventional diagnostic aids.

Disadvantages

- The high cost of equipment.
- The doubts in standardization and need for recurrent calibration.

FLARE METER

It is a non-invasive, non-pain, in vivo, fast, accurate, compact equipment that enables the quantitative measurement of aqueous flare. It is a non-slit-lamp based and is easier to use.

The FM-600 is based on the principle of laser light scattering detection. The instrument uses a diode laser beam (63 nm) to scan a measuring window that is projected inside the anterior chamber of the eye. As an aqueous protein (component of inflammation) passes through the focal point of the laser, light scattering occurs. The intensity of the scattered light (directly proportional to the amount of protein particles flare) is detected by a photomultiplier tube, which generates an electrical signal. This signal is immediately digitized to eliminate outside noise interference and are processed by a computer which displays the results for user analysis. The unit of measurement employed by the FM-600 is 'Photon Count' per millisecond.

Limitations

- It may be unreliable in eyes with extensive posterior synechiae or mature cataract due to increased background scattering of light.
- It is unable to measure in eyes with corneal opacity or very shallow anterior chamber.
- It is clinically less reliable in comparison with slit-lamp biomicroscopy.

OPTICAL INSTRUMENTS AND TECHNIQUES FOR POSTERIOR SEGMENT EVALUATION

Though the conventional direct and indirect ophthalmoscopies are still the most commonly used techniques, the ophthalmic imaging technology has undergone explosive growth in the past few years. Current techniques of posterior segment evaluation and imaging have contributed significantly to the understanding of pathophysiology and treatment of a variety of posterior segment disorders. Some of the common optical instruments and techniques

for posterior segment evaluation include the following:

- Ophthalmoscopy
- Slit-lamp biomicroscopic examination of the fundus
- Fundus camera
- Wide-field imaging system (retinal camera)
- Scanning laser ophthalmic techniques
  SLO
  CSLO or scanning laser tomography (SLT)
  RTA
  SLP (retinal nerve fibre analyser)
- Optical coherence tomography
- OCT ophthalmoscopy

OPHTHALMOSCOPY

Ophthalmoscopy is a clinical examination of the interior of the eye by means of an ophthalmoscope. It is primarily done to assess the state of fundus and detect the opacities of ocular media. The ophthalmoscope was invented by Babbage in 1848; however, its importance was not recognized till it was reinvented by *von Helmholtz* in 1850. Ophthalmoscopic methods of examination in vogue are as follows:

- Distant direct ophthalmoscopy,
- Direct ophthalmoscopy,
- Monocular indirect ophthalmoscopy and
- Binocular indirect ophthalmoscopy.

DISTANT DIRECT OPHTHALMOSCOPY

It should be performed routinely before the direct ophthalmoscopy, as it gives a lot of useful information (vide infra). It can be performed with the help of a self-illuminated ophthalmoscope or a simple plain mirror with a hole in the centre.

Procedure

The light is thrown into the patient's eye – with the patient sitting in a semi-dark room – from a distance of 20–25 cm, and the features of the red glow in the pupillary area are noted.

Applications of Distant Direct Ophthalmoscopy

1. ***To diagnose opacities in the refractive media.*** Any opacity in the refractive media is seen as a black shadow in the red glow. The exact location of the opacity can be determined by observing the parallactic displacement. For this, the patient is asked to move the eye up and down while the examiner is observing the pupillary glow. The opacities in the pupillary plane remain stationary, those in front of the pupillary plane move in the direction of the movement of the eye and those behind it will move in opposite direction (Fig. 12.48).

2. ***To differentiate between a mole and a hole of the iris.*** A small hole and a mole on the iris appear as a black spot on oblique illumination. On distant direct ophthalmoscopy, the mole looks black (as earlier), but a red reflex is seen through the hole in the iris.

3. ***To recognize detached retina or a tumour arising from the fundus.*** A greyish reflex seen on distant direct ophthalmoscopy indicates either a detached retina or a tumour arising from the fundus.

DIRECT OPHTHALMOSCOPY

It is the most commonly practised method for routine fundus examination.

Optics of Direct Ophthalmoscopy

The modern direct ophthalmoscope (Fig. 12.49) works on the basic optical principle of glass plate ophthalmoscope introduced by *von Helmholtz*. Optics of direct ophthalmoscopy is depicted in Figure 12.50.

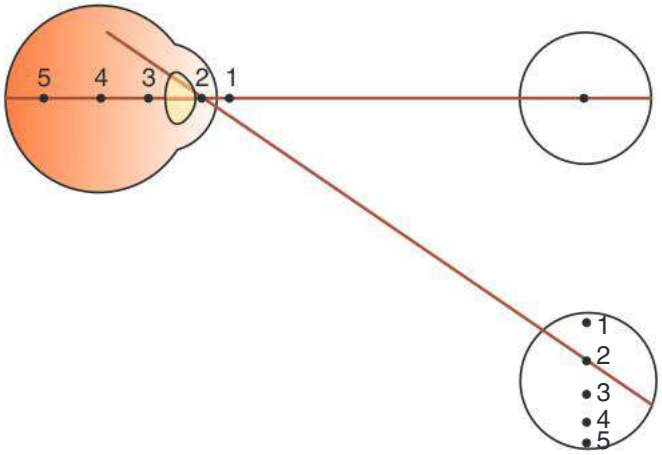


Fig. 12.48 *Parallactic displacement on distant direct ophthalmoscopy.*

Fig. 12.49 *Direct ophthalmoscope.*

A convergent beam of light is reflected into the patient's pupil (Fig. 12.50, dotted lines). The emergent rays from any point on the patient's fundus reach the observer's retina through the viewing hole in the ophthalmoscope (Fig. 12.50, continuous lines). The emergent rays from the patient's eye are parallel and brought to focus on the retina of the emmetropic observer when accommodation is relaxed.

- *In a hypermetropic patient*, the emergent ray from the illuminated area of retina will be divergent and thus can be brought to focus on the observer's retina, if the latter accommodates, or by the help of a convex lens (Fig. 12.51).
- *In a myopic patient*, the emergent rays will be convergent and thus can be brought to focus on the observer's retina by the help of a concave lens (Fig. 12.52).

Therefore, if the patient or/and the observer is/are ametropic, a correcting lens (equivalent to the sum of the patient's and observer's refractive error) must be interposed (from the system of plus and minus lenses, in-built in the modern ophthalmoscopes).

Characteristics of the Image Formed

In direct ophthalmoscopy, the image is erect, virtual and about 14–15 times magnified (Table 12.3) in emmetropes (more in myopes and less in hypermetropes).

As shown in Figure 12.53, the emergent rays from the illuminated area of retina AB are parallel. These parallel rays intercepted by the

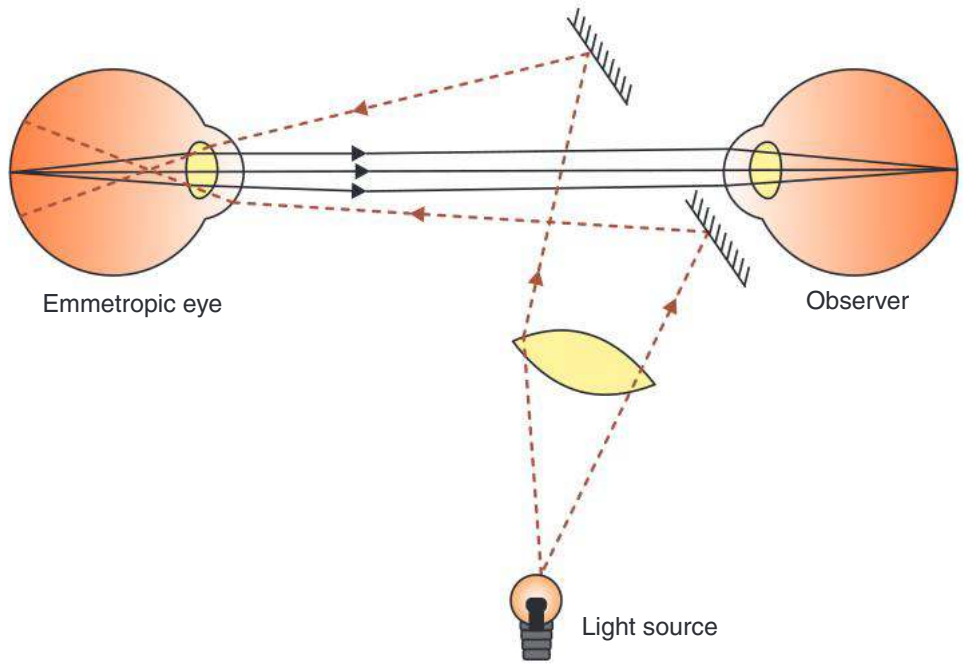


Fig. 12.50 *Optics of direct ophthalmoscopy in an emmetropic patient.*

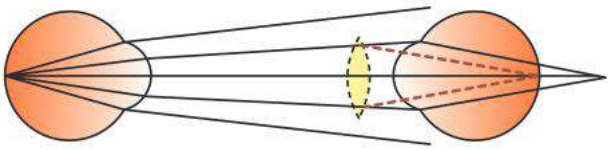


Fig. 12.51 *Optics of direct ophthalmoscopy in a hypermetropic patient.*

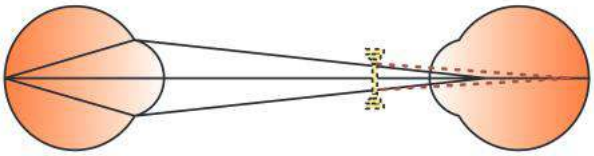


Fig. 12.52 *Optics of direct ophthalmoscopy in a myopic patient.*

observer's eye are projected behind the observed eye at A_2B_2. These points A_2B_2, theoretically, are situated at the observer's minimal distance of distinct vision, i.e. about 25 cm from the observer's eye. The image A_1B_1 of the observed fundus is equal to the size of the part of fundus AB observed.

In Figure 12.53, Δs $A_2B_2N_1$ and $A_1B_1N_1$ are equiangular. Therefore,

$$\frac{A_2B_2}{A_1B_1} = \frac{B_2N_1}{B_1N_1}$$

Since $A_1B_1 = AB$, therefore,

$$\frac{A_2B_2}{AB} = \frac{B_2N_1}{B_1N_1}$$

$$= \frac{250}{17} = 14.9$$

Hence, the image in direct ophthalmology is about 15 times magnified in emmetropic patients.

Field of Vision in Direct Ophthalmoscopy

The ophthalmoscopic field of vision (Table 12.3) is always smaller than the field of illumination in direct ophthalmoscopy. It is affected by the following factors:

- It is directly proportional to the size of the pupil of observed eye.
- It is directly proportional to the *axial length* of the observed eye.
- It is inversely proportional to the distance between the observed and the observer's eye.

Table 12.3 *Magnification, field of view and characteristics of the image formed with different techniques of fundus examination*

Technique	Magnification	Field of view	Characteristics of image	Principal use
Direct ophthalmoscopy	14×	5 degrees	Erect, virtual	Routine view of disc and surrounding area
Indirect ophthalmoscopy				
• With +14 D	4×	40 degrees	Inverted, reversed and real	Fundus lesion inspection
• With +20 D	3×	45 degrees	Inverted, reversed and real	Routine examination
• With +30 D	2×	50 degrees	Inverted, reversed and real	Routine examination
Biomicroscopic examination				
• With +78 D	10×	30 degrees	Inverted, reversed and real	Posterior pole observation
• With +90 D	7.5×	40 degrees	Inverted, reversed and real	Posterior pole observation
• With Hruby lens	12×	10 degrees	Erect, virtual	Optic disc and vitreous observation
• With Goldmann's fundus contact lens	10×	20 degrees	Erect, virtual	Optic disc and macula inspection
Fundus camera	2.5×	30 degrees	Erect, virtual photodocumentation	

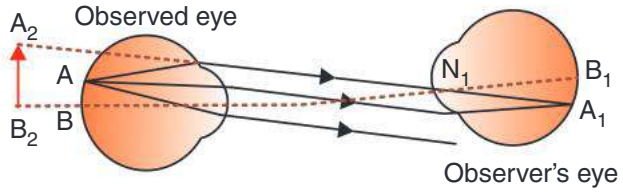


Fig. 12.53 *Magnification in direct ophthalmoscopy.*

- The smaller the sight hole of the ophthalmoscope, the better the field of vision.

Technique

Direct ophthalmoscopy should be performed in a semi-dark room with the patient seated and looking straight ahead, while the observer standing or seated slightly over to the side of the eye to be examined (Fig. 12.54). The patient's right eye should be examined by the observer with his or her right eye, and left with the left.

The observer should reflect beam of light from the ophthalmoscope into patient's pupil. Once the red reflex is seen, the observer should move as close to the patient's eye as possible (theoretically at the anterior focal plane of the patient's eye, i.e. 15.4 mm from the cornea).

The direct ophthalmoscope should then be focused by twirling the dial for the Reskoss disc, which has several plus- and minus-powered lasers. The optimal focusing lens on the Reskoss disc depends on the patient's refractive error, the examiner's refractive error (including unintended accommodation) and the examination distance (Table 12.4).

Once the retina is focused, the details should be examined systematically starting from disc, blood vessels, the four quadrants of the general background and the macula by utilizing the various illumination options and apertures provided in the direct ophthalmoscope (Table 12.5).

Fig. 12.54 *Technique of direct ophthalmoscopy.*

Table 12.4 *Direct ophthalmoscope's refractive power versus patient's spherical equivalent while focusing*[a]

Direct ophthalmoscope's refractive power	Patient's refractive error
–30 D	–15 D
–20 D	–12 D
–10 D	–8 D
–5 D	–4 D
–0	–Plano
+5 D	+6 D
+10 D	+15 D

[a]When the examiner's eye is emmetropic or corrected and the examination distance between the ophthalmoscope and cornea is 20 mm.

Table 12.5 *Various apertures and illumination options with direct ophthalmoscope*

Aperture description	Use
Large spot	For viewing through a dilated pupil
Small spot	For viewing through a small pupil
Red-free fibre	Useful in detecting changes in the nerve fibre layer and identifying microaneurysms and other vascular anomalies
Slit	For evaluating contour of retinal lesions
Reticule or grid	For measuring vessel calibre or diameter of a small retinal lesion (marked in 0.2 mm increments)
Fixation target	For testing fixation pattern (central or eccentric)
Reskoss disc	Plus and minus lenses are for focusing the retina

MONOCULAR INDIRECT OPHTHALMOSCOPY

Structural features. The monocular indirect ophthalmoscope consists of (Fig. 12.55):

- *Illumination* rheostat at its base,
- *Focusing lever* for image refinement,
- *Filter dial* with red-free and yellow filters,

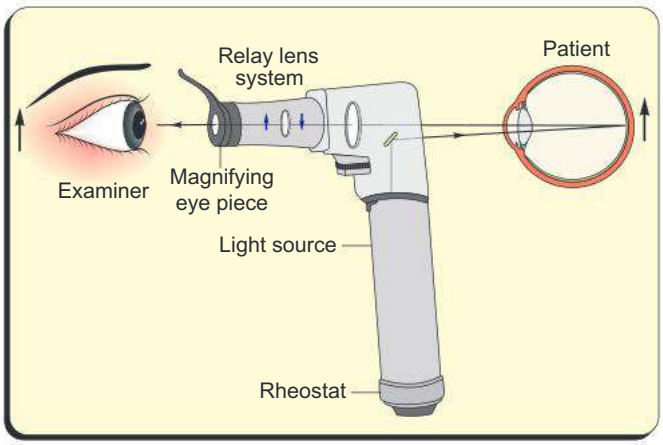


Fig. 12.55 *The optical principle of monocular indirect ophthalmoscopy, demonstrating the resultant erect magnified image.*

- *Forehead rest* for steady proper observer head positioning and
- *Iris diaphragm* lever to adjust the illumination beam diameter.

Optics. An internal relay lens system re-inverts the initially inverted image to a real erect one, which is then magnified. This image is focusable using the focusing lever/eyepiece system (Fig. 12.55).

Indications for use of monocular indirect ophthalmoscopy include:

- Need for an increased field of view,
- Small pupils,
- Uncooperative children,
- Patient's intolerance of bright light of binocular indirect ophthalmoscope and
- Basic fundus screening.

Extent of view. Although vitreous base views are possible with monocular indirect ophthalmoscopy, its greatest effectiveness extends anteriorly to the peripheral equatorial region. The more than 40 degree field of view of the monocular indirect ophthalmoscope is approximately the same as that of binocular indirect ophthalmoscope.

Advantages of monocular indirect ophthalmoscopy include:

- Increased field of view similar to indirect ophthalmoscopy and

- Erect real imaging similar to direct ophthalmoscopy.

Disadvantages include:

- Lack of stereopsis,
- Limited illumination,
- Fixed magnification and
- Fair to good resolution.

BINOCULAR INDIRECT OPHTHALMOSCOPY

Indirect ophthalmoscopy, introduced by Nagel in 1864, is now a very popular method for examination of the posterior segment. Indirect ophthalmoscopy was considered as an elementary part of examination by only the posterior segment or the retinal surgeons in yesteryears. It was the eagerness on the part of the examiner, who used only direct ophthalmoscopy, so as to come to a hasty diagnosis. He used to organize his thoughts on this cursory examination of the retina, and assumptions were made for the final diagnosis. However, in this modern era, indirect ophthalmoscopy is of great general use in ophthalmology and requires much effort and practice by the anterior as well as the posterior segment surgeons.

OPTICS

Optical principle. The principle of indirect ophthalmoscopy is to make the eye highly myopic by placing a strong convex lens in front of patient's eye so that the emergent rays from an area of the fundus are brought to focus as a real inverted image between the lens and the observer's eye, which is then studied (Fig. 12.56A).

Optical system of binocular indirect ophthalmoscope. Optics of modern binocular indirect ophthalmoscopy is shown in Figure 12.56B. Binocularity is achieved by reducing the observer's inter-pupillary distance from about 60 mm to approximately 15 mm by prisms/mirrors (Fig. 12.57). Even this artificial reduction of inter-pupillary distance requires larger patient's pupils for binocular viewing than those for the monocular viewing.

Field of illumination. As shown in Figure 12.58, the field of illumination is more in myopia and less in hypermetropia as compared to emmetropia.

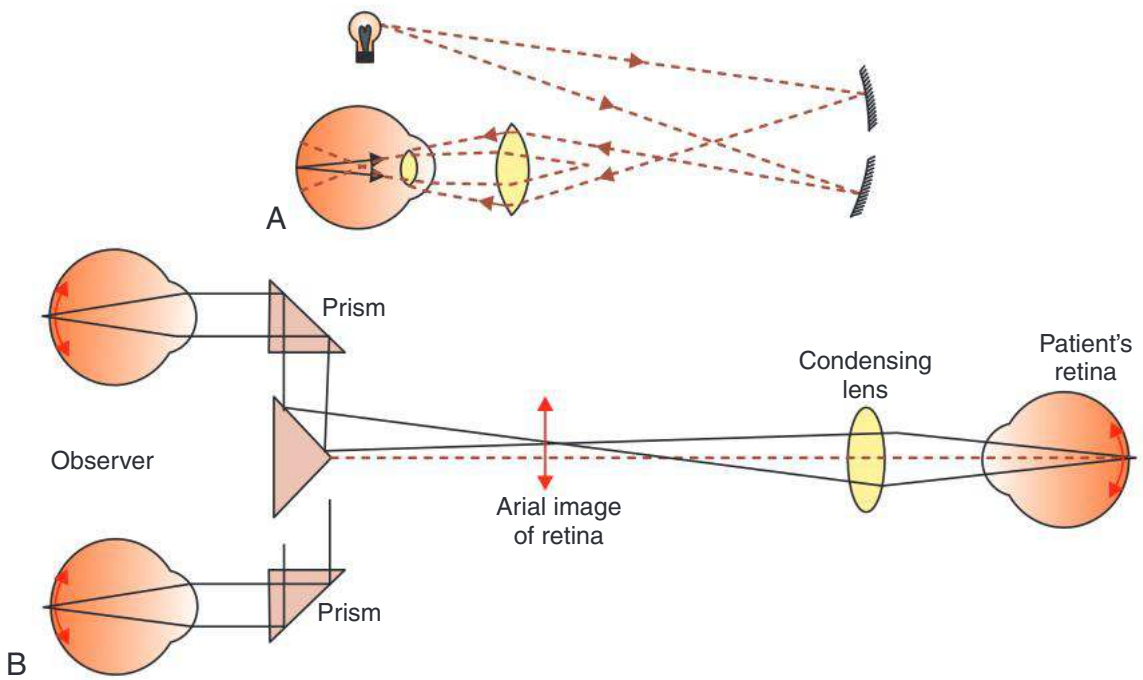


Fig. 12.56 *A, Optics of indirect ophthalmoscopy and B, optical system of a modern binocular indirect ophthalmoscope.*

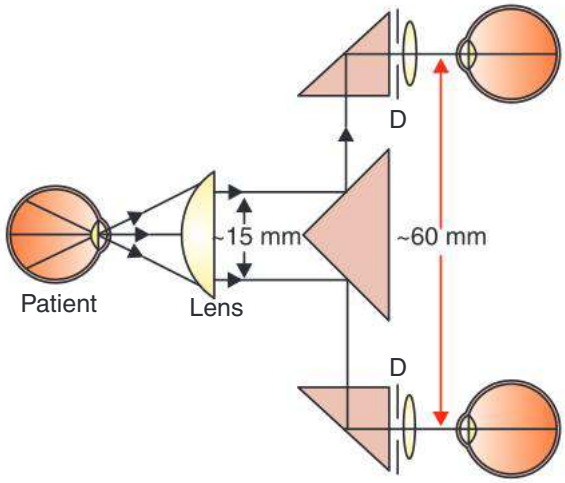


Fig. 12.57 *Stereopsis is produced by the binocular indirect ophthalmoscope. Note how the two prisms widen the incoming beams so that they are incident to the eyes of the observer.*

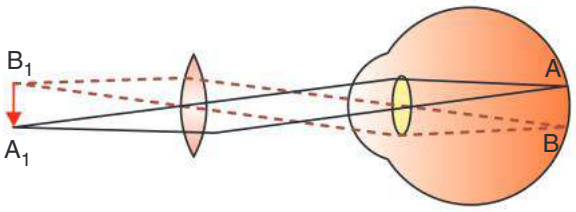


Fig. 12.59 *Image formation on indirect ophthalmoscopy in emmetropia.*

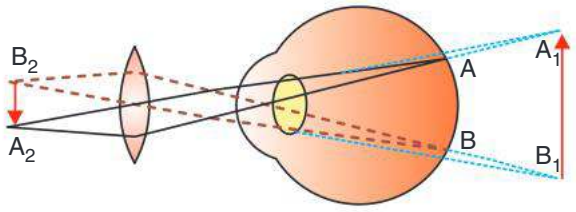


Fig. 12.60 *Image formation on indirect ophthalmoscopy in hypermetropia.*

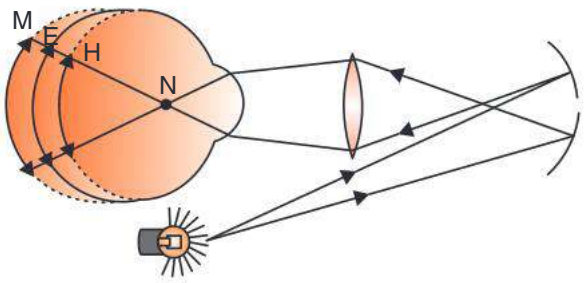


Fig. 12.58 *Field of illumination in various refractive errors.*

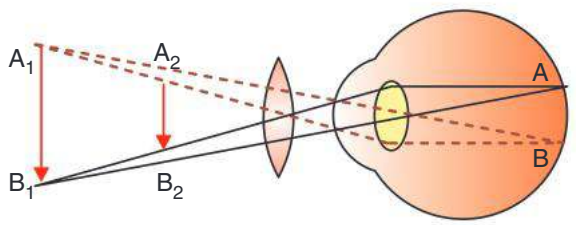


Fig. 12.61 *Image formation on indirect ophthalmoscopy in myopia.*

Image Formation

1. ***Image formation in emmetropia.*** The emergent rays from the illuminated area of retina are parallel in emmetropic patients and are, therefore, brought to focus by the condensing lens at its principal focus (Fig. 12.59). Thus, an inverted image of the retina is formed in the air between the condensing lens and the observer.

2. ***Image formation in hypermetropia.*** The emergent rays from the illuminated area of retina are divergent in hypermetropic patients and thus appear to come from an imaginary enlarged upright image situated behind the eye (Fig. 12.60). The condensing lens, therefore, uses this as an object and forms an inverted image of it. Since the rays are divergent, the final image is situated in front of the principal focus.

3. ***Image formation in the myopic eye.*** The emergent rays from the illuminated area AB of retina in a myopic patient are convergent and, therefore, an inverted image A_1B_1 of it is formed in front of the eye. The condensing lens forms the final image A_2B_2 situated within its own focal length (Fig. 12.61).

Characteristics of the Image

The image formed in indirect ophthalmoscopy is real, inverted and magnified. Magnification of image depends upon the dioptric power of the convex lens, position of the lens in relation to the eyeball and refractive state of the eyeball. About 5× magnification is obtained with a +13 D lens. With a stronger lens, image will be smaller but brighter and field of vision will be more. The important characteristics of the

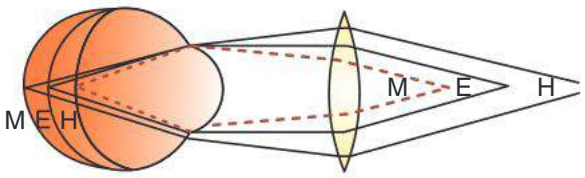


Fig. 12.62 *The relative positions of the images in indirect ophthalmoscopy in emmetropia (E), hypermetropia (H) and myopia (M).*

image formed by an indirect ophthalmoscope are as follows:

1. Relative position of images formed in emmetropic, myopic and hypermetropic eye. The relative positions of the images formed in emmetropic, myopic and hypermetropic eye, when the condensing lens used is situated at its own focal distance from cornea, are shown in Figure 12.62.

- *In emmetropia,* the emergent rays are parallel and thus focused at the principal focus of the lens, i.e. at E.
- *In* hypermetropia, the emergent rays are divergent and are, therefore, focused farther away from the principal focus, i.e. at H.
- *In myopia,* the emergent rays are convergent and are, therefore, focused near to the lens than its principal focus, i.e. at M.

2. Size of the image vis-à-vis refractive condition of the eye.

i. *In an emmetropic eye,* the size of image always remains the same and is situated at its principal focus, because the rays emerging for such an eye are parallel (Figs 12.59 and 12.63).

ii. *In hypermetropia,* the size of image will be as follows:

- *Equal to an emmetropic eye*, if the condensing lens is held at such a distance that its principal focus (f) corresponds to the anterior focus of eye (Fig. 12.63A).
- *Larger than the emmetropic eye*, if the condensing lens is held at such a distance that its principal focus (f) is nearer than the anterior focus of the eye (F) (Fig. 12.63B).
- *Smaller than the emmetropic eye*, when the principal focus of the condensing lens (f) is farther away than the anterior focus of eye (Fig. 12.63C).

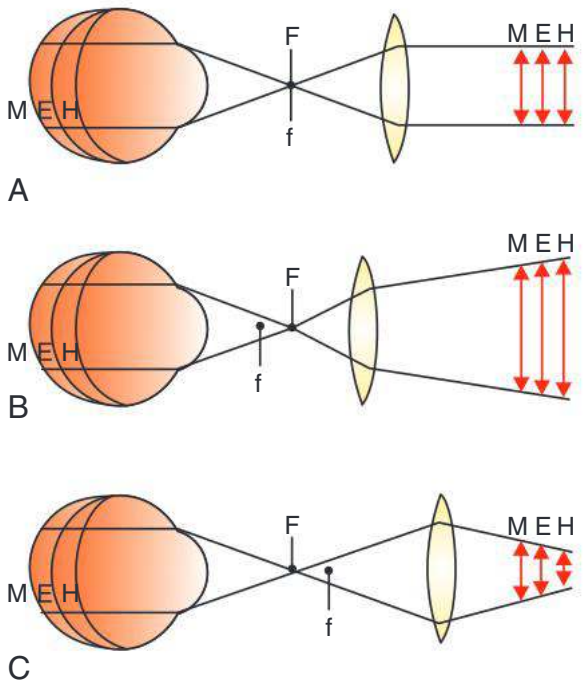


Fig. 12.63 *The size of the image in different refractive states (M, myopia; E, emmetropia; H, hypermetropia) when the condensing lens is held at such a distance that its principal focus (f): A corresponds to the anterior focus of the eye (F); B is nearer than the anterior focus of the eye and C is farther away from the anterior focus of the eye.*

iii. *In myopia,* the size of image will be as follows:

- *Equal to an emmetropic eye*, if the condensing lens is held at such a distance that its principal focus (f) corresponds to the anterior focus of eye (F) (Fig. 12.63A).
- *Smaller than the emmetropic eye*, if the condensing lens is held at such a distance that its principal focus (f) is nearer than the anterior focus of the eye (F) (Fig. 12.63B).
- *Larger than the emmetropic eye*, when the principal focus of the condensing lens (f) is farther away than the anterior focus of eye (Fig. 12.63C).

3. *Image magnification in indirect ophthalmoscopy.* Lateral (transverse, linear) magnification in an indirect ophthalmoscope is a function of the power of the condensing lens and power of the patient's eye. It may be expressed as

power of the eye (60 D) to the power of the condensing lens. Therefore, a 20 D lens produces 3× lateral magnification and a 30 D lens produces 2× magnification (Table 12.3). Although the axial image remains constant in size for a given lens, if it is viewed from more than 25 cm (the reference point for the designation of magnification), the perceived magnification decreases proportionately to the viewing distance.

Field of Illumination and Observation

The field of observation is always larger than the field of illumination in indirect ophthalmoscopy. The size of the pupil does not affect the size of field of observation, provided it is larger than the image of the observer's pupil formed by the condensing lens in the observed pupil.

The field of observation is in fact a function of magnification and the condensing lens diameter. An x-fold decrease in magnification equals an x^2 increase in the field of observation (Table 12.3).

PRACTICE OF INDIRECT OPHTHALMOSCOPY

Prerequisites

- Indirect ophthalmoscope
- Dark room
- Convex lens 14 D/+20 D/+28 D/30 D (nowadays commonly employed lens is of +20 D)
- Pupils of the patient should be dilated

Technique

The procedure is explained to the patient and he/she is made to lie in the supine position, with one pillow on a bed or couch and instructed to keep both eyes open. The examiner throws the light into the patient's eye from an arm's distance (with the self-illuminated ophthalmoscope). In practice, binocular ophthalmoscope with head band or that mounted on the spectacle frame is employed most frequently (Fig. 12.64). Keeping the eyes on the reflex, the examiner then interposes the condensing lens (+20 D, routinely) in the path of beam of light – close to the patient's eye – and then slowly moves the lens away from the eye (towards himself or herself) until the image of the retina is clearly seen. The examiner moves around the head of the patient to examine different quadrants of the fundus. He or she has to stand opposite the clock hour position to be examined; e.g. to examine inferior quadrant (around 6 o'clock meridian), the examiner stands towards patient's head (12 o'clock meridian) and so on. By asking the patient to look in extreme gaze, and using scleral indenter, the whole peripheral retina up to ora serrata can be examined.

Scleral Indentation

This is done with the depressor placed on the patient's lids. This helps in making prominent the just or barely perceptible lesions. One can better appreciate the different tissue colours and densities.

- The examiner should move the scleral depressor in a direction opposite to that in which he or she wishes the depression to appear.
- The scleral depressor should be rolled gently and tangentially over the eye surface.
- The patients are most sensitive to scleral depression in superonasal quadrants.
- Sometimes a topical anaesthetic may be applied and a scleral depressor is placed directly on the medial conjunctiva, causing little patient discomfort.
- The temporal part of the upper lid is sufficiently lax so that the depressor can be placed inferiorly in the horizontal meridian.
- Sometimes when more posterior areas of fundus are to be examined, the examiner asks the patient to look slightly towards his or her position.

Small Pupil Ophthalmoscopy

In cases where the pupils do not dilate or if media opacities are enough so as to allow only few rays to enter the retina through a small clear media, small pupil ophthalmoscopy is required. Theoretically, it is possible to see the retina binocularly through 0.6-mm pupil with the 30 D lens. Indirect ophthalmoscopy can be

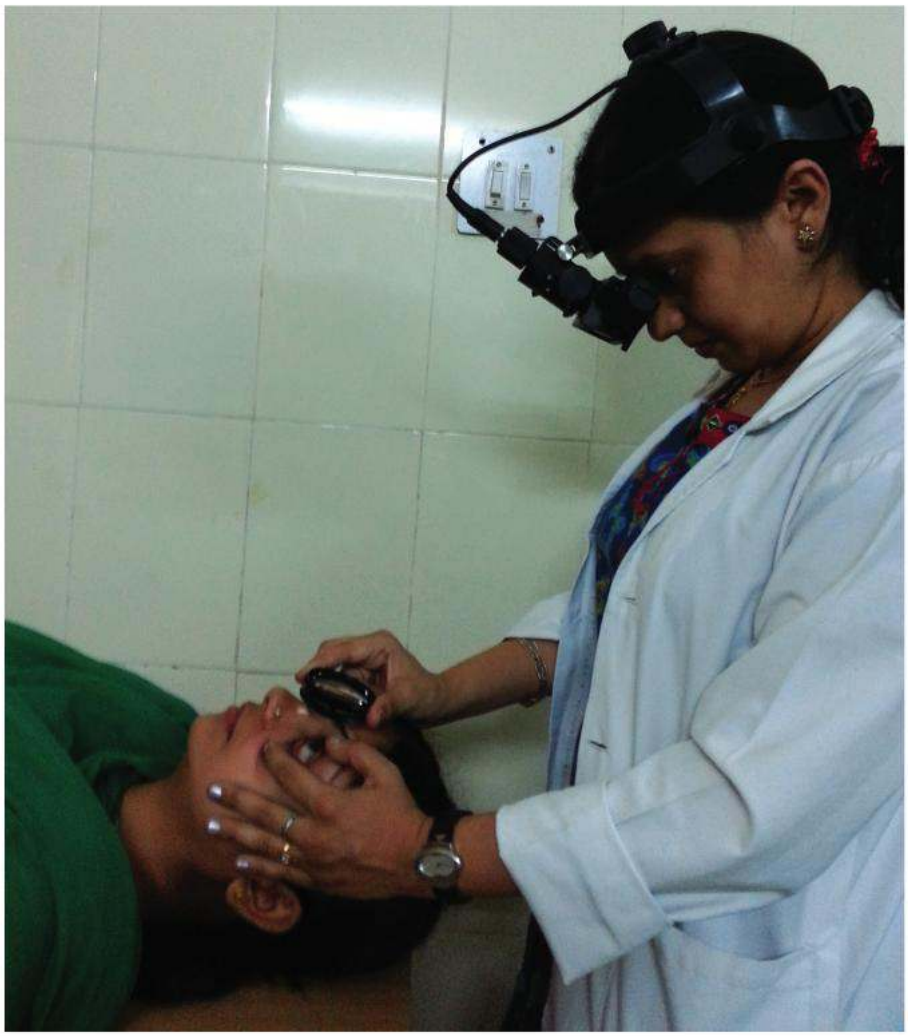


Fig. 12.64 *Technique of indirect ophthalmoscopy.*

performed through a small pupil without small pupil ophthalmoscope by using 30 D lens held as far as possible. When looking through a small pupil, it is convenient to visualize the retina, if light source is directed high in examiner's field of vision. Slight blurring can occur.

Fundus Drawing

The image seen with the indirect ophthalmoscope is vertically inverted and laterally reversed; the top of the retinal chart is placed towards the foot end of the patient (i.e. upside down) (Fig. 12.65). This corresponds to the image of the fundus obtained by the examiner. The fundus drawing is made on a special Amsler's chart, which has 12 clock hours marked and three concentric circles made on it. The innermost circle represents to the equator, the middle circle the ora serrata and the outermost circle the midpoint of pars plana.

Normal anatomical landmarks. For mapping of the finding, it is very useful to note the position of any lesion with respect to the ***normal anatomical landmarks*** on the retina (Fig. 12.66):

- *Vortex veins ampulla* are seen along the equator.
- *Long ciliary veins* may be seen at 3 o'clock and 9 o'clock positions.
- *Branching vessels* may also be used and marked to draw the pathology seen.

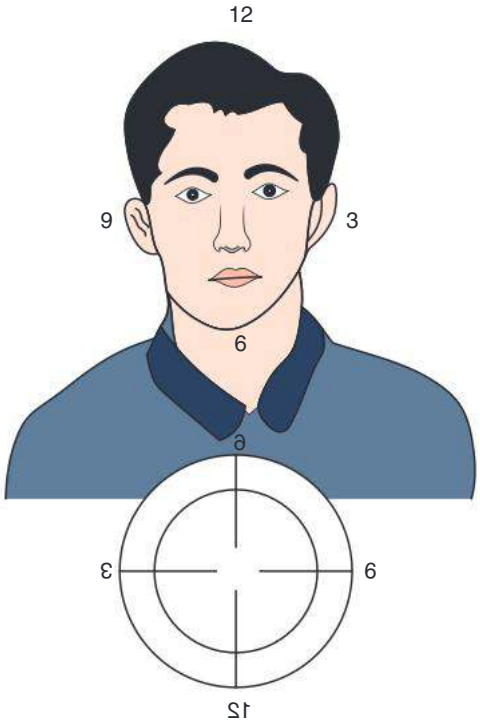


Fig. 12.65 *Position of the chart for drawing during indirect ophthalmoscopy.*

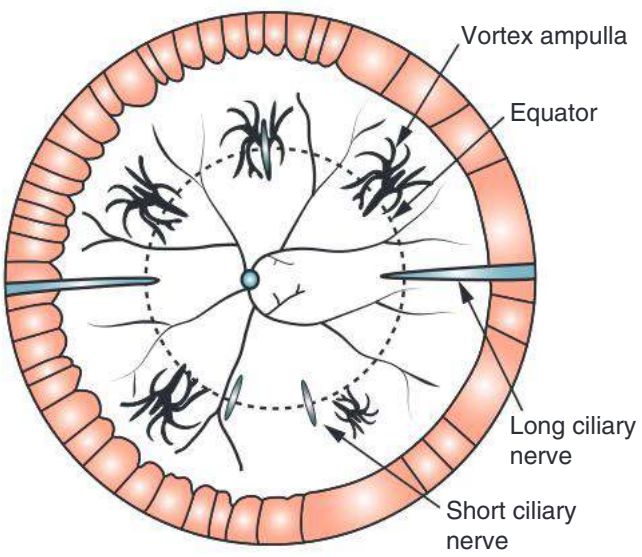


Fig. 12.66 *Normal anatomical landmarks which can be used as aids to draw the location of design seen on fundus examination.*

Symbols and colour codes used to draw the fundus, as accepted internationally, are as below (Fig. 12.67):

- *Optic disc* is always shown with red margins.
- *Arteries* are drawn as red lines.
- *Veins* are drawn as blue lines.

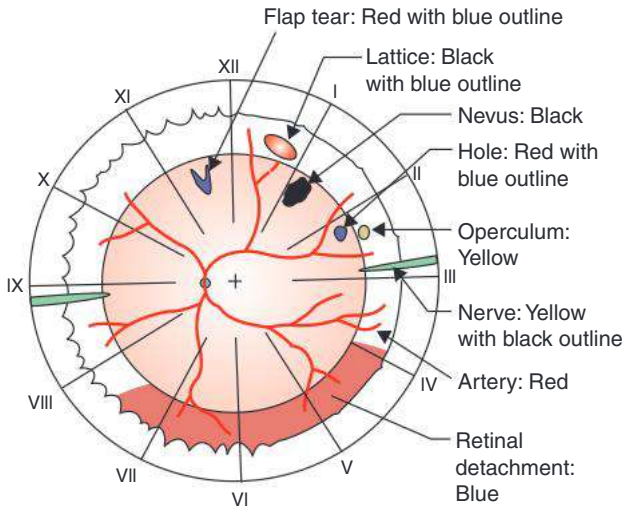


Fig. 12.67 *A sample fundus diagram showing the universal colour-coding system for a few common lesions and structure.*

- *Attached retina* is shown red.
- *Thin retina* is indicated by red hatching outlines in blue.
- *Detached retina* is drawn with blue.
- *Retinal tears* are shown as red with blue outline. Flap of the retinal tear is also drawn blue.
- *Lattice* degeneration is shown as blue hatchings outlined in blue.
- *Retinal pigment* is shown as black.
- *Retinal exudates* are shown as yellow.
- *Choroidal lesions* are depicted brown.
- *Vitreous* opacities are depicted as green.

Applications, Difficulties, Advantages and Disadvantages

Applications of Indirect Ophthalmoscopy

It is essential for the assessment and management of retinal detachment and other peripheral retinal lesions.

Difficulties

1. The technique is difficult and can be mastered by hours of practice.

2. Reflexes from the corneal surface can be decreased by holding the condensing lens at a distance equal to its focal length from the anterior focus of the eye.

3. Formation of reflexes by the two surfaces of convex lens can be eliminated by slightly tilting the lens and the use of aspheric lens.

Advantages of Indirect Ophthalmoscopy

1. Larger field of retina is visible. There is a 10-fold increase in the area of retina visible as compared to direct ophthalmoscopy.
2. Lesser distortion of the image of the retina.
3. Easier to examine, if the patient's eye movements are present and with high spherical or astigmatic refractive errors.
4. Easy visualization of the retina anterior to the equator, where most retinal holes and degenerations exist.
5. It gives a 3D stereoscopic view of the retina with considerable depth of focus.
6. It is useful in hazy media because of its bright light and optical property.

Disadvantages of Indirect Ophthalmoscopy

1. Magnification in indirect ophthalmoscopy is 5 times, whereas in direct ophthalmoscopy it is 15 times.
2. Indirect ophthalmoscopy is impossible with very small pupils.
3. The patient is usually more uncomfortable with the intense light of indirect ophthalmoscope and with scleral indentation.
4. The procedure is more cumbersome, requires extensive practice both in technique and in interpretation of the images visualized.
5. Reflex sneezing can occur on exposure to bright light.

BIOMICROSCOPIC EXAMINATION OF FUNDUS

Biomicroscopic examination of the fundus can be performed after full mydriasis, using a slit-lamp and any one of the following lenses.

1. HRUBY LENS BIOMICROSCOPY

Hruby lens (Fig. 12.68A) is a plano-concave lens with dioptric power 58.6 D which neutralizes the optical power of the normal eye (+60 D) and forms a virtual, erect image of the fundus (Fig. 12.68B). This lens provides a small field with low magnification and cannot visualize the fundus beyond equator.

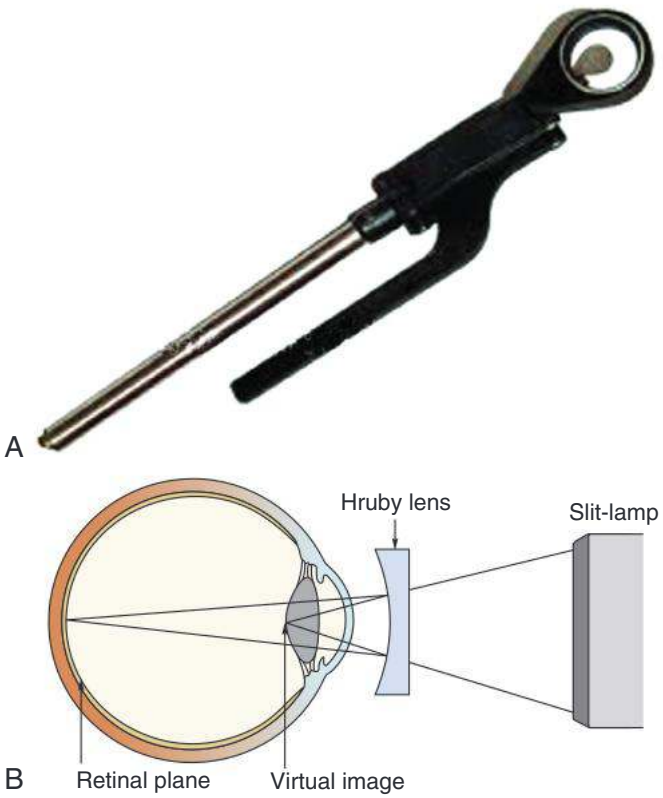


Fig. 12.68 *A, Hruby lens and B, optics of Hruby lens.*

2. CONTACT LENS BIOMICROSCOPY OF FUNDUS

Contact lens biomicroscopy combines stereopsis, high illumination and high magnification with the advantages of slit-beam. Following lenses are available for contact lens biomicroscopy of the fundus.

Modified Koeppe Lens

Modified Koeppe lens, i.e. posterior fundus contact lens (Fig. 12.69A) can be used to examine the posterior segment. It provides a virtual and erect image (Fig. 12.69B).

Goldmann's Three-Mirror Contact Lens

Goldmann's three-mirror contact lens (Fig. 12.69C) consists of a central contact lens and three mirrors placed in the cone, each with different angles of inclination. With this, the central as well as peripheral parts of the fundus can be visualized. It also provides a virtual and erect image (Fig. 12.69B).

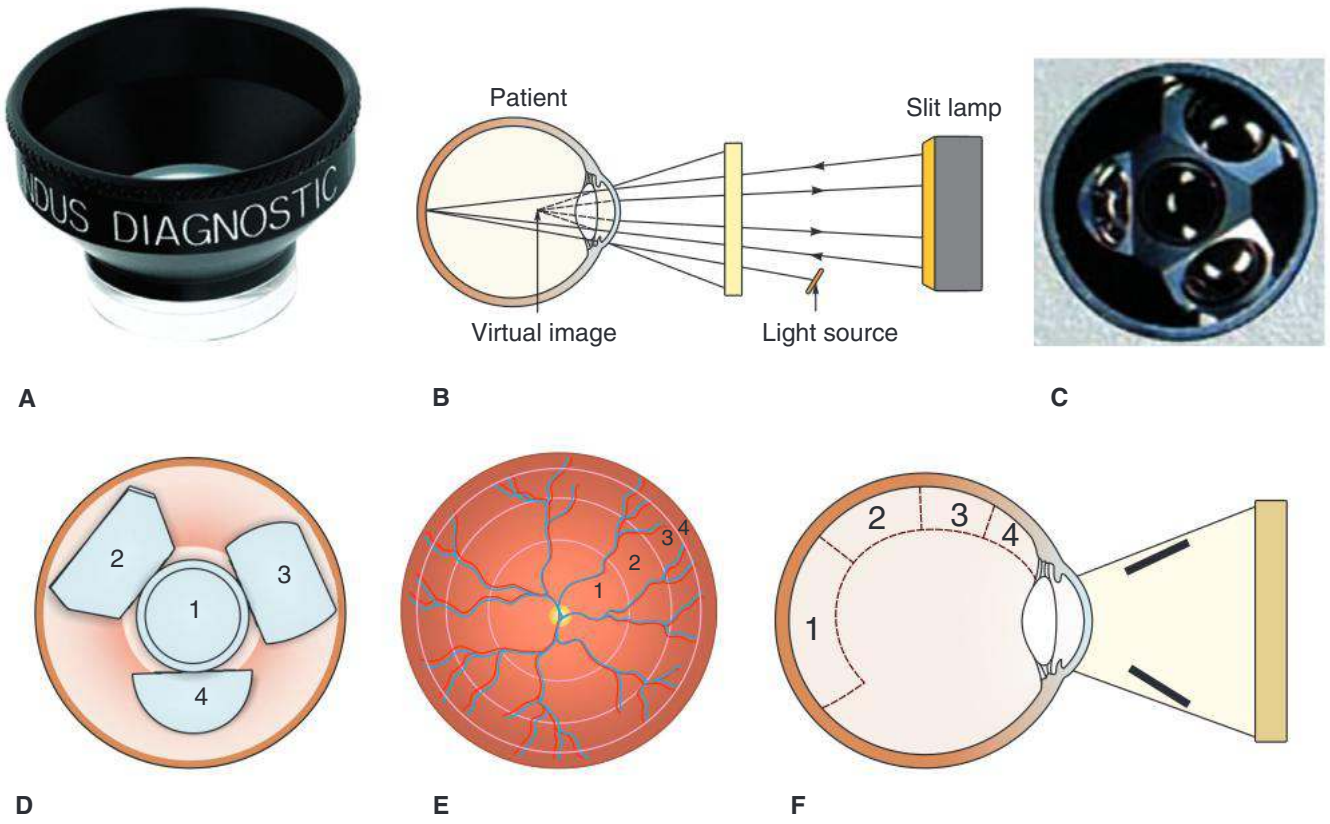


Fig. 12.69 *Contact lenses for biomicroscopy of fundus: A, modified Koeppe lens; B, optics of contact lens biomicroscopy; C, Goldmann's three-mirror contact lens; D, front view of the Goldmann's three-mirror lens with its four optical surfaces (1, for central posterior pole; 2, for equatorial area; 3, for anterior peripheral fundus; 4, for ora serrata and pars plana); E, diagrammatic projection of viewing range for each component of Goldmann's lens; F, panoramic diagram of specific viewing range for each lens component.*

Technique

- Dilate the pupils as for indirect ophthalmoscopy.
- Instill topical anaesthetic drops.
- Insert coupling fluid into the cup of the contact lens, but do not overfill.
- Ask the patient to look up, insert the inferior rim of the lens into the lower fornix and press it quickly against the cornea.
- Always tilt the illumination column except when viewing the 12 o'clock position in the fundus (i.e. with the mirror at 6 o'clock).
- When viewing the different positions of the peripheral retina, rotate the axis of the beam so that it is always at right angles to the mirror.
- To visualize the entire fundus, rotate the lens for 360 degrees using the 59, 67 and 73 degree tilted mirrors to give views of the peripheral retina, the equatorial fundus and the area around the posterior pole, respectively (Fig. 12.69D–F).
- To obtain a more peripheral view of the retina, tilt the lens to the opposite side and ask the patient to move the eyes to the same side. For example, to obtain a more peripheral view of 12 o'clock position (with mirror at 6 o'clock), tilt the lens down and ask the patient to look up.
- Examine the vitreous cavity with the central lens, using a horizontal and a vertical slit-beam, and then examine the posterior pole.

Note. Since examination with contact lens biomicroscopy involves anaesthetizing the cornea and a direct touch, so it is neither liked much by the patients nor by the examiners. Therefore, presently, fundus contact lenses are primarily used for therapeutic purposes (retinal photocoagulation, etc.) and not for diagnostic purposes except for certain special circumstances. Nowadays examination with fundus non-contact lenses is being preferred for diagnostic purposes.

Wide-field (panfundoscopic) indirect contact
Wide-field (panfundoscopic) indirect contact lenses with a field of view up to 130 degrees are available for fundus examination and for performing laser photocoagulation. The image produced by such lens is inverted.

3. INDIRECT FUNDUS BIOMICROSCOPY

Indirect fundus biomicroscopy, also known as non-contact fundus biomicroscopy, has become quite popular in the last decade or so – to the extent that it has become an integral part of routine eye examination. As mentioned earlier, the non-contact lenses have replaced the contact lenses for diagnostic purposes.

Fundus non-contact lenses most commonly used for indirect slit-lamp biomicroscopy are +78 D (Fig. 12.70A) and +90 D (Fig. 12.70B), but other lenses are also available (+60, +130 D, etc.). Almost all condensing lenses used with slit-lamp are double-aspheric lenses, so it does not matter which side is held towards the patient.

Fig. 12.70 *Indirect fundus biomicroscopy: A, 78 D lens; B, 90 D lens; C, technique of examination.*

Optics of indirect fundus biomicroscopy is exactly similar to that of indirect ophthalmoscopy (see page 491, Fig. 12.56A). Thus, a real, inverted image is formed between the condensing lens and objective lens of slit-lamp.

Magnification provided by fundus non-contact lenses is calculated by dividing power of the eye by the power of lens. For example, +90 D lens provides a magnification of 60/90 = 0.75×, i.e. a minification of the image. However, the magnified image is seen because of the magnification provided by the slit-lamp. Thus, 7.5× magnification seen with +90 D lens (Table 12.3) is due to 10× of slit-lamp.

Field of view. High-powered lens provides larger field of view but lesser magnification, e.g. the +90 D lens provides bigger field of view but gives lesser magnification than +78 D lens (Table 12.3).

Technique of indirect fundus biomicroscopy is summarized below (Fig. 12.70C):

- Set the slit-lamp magnification to 10× or 16×.
- Adjust the slit-beam to about 4 mm wide with the brightest light intensity.
- Set the illumination angle coaxial with the slit-lamp-viewing system.
- Hold +78 or +90 D condensing lens stationary between thumb and forefinger, approximately 5–10 mm from the patient's cornea.
- Examine the fundus by moving the joystick and vertical adjustment of the slit-lamp, but hold the lens still.
- Increase the width of the beam to obtain a larger field of view.
- Increase the magnification for greater detail as necessary.
- To view the peripheral retina, ask the patient to look into appropriate positions of gaze as with standard indirect ophthalmoscopy.

FUNDUS CAMERA AND RELATED DEVICES

FUNDUS CAMERA

OPTICAL PRINCIPLE

All fundus cameras are technically indirect ophthalmoscopes, and currently they are all based upon the principles of Gullstrand's ophthalmoscope. That is, the illumination and observation pathways pass through different portions of the patient's pupil to avoid reflections from the cornea and from the surfaces of the crystalline lens. Also, an inverted aerial image of the fundus is formed within the fundus camera, and this aerial image, in turn, is reimaged on to the film plane.

OPTICAL SYSTEM

The optical system of the fundus camera thus consists of two major components: the illumination system and the observation and photography system. Each of these components occupies its own independent pathway within the apparatus and shares with the other only one common point, the front or ophthalmoscopic lens (Fig. 12.71).

Illumination System

The fundus cameras employ two light sources: a low-intensity incandescent lamp for viewing the fundus and focusing the instrument and a high-powered electronic flashtube for taking the photograph. In the Zeiss fundus camera, these two light sources are optically combined through the semi-reflecting surface (Fig. 12.71). In most of the other commercially available fundus cameras, the incandescent lamp and electronic flashtube are mounted on to a common base, and a transillumination method is used to combine the pathway of the two lights.

From this point onwards, the light from two light sources following a common pathway passes through a diaphragm, the adjustment of which controls the size of illuminated patch upon the patient's retina. This diaphragm is imaged at the surface of a holed mirror, which is itself imaged by the ophthalmoscopic lens in the plane of the patient's pupil. These two optical elements confine the illuminating beam to an annulus (a ring of light), the width of which is controlled by the diaphragm.

Observation and Photographic System

The holed mirror, which is imaged by the ophthalmoscope lens in the plane of the patient's pupil, forms the entrance pupil of the viewing

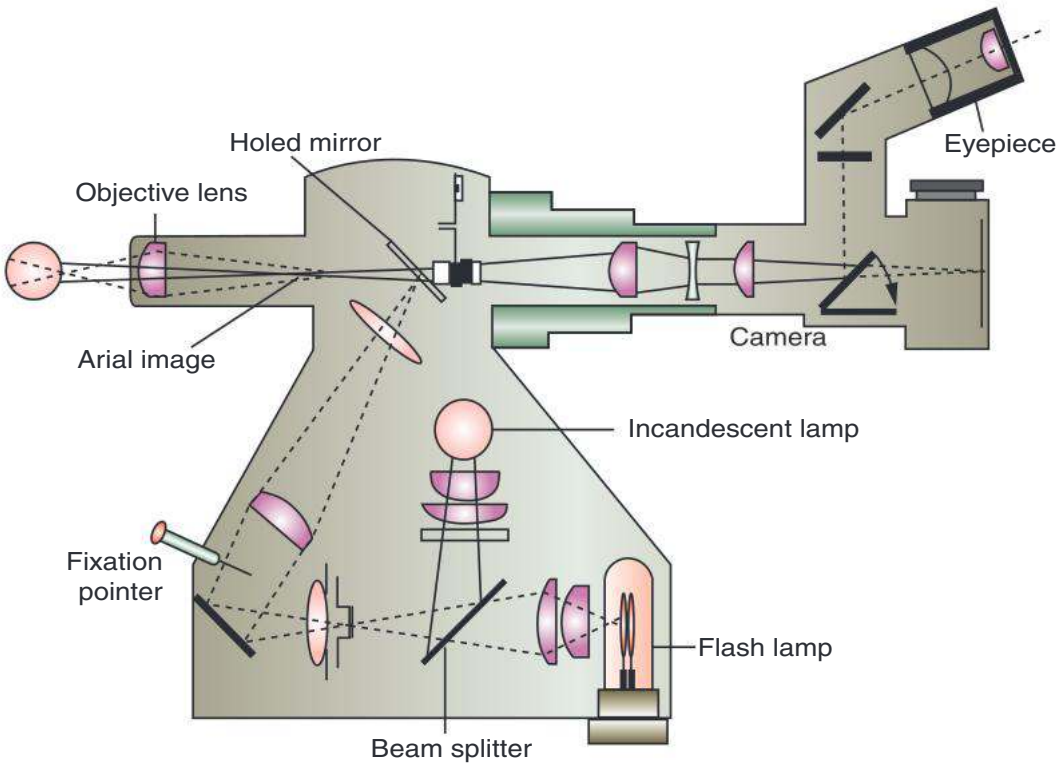


Fig. 12.71 *Schematic view of the Zeiss fundus camera to show outlines of the optical system.*

system. It confines the viewing beam to central region of the pupil. It also confines the illuminating beam to an annulus that surrounds the viewing beam. The illuminating and viewing paths are, therefore, separated in the plane of the patient's pupil, thereby making the instrument reflex-free.

The ophthalmoscopic lens produces an image of the fundus between the holed mirror and the ophthalmoscopic lens. This image is viewed through the hole with a compound microscope. The objective of this microscope forms an image of the fundus, via a flip mirror, upon the ground glass screen that is placed at the focal point of the viewing eyepiece. When the photograph is taken, the flip mirror that diverts the image into the eyepiece for observation swings out of the optical pathway, thus permitting the image to be projected on to the film for photography (Fig. 12.71).

The photographic component of the early instruments consisted of a small film carrier and a shutter mechanism. However, with the advent of fluorescein angiography, the simple film carrier has been replaced by a sophisticated, electronic motorized 35 mm camera system.

COMMERCIALLY AVAILABLE FUNDUS CAMERAS

Fundus camera may be stand mounted or hand held. Either type of camera can be mydriatic, requiring a pharmacologic agent to dilate the patient's pupil, or non-mydriatic, permitting retinal photography through the patient's natural pupil. Furthermore, they may come separately or have the facility of OCT incorporated in them.

Hand-held fundus camera. The available hand-held fundus cameras are Canon PowerShot G1 or Nikon Cool Pix set in the non-flash mode coupled with a light source mounted paraxial to the camera lens. This is coupled with a 20-D lens for adequate focus, will yield an image of the retina, but require tremendous skill and balance and the image quality is variable.

Smart phone attachment for fundus imaging. The innovative D-Eye Portable Eye and Retinal Imaging System easily attaches to a smart phone creating an ophthalmic camera for vision care screening and evaluation. (Also see page 549.)

Mydriatic stand-mounted fundus camera. They permit quick, relatively easy, high-quality fundus photography. Furthermore, they may be small-angle and wide-angle cameras. Commercially available small-angle fundus camera of approximately 20, 30 and 50 degrees field, currently being used, are Zeiss FF450, Topcon TRI, Nidek. The wide angle include Heidelberg Spectralis and OPTOS.

Non-mydriatic stand-mounted camera are usually equipped with two CCDs, one is a black and white infrared low resolution used for alignment of the patient's retina (image is viewable on a small CRT screen located on the base of the non-mydriatic retinal camera), while the second is used to actually capture the colour image of the retina through the naturally dilated pupil in a dimly lit room. The available models are Canon CR4-45 NM and Nidek – Non-mydriatic AFC-330.

Icam (Optovue, Inc. Fremont, CA). It has LED light for alignment of patient's eye and white light to capture image.

3 Nethra (Forus Inc. Bengaluru, India). In it, low-power LED light is used for image capture and can image both posterior and anterior segments.

Digital Retinography System (Centervue, Pandove, Italy). It is a non-mydriatic miniature table top fundus camera.

Easy scan (i Optics, Den Haag, The Netherlands). It works on the principle of scanning laser ophthalmoscopy.

Others include: TRC – NW 8F plus, VISUCAM 200, Non myd 7, Canon CR-2 Oculus Image cam 2, etc.

Advantages of the Fundus Camera

- Colour photography.
- Monochromatic photography – red-free for visualizing haemorrhages and abnormal retinal vessels, green-free or red filters to reveal the choroidal vascular patterns, which the choroidal vessels appear as white while retinal vessels that appear as black and blue reflectance will highlight the nerve fibre layer.
- Fundus autofluorescence.
- Fluorescein angiography.
- Indocyanine green angiography.

MODIFICATIONS IN FUNDUS CAMERA

1. Fluorescein Angiography System

Fundus cameras have been modified for fluorescein angiography by the addition of appropriate filters in the illumination and observation pathways (Fig. 12.72). Special power supplies are necessary to allow multiple exposures per second.

2. Digital Fluorescein Angiography System

Recently, digital fluorescein angiography (DFA) is being used increasingly. The DFA system uses a CCD detector in the camera in place of a film. One of the commercially available DFA system manufactured is shown in Figure 12.73.

Advantages of Digital Fluorescein Angiography

- The images can be instantaneously viewed on a high-resolution monitor. This allows the observer to manipulate the parameters (e.g. light intensity, centration of photography) while the study is in progress to obtain the optimum image.
- The images are recorded either on a computer hard drive or CD-ROM. The electronic recording allows immediate viewing of images and permits prompt management of the disease process.
- The angiograms can be electronically transmitted or printed from the digital data.

Disadvantage of Digital Fluorescein Angiography

- The quality of the DFA is inferior to the film-based photographs; however, it is adequate for clinical purposes.
- The computer systems are quite expensive and technology changes rapidly making systems obsolete.
- Computer monitors printers require additional space.
- The operation of the system requires training and maintenance.

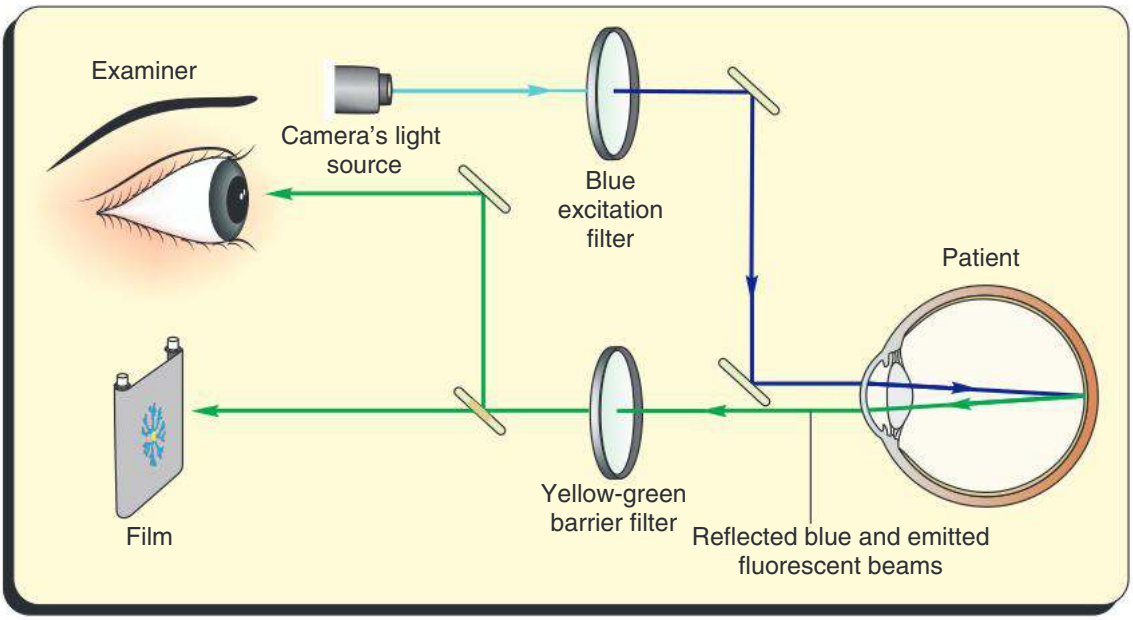


Fig. 12.72 *Blue excitation filter in the fundus camera produces blue light, which excites the unbound fluorescein molecules. The reflected blue light is absorbed by the yellow-green filter allowing only the fluorescein particles to be recorded on the film.*

Fig. 12.73 *Digital fluorescein angiography system.*

Commercially Available Digital Fluorescein Angiography Systems

With the advent of the technology, many fundus cameras are available. The ones most commonly used are as follows:

I. ***Zeiss FF 450 PLUS***. It has the following features:

- Field angles and corresponding magnifications are 50 degrees (11×), 30 degrees (19×) and 20 degrees (29×).
- Filters having motorized switching are also available. They are red, green and blue filters.
- Also, a special filter for the autofluorescence.
- It has 10× eyepiece with a reticle.
- With the facility of Montage (PanoramicView), which can be constructed automatically with the inbuilt software and also can be produced manually.

II. ***TopconFundus Camera (TRC-NW8F, Topcon TRC-NW8, TRC- NW8F, TRC-50DX)*** is a multifunction, easy-to-use, autofocus, autocapture fundus camera. It has an image net digital software. It is capable of acquiring, displaying, enhancing, analysing and saving the digital images.

III. ***Nidek F10***. It is a confocal digital ophthalmoscope. This produces non-invasive imaging with the retro mode and FAF (fundus autofluorescence). It produces fundus images of multiple depths with various light sources and SLO colour images and high-contrast images of FA (fluorescein angiography) and IA (indocyanine green). It has improved optical systems (catadioptric system) for less aberration. The device has got four light sources having different wavelength that offers four fundus images of

multiple depth on each wavelength as well as provides one SLO colour imaging on three wavelengths.

3. Wide-Field Digital Fundus Fluorescein Angiography

It has also been introduced, especially for use in children.

4. Non-mydriatic Fundus Cameras

These use infrared light and semi-automatic or automatic focusing systems to allow fundus photography without dilating drops. The infrared light is invisible to the patient, and the pupil dilates physiologically. After alignment and focusing are completed, the white light flash is triggered, and the photograph is taken before the pupil has a chance to constrict.

5. Wide-Angle Fundus Cameras

Up to 60 degrees have appeared, having large diameter and aspheric objective lenses. Wide-angle photographs even up to 148 degrees are possible, but a contact type of objective lens and special illumination system are necessary for such photographs.

6. Television Ophthalmoscopy

Several attempts at television ophthalmoscopy have been made using fundus camera optics. In general, excessive illumination is required, and resolution is poor.

7. Scanning Laser Ophthalmoscopy

A promising new system is the SLO, where only a single spot of laser light is scanned over the fundus, with each point being recorded as it is illuminated. The primary advantage of this system is the extremely low level of total light required. (For details see page 508.)

WIDE-FIELD RETINAL IMAGING SYSTEMS

Wide-field retinal imaging systems have been developed with the capability of capturing up to 200 degree field of view with one picture as compared to only 30–60 degree field of view with current standard fundus photography system. The salient features of the following three commercially available wide-field retinal imaging systems are described here in brief:

- Retcam II and Retcam III
- Panoret 1000A
- Panormic 200
- Optomap Optos camera (ultrawide-field [UWF] retinal imagine system)

RETCAM II AND III

Retcam II (Retinal camera II) is the advanced version of Retcam 120 (manufactured by Massie Research Lab, Dublin, CA).

Components of Retcam II

It is a mobile wide-field digital imaging system comprising the following major components (Fig. 12.74):

- *Three-chip CCD medical grade digital video cameras* is the heart of Retcam II. It is lightweight (so easy to position) and is attached to the light source and image capture unit.
- *Hand-held image capture unit* is attached with the camera by a long cable for easy patient access.
- *High-index corneal contact lenses* form the essential part of the image-capturing unit. These lenses allow capturing of oblique rays emerging from the peripheral retina. The changeable lenses (nose pieces) available to be attached to the image-capturing unit of Retcam II are as follows (Fig. 12.75):
  ROP (retinopathy of prematurity) lens, for premature infants which allows 130 degree field of view.
  Standard children lens, a 120 degree field-of-view lens for paediatric to young adult patients.
  High magnification lenses, a 30 degree field-of-view lens for fine details.
  80 degree *lens* for higher contrast paediatric and adult imaging.
  Portrait lens or external lens for area or external imaging.
- *Image processing unit comprises* a Windows or T computer system which gets the information from the camera. This unit is equipped with a new multi-purpose software.

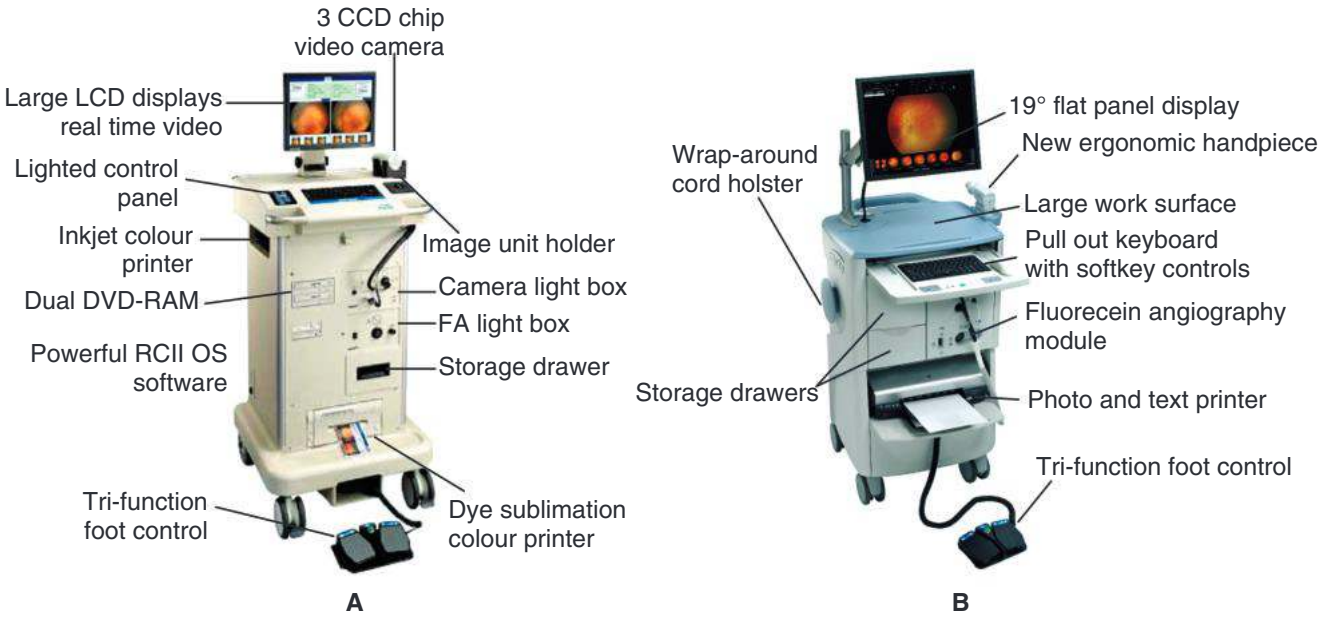


Fig. 12.74 *A, Retcam II, the wide-field retinal imaging system; B, Retcam III.*

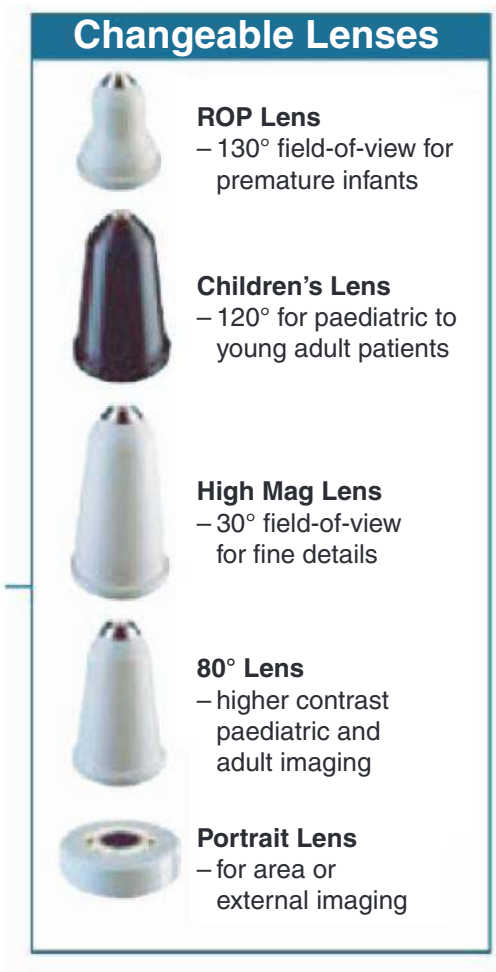


Fig. 12.75 *Changeable high-index lens available for attaching with image-capturing unit of Retcam II.*

- *Flat liquid crystal display (LCD) colour display* on 17-in. monitor allows the images to be viewed in real-time motion during acquisition.
- *Tri-function foot control* connected to the camera controls image focus, illumination and capture.

Special Features of Retcam II

- *Cone-shaped lens* provided with it is very handy to hold while scanning the retina.
- *Wide, 130 and 120 degrees, real-time image* of the fundus is particularly useful in diagnosis and documentation of diseases such as retinoblastoma and ROP.
- *Images are stored in digital format*, thus are retrievable easily.
- *Camera has a large storage device* with good facility of transferring the images in other media like CD, USB and other DVD devices. The data can be shared with others for seeking an opinion.
- *Comprehensive database* keeps track of each imaging section for the patients, allowing for later or side-by-side review of the cases. This is particularly useful in assessing response to treatment as in chemoreduction for retinoblastoma and laser photocoagulation for ROP.
- *Fluorescein angiography can also be performed with it. It is* another major feature of this

equipment. It is provided with a barrier filter, which helps to take the angiogram by still mode and continuous video for 20 s.
- In-built colour printer allows the print images and the detailed case report of the patient.

Features of Retcam III
Additional features of Retcam III (Fig. 12.74B) are summarized below.

Procedure
It involves following steps:

- *Pupils* are dilated fully.
- *Anaesthesia*. Neonates and infants can be easily examined under topical anaesthesia achieved with proparacaine eyedrops. Older children may be given short-term sedation for the procedure.
- *Separation of lids* is done with the help of a paediatric lid speculum, after placing the patient in supine position.
- *Fixation of the head* is then achieved.
- *Coupling solution* like methylcellulose gel is applied to the cornea.
- *Image capture unit* with desired lens is then positioned with gentle contact to the anterior corneal surface. Illumination and focus are controlled by the operator with the foot switch. Often a quick scan of the entire retina can be performed in live video motion before acquisition of images. Once the desired field of view has been identified, the images can be captured with the foot switch control.

Limitations of Retcam
- *Pupillary dilation* is extremely important for it, so not useful where pupillary dilation is a problem.
- *Other limitations* include need for camera lens–cornea contact, need for eyelid speculum and technical limitations of the camera.
- *Lack of stereopsis* and some loss of magnification of retinal field in exchange for a wide-angle field of view may also be seen as a limitation.
- *Cannot be used in adults* because with lens opacities that begin in adolescence and accumulate with age, the entering light is scattered more widely, causing decreased contrast sensitivity.

Advantages
- *Mobile, self-contained system* for use in nursery, ICU, operating rooms, etc.
- *Easy to use* – even technicians or nurses can operate.
- *Avoids stress and expertise* of indirect ophthalmoscopy and scleral indentation.
- *Inter-observer variability* is eliminated.
- *Teaching tool for students*, and parents can be counselled.
- *Easy case management* with access to images, video clips, patient data, instant retrieval and side by side comparison.

Applications of Wide-Field Imaging System
- *Paediatric retinal disorders* can be easily diagnosed, followed and objectively documented. Especially useful in ROP, retinoblastoma, shaken baby syndrome.
- *Paediatric anterior segment imaging*, gonioimaging for glaucomatous damage, iris lesions.
- *Fluorescein angiography* can also be performed with advances in the technique.

PANORET-1000 AA
Principle
This wide-field imaging system employs the principles of trans-scleral illumination propagated by Pomerantzeff.

Advantages
Because a trans-scleral light source provides diffuse illumination, so this system

- Can be used in the presence of media opacities,
- Can be used in cases where pupillary dilation is a problem,
- Can also be used in adults and
- Both fluorescein angiography and indocyanine green angiography can also be performed.

Limitations
- Patients with heavily pigmented uvea are not well imaged.

- Since it is introduced recently, so there is limited clinical experience with its use.

PANORAMIC 200 NON-MYDRIATIC SLO

Principle

It is a non-contact non-mydriatic system based on the use of both a green (532 nm) and red (633 nm) laser to produce a digital image of 2000 by 2000 pixels. The resolution of image ranges from 20 to 40 μm per pixel.

Applications

It is often used as a screening tool for diabetic retinopathy, age-related macular degeneration (ARMD) and glaucomatous disc changes.

Advantages

Field of view is 200 degrees in a single image.

Limitations

Being a table-mounted non-mobile unit, it cannot be used in small children and uncooperative patients.

UWF RETINAL IMAGING TECHNOLOGY

Optomap (Optos Plc., Dunfermline, UK) uses UWF retinal imaging system with which a 200 degree view of the retina is imaged in a single capture. It utilizes a combined SLO with an ellipsoidal mirror to obtain images of the retinal periphery without the need for bright illumination lighting or a contact lens and pupillary dilatation.

This system provides the ability to capture:

- Red and green reflectance imaging,
- Fundus autoflourescence and
- Flouroscein/indocyanine green angiography.

FUNDUS IMAGING WITH A SMART PHONE

A smart phone can be used as an indirect ophthalmoscope when coupled with a condensing lens. It can be used as a direct ophthalmoscope after minimal modification, wherein the fundus can be viewed without an intervening lens in young patients with dilated pupils. This technique has the potential for mass screening, enables ophthalmologists without a fundus camera to document and share findings, is a tool for telemedicine and is rather inexpensive.

For details see page 549.

RTX1 ADAPTIVE OPTICS RETINAL CAMERA

This technology provides non-invasive, in vivo, enface, images of the retina at an unprecedented resolution. It compensates the higher order aberrations originating from the cornea and the lens by using deformable mirror. It reduces the effect of wavefront distortions. The main application of adaptive optics (AO) imaging is to assess the photoreceptor mosaic, its regularity and spacing and the density. It has an exceptional resolution of 2–3 μm. It enables the examination of extrafoveal cone photoreceptors, arteriolar structure (lumen and wall), thin borders of macular lesions like Mactel types 2, thin borders of lamina cribrosa, microcystic oedema and nerve fibre bundles at the disc edges. It captures an image of central 4 degree × 4 degree area, although a panoramic area can be obtained to study the larger area.

These systems have been coupled to scanning laser ophthalmoscope (SLO), flood illuminated camera (rtx1) and OCT. AO-based retinal imaging can provide a sensitive structural outcome measures for clinical trials with new therapies for retinal degenerations.

Limitations

- Lack of normative data and no demographic data available.
- Lack of adequate resolution in the foveal centre.

LASER SCANNING IMAGING TECHNIQUES

- SLO
- CSLO
- Spectralis HRA plus OCT
- RTA
- SLP

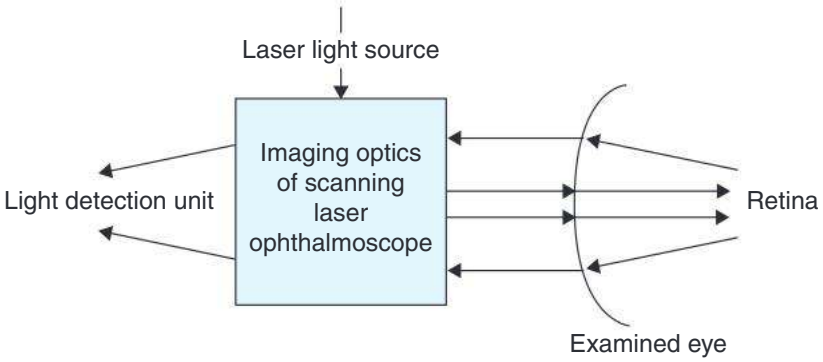


Fig. 12.76 *Optics of scanning laser ophthalmoscope as inverted indirect ophthalmoscope. Note that the light enters the eye through a small illumination aperture and the returned light is collected over a large viewing aperture.*

SCANNING LASER OPHTHALMOSCOPY

SLO was invented by Webb, Pomerantzeff and Hughes in 1979. The word scanning here refers to the illumination system, which samples the retina point by point rather than capturing the image as a whole, as is done with a conventional fundus camera.

Principle

The SLO operates essentially as an inverted indirect ophthalmoscope. This means that a small illumination aperture is used to illuminate the eye while a large viewing aperture collects all the light emitted by the eye (Fig. 12.76). The small aperture creates a very narrow moving beam of light which can bypass most ocular media opacities (i.e. corneal scars, cataracts, vitreous haemorrhage) to reach the surface of the retina and record its surface detail. A live video image of the retina is displayed on a computer monitor and test results are digitally recorded (Fig. 12.77).

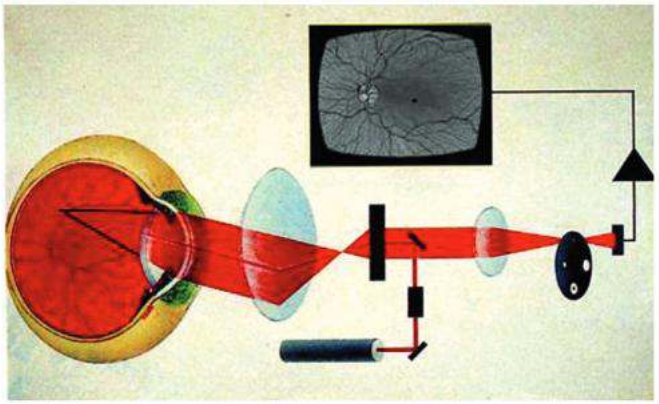


Fig. 12.77 *Optical path of recording of scanning laser ophthalmoscope (SLO).*

Applications of SLO

1. ***Scanning laser acuity potential test***. The letter E corresponding to different levels of visual acuity (ranging from 20/1000 to 20/60) is projected directly on the patient's retina. The examiner can direct the test letters to foveal and/or extrafoveal location within the macula and determine a subject's potential visual acuity.

This may be especially helpful in individuals who have lost central fixation but who may still possess significant eccentric vision. It is also useful in separating out the component of retinal function from anterior segment contributions to overall visual dysfunction when contemplating surgical interventions.

2. ***Microperimetry/scotometry***. The SLO can visualize a particular area of the retina and test its sensitivity to visual stimuli, thereby generating a map of the seeing and non-seeing areas. If central vision is lost, the patient can potentially be trained to use an adjacent retinal site to substitute for central visual function.

3. ***High-speed FA/ICGA***. Fluorescein and indocyanine green angiography (FA/ICGA) performed using the SLO is recorded at 30 images per second, producing a real-time video sequence of the ocular blood flow. The standard fundus camera sequence is limited by flash recycling to one to two frames per second and is unreliable in its ability to document details of choroidal filling which occurs over a 1–2 s span of time.

The higher speed of image acquisition more completely captures the chorioretinal filling sequence and can be used to accurately identify the choroidal feeder vessels of neovascular membranes. Guided by high-speed FA/ICGA results, laser treatment of sight-threatening diseases like exudative ARMD can be carried out with pinpoint accuracy.

SLO Versus Conventional Fundus Camera

1. SLO samples the retina point by point, while the fundus camera captures the image as a whole.
2. In SLO, a single point on retina is illuminated for less than 1,000,000th of a second, while the conventional fundus camera illuminates the eye for several milliseconds during flash capture.
3. The SLO captures a temporal image, while conventional fundus camera captures a spatial image.
4. In SLO, light source is always laser, so it can achieve white light imaging comparable to conventional white light fundus photography.

Advantages of SLO Over Conventional Fundus Camera

- Low light level
- Highly light efficient
- Continuous imaging
- Large depth of field
- Instantaneous image availability for review
- The high capture speed allows dynamic image studies such as blood flow
- Allows excellent imaging even in the presence of media opacities

CONFOCAL SCANNING LASER OPHTHALMOSCOPY

CSLO, also known as SLT, was introduced by Webb and associates in 1987. The term *confocal* has been derived by combining the terms *conjugate* and *focal*, and it describes that the locations of the focal plane in the retina and the focal plane in the image sensor are located in conjugate positions. Confocality of the system is achieved by placing a pinhole in front of the detector, which is conjugate to the laser focus (Fig. 12.78). The size of the pinhole determines the degree of confocality, such that a small pinhole aperture will give a highly confocal image. Commercially available CSLOs include:

- HRT and
- Top SS.

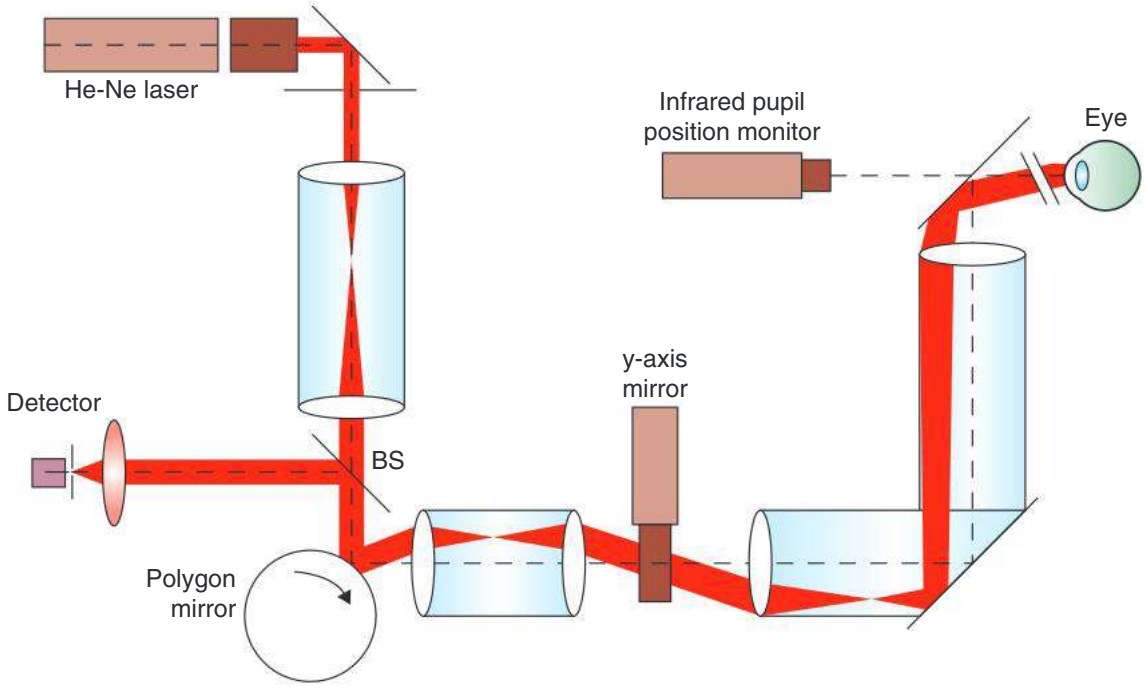


Fig. 12.78 *Optics of confocal scanning laser ophthalmoscope (CSLO).*

HEIDELBERG RETINA TOMOGRAPHY

HRT, the most popular instrument, is available in two models – the HRT I (introduced in November 1991) and the HRT II C (introduced in April 1999). For both the models, the laser source is a *helium–neon diode laser* of wavelength 670 nm. The laser raster scans the x–y plane to obtain confocal optical sections of the retina. Once one plane has been scanned, the laser changes focus to scan a slightly deeper plane of the retina. This continues until a series of confocal optical sections through the depth of the fundus are obtained.

INSTRUMENT PROFILE

The instrument is small, light, portable and is table-mounted along with a notebook computer (Fig. 12.79). Press of signal button acquires optical section images within 32 ms and with a repetition rate of 20 Hz in two dimensions. From the images obtained in this prescan of 4–6 mm depth, the software computes and automatically sets the correct location of the focal plane, the required scan depth for that eye and the proper sensitivity to obtain images with correct brightness. The HRT operation software automatically defines a reference plane for each individual eye. The reference plane is defined parallel to the peripapillary retinal surface and is located 50 μm posteriorly to the retinal surface at the papillomacular bundle. The reason for this definition is that during development of glaucoma, the nerve fibres at the papillomacular bundle remain intact longest and the nerve fibre layer thickness at that location is approximately 50 μm. We can, therefore, assume to have a stable reference plane located just beneath the nerve fibre layer. All structures located below the reference plane are considered to be cup; all structures located above the reference plane and within the contour line are considered to be the rim.

Fig. 12.79 *The Heidelberg retinal tomograph II.*

ACQUISITION AND GENERATION OF TOPOGRAPHY IMAGE

HRT I

Image acquisition. The HRT I makes *32 scans through the retina resulting in a stack of optical sections* which represent both an area (x–y) and depth (z) image of the retinal structure under investigation (Figs 12.80 and 12.81A). The field of view can be set to three levels – 10 degree × 10 degree, 15 degree × 15 degree or 20 degree × 20 degree. The depth to which the laser scans varies between 0.5 and 4.0 mm in 0.5 mm steps. Thirty-two optical sections are generated at all of these depth levels, so the spacing between sections is closer at the lower depth levels and

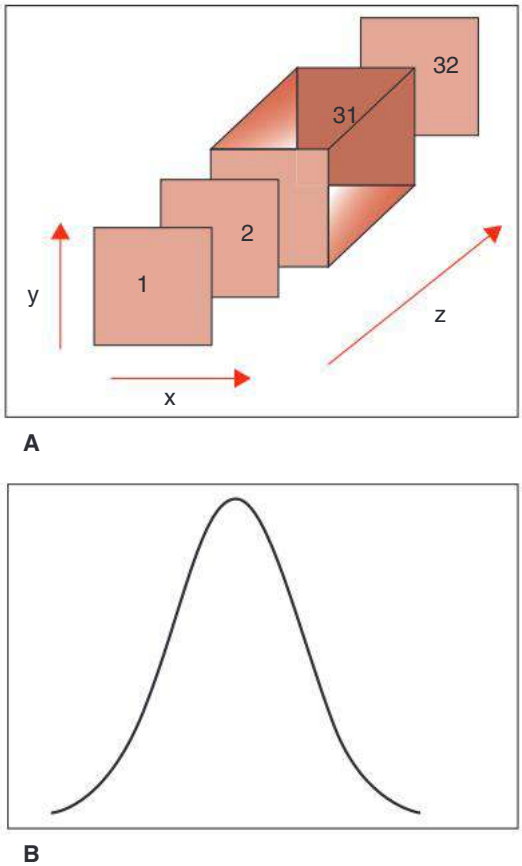
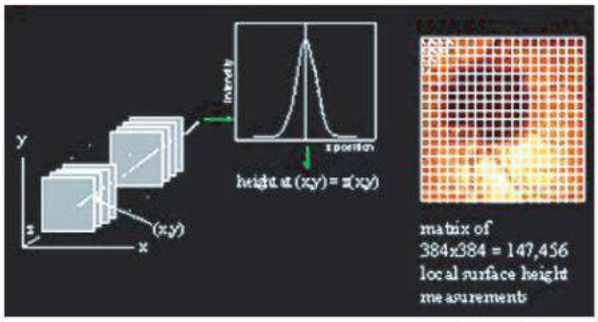
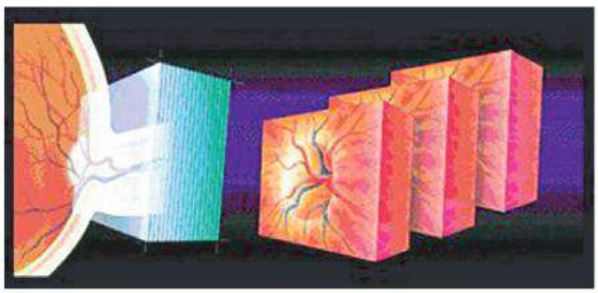


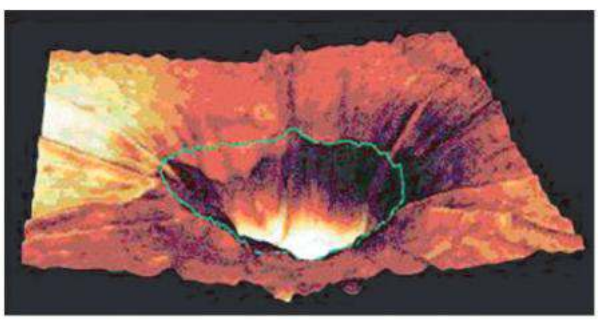
Fig. 12.80 *HRT I image acquisition: A, a stack of 32-image series and B, z-profile of pixel (x, y) in image series.*



A



B



C

Fig. 12.81 *Principle of scanning laser tomography – concept of 3D image composition based on 32 confocal sections: A, a stack of 32 confocal sections (the software aligns the images but only compensates for small eye movements) the axial intensity distribution for each of the 256 × 256 pixels is plotted and the axial location of the maximum is coded into a 2D image with 256 × 256 pixels; B, three separate image series acquired; C, 3D image of optic nerve head.*

greater at the higher depth levels. The camera must be placed 15 mm from the examined eye, and the operator centres the optic disc on the monitor. The HRT I software has a quality control mechanism, which informs the operator whether the image series is of good quality. Changes in focus and depth setting are advised until the series acquired is optimum. However, the operator has to examine the image series to establish whether there are any image-distorting eye movements. In such cases, the series have to be rejected. Generally, three optimum image series are obtained for each eye under examination (Fig. 12.81B). The topography images are then generated (Fig. 12.81C).

Generation of the topography image. Each confocal section of the 32-image series consists of 256 × 256 pixels. Each pixel location (x, y) has a varying brightness through the series. The distribution of reflected light intensity of each pixel through the 32 series is called the z-profile (Fig. 12.80). The z-profile is a symmetric distribution with a maximum at the location of the light-reflecting surface. By determining the position of the profile maximum, the height of each pixel can be determined (Fig. 12.81). The topography map is a colour-coded representation of each pixel position within the 32 series. Each of the 32 confocal sections has been designated an arbitrary red value. Section 1 is dark red, section 32 is saturated white and the sections in between decrease in redness from 1 down to 32 in equal steps.

Alongside the topography image is a reflectivity image, which gives the most visual information about the optic disc under examination – similar to a fundus photo (Fig. 12.80).

HRT II

Image acquisition. The HRT II differs quite considerably from the HRT I. There is one field of view (15 degrees), and each optical section has a resolution of 384 × 384 pixels. In contrast to the HRT I, which can be used for the acquisition of both optic nerve head (ONH) and macular images, the HRT II has been designed specifically for the grabbing of ONH images alone.

In image acquisition, the operator enters the patient's details and a rough setting of the examined eye's refraction. The patient is instructed to look at an internal fixation light, which results in an automatic centration of the ONH on the monitor. The acquisition button is activated, and the CSLO proceeds with image acquisition.

An automatic prescan with 4–6 mm depth is performed, and from the images obtained from this prescan, the software computes and automatically sets the correct location of the focal plane – the required scan depth for that eye and the sensitivity to obtain images with correct brightness. Following this, the system automatically acquires three image series with

the predetermined acquisition parameters. The number of image planes acquired per series depends on the required scan depth – 16 images per millimetre scan depth are acquired. There is an automatic quality control during image acquisition, and so if one or more of the acquired image series cannot be used for any reason, additional images are acquired automatically until three good quality image series have been obtained. After image acquisition, the images are saved on the hard disc and the three topography images and the mean topography image are computed automatically.

This semi-automated image acquisition of the HRT II means that in busy practice situations, staff with minimal experience of using the instrument should be able to acquire images.

HRT III

HRT III was introduced in 2005 and incorporated advances in software and hardware yet maintained a stable platform to allow analyses on date acquired with previous generations of HRT. Software advances include the Glaucoma Probability and score (GPS) and new asymmetry and progresion analyses. The database of HRT III has been expanded and is stratified by ethinc groups. Quality control checks were enhanced to provide real time image feedback during acquisition for focus, Illumination, and disc centering among others.

HRT III has:

- Lateral resolution-10 um /pixel
- Longitudnal resolution-62 um /plane
- Image acquisition time - 1.0 sec.

IMAGE ANALYSIS AND EXAMINATION OF RESULTS

I. SLT in Glaucoma

The applications of SLT in glaucoma are as follows:

1. Initial Examination to Discriminate Between the Normal Eyes, Glaucoma Suspects and Glaucomatous Eyes

The printout of initial report has following details (Fig. 12.82):

Topography and reflectivity image. As described earlier (Fig. 12.80), the topography image is a colour-coded map. The redder areas are on the surface and the white areas are deeper in the scan (Fig. 12.82).

The reflectivity image approximates a mean brightness of all images. In the reflection image, the ONH is divided into six sectors. These sectors are compared to a normal database and then classified. Moorfield's regression analysis means that the rim (green and blue) and the disc area (green, blue and red) for each sector are compared to a normal database. Depending on the patient's age and overall disc size, the eye is then statistically classified as 'within normal limit', 'borderline' or 'outside normal limit'.

Horizontal/vertical height profile, i.e. height profile along the white horizontal and the white vertical line in the tomography image. The subjacent reference line (red) indicates the location of the reference plane (separation between cup and neuroretinal rim). The two black lines perpendicular to the height profile denote the borders of the disc as defined by the contour line.

Mean height contour graph. The height difference between the reference line (red) and the height profile corresponds to the retinal nerve fibre layer (RNFL) thickness along the contour line.

Stereometric analysis of ONH. For both instruments, an operator has to define the edge of the ONH, and this is done using the mouse. Once the ONH margin, i.e. contour line which matches the inner edge of scleral ring (Elschnig's ring) has been defined, area and volumetric information about the ONH are obtained.

The result of this analysis is a set of stereometric parameters. The most important parameters are disc area, cup and rim area, cup and rim volume and mean and maximum cup depth, a measure for the 3D shape of the cup and for the mean thickness of the RNFL along the contour line (Fig. 12.82). Most of the stereometric parameters provided by the HRT change significantly with progression of glaucoma; the standard errors of the means in the visual field groups are very small, and the means differ significantly

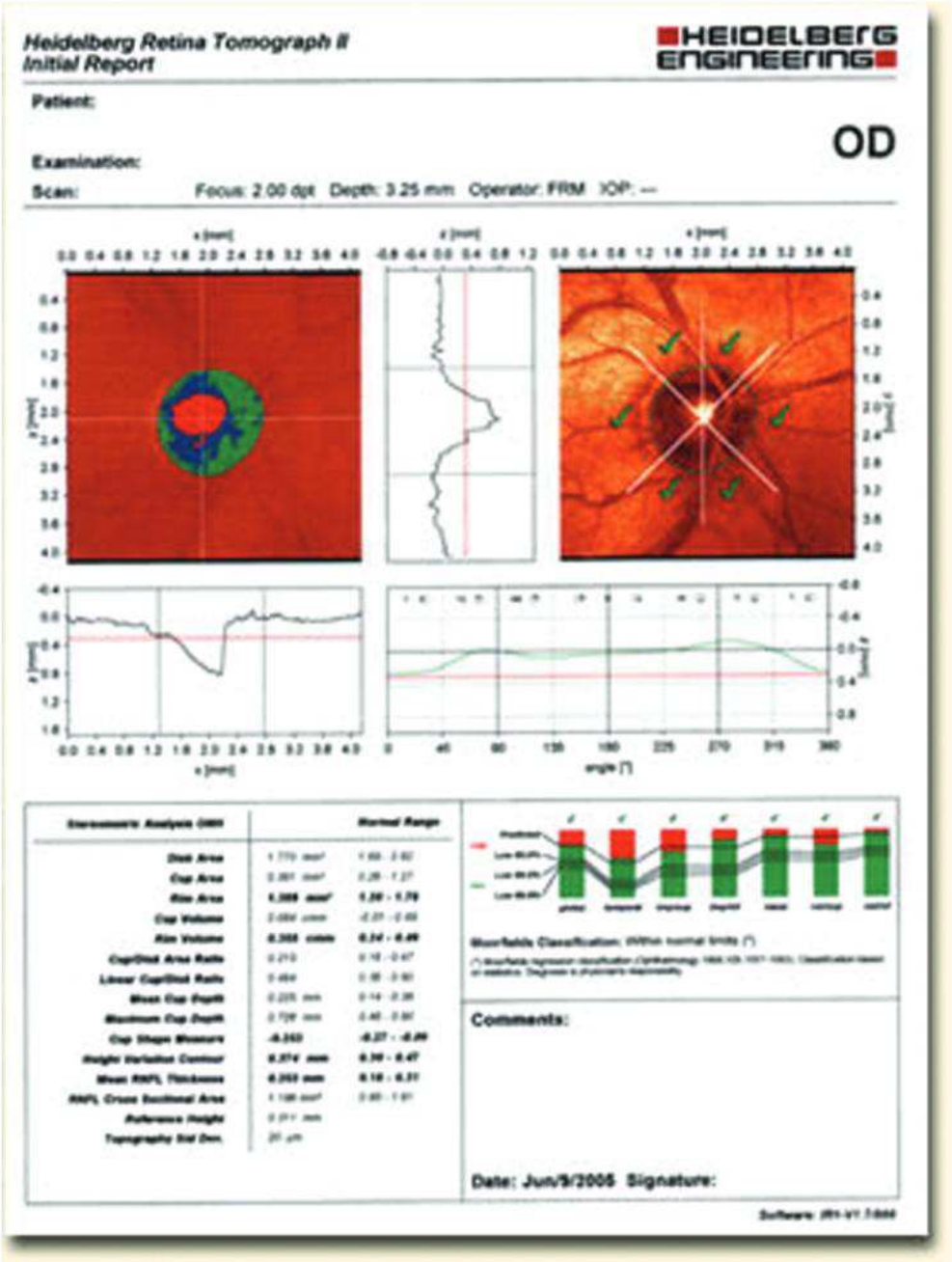


Fig. 12.82 *Initial examination report with the HRT II.*

between groups. The parameters are useful, therefore, to follow the progression of the disease. But the physiological variability of the ONH configuration is high and so are the standard deviations of the parameter values. The distributions of the parameter values of the different groups overlap each other. Hence, it is difficult (except in advanced cases) to classify an individual eye as being normal or glaucomatous based on individual stereometric parameters.

Disc analysis with HRT II – Moorfield's analysis feature. Once the contour line has been drawn, there is the option of using the Moorfield's regression feature. This compares the optic disc imaged to a normal database and predicts the normality of the disc.

Variability in acquisition can occur due to manual contour line drawing, inter- and intra-test examinations. To overcome this, Moorfield's study revealed the advantage of examining the rim area in sectors. This graphic visualizes the

result of the Moorfield's regression analysis. The whole column represents the total ONH area in this specific sector. It is divided into the percentage of rim area (green) and percentage of cup area (red). The age-dependent limits of the confidence intervals are as follows:

- If the percentage of the rim is larger than or equal to the 95% limit, the respective sector is classified as 'within normal limit'.
- If the percentage of the rim is between the 95% and the 99.9% limits, the respective sector is classified as 'borderline'.
- If the percentage of the rim is lower than the 99.9% limit, the respective sector is classified as 'outside normal limit'.

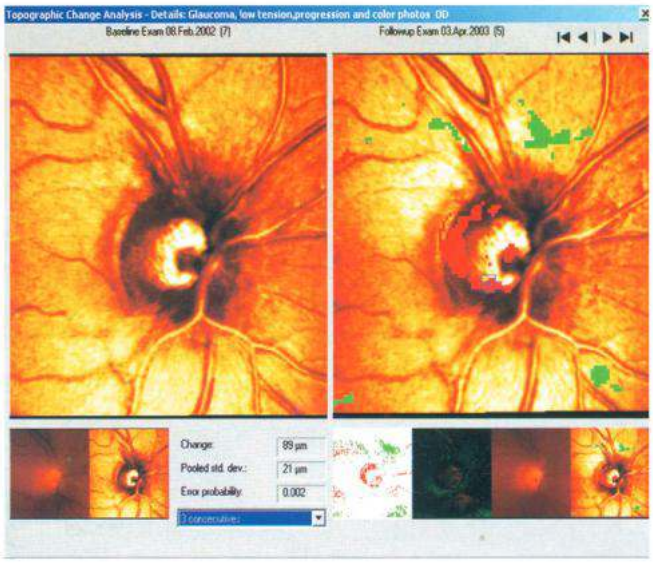


Fig. 12.83 *Change probability maps.*

2. Follow-up Examination to Study the Progression

Glaucoma is a progressive disease, and there is significant individual variability which makes labelling an eye glaucomatous after one single test hazardous. Therefore, proven progression of the disease becomes critical to the diagnosis and management. The baseline measurements are extremely important, since those parameters alone are taken for further retesting. Therefore, the image quality (as ascertained by standard deviation) should be good and it should be ensured that ONH is centred, illumination is even, refractive error is incorporated and eye movements are minimal. It is claimed that disc changes are more frequent than field changes. Progression requires three consecutive readings (baseline + three follow-ups) to perform a topographic change analysis.

Topographic change analysis can be done by two methods:

i. *Change probability maps* (Fig. 12.83) are independent of the reference plane and the contour line and are calculated automatically, comparing mean topography images.
   - Red signifies 'significant' depression.
   - Green signifies 'significant' elevation.
   - The change is calculated by local change in surface height, measured in microns, at the location selected. A height change is considered significant:
     - If it is repeated in at least two (better is three) consecutive follow-up examinations.
     - If it is region of at least 20 connected super pixels.

ii. *Parametric change* is evaluated in the follow-up diagram that plots normalized stereometric values versus time. If average normalized parametric value decreases by more than –0.05 significant in two consecutive examinations, it is deemed 'suspected' and if it appears in three consecutive examinations, it is considered 'confirmed' progression (Fig. 12.84).

Frequency of examinations. Time determines the speed of progression, and repeated examinations cannot detect disease. High-risk cases on basis of race, age, family history and raised intraocular pressure should undergo a 6 monthly examination and other patients may be followed up annually. Examinations may be done more frequently for the first 18 months in patients showing signs of clinical progression so as to start detecting statistical 'change'.

II. SLT in Macular Diseases

Researchers have developed a software algorithm that analyses the axial intensity distribution and

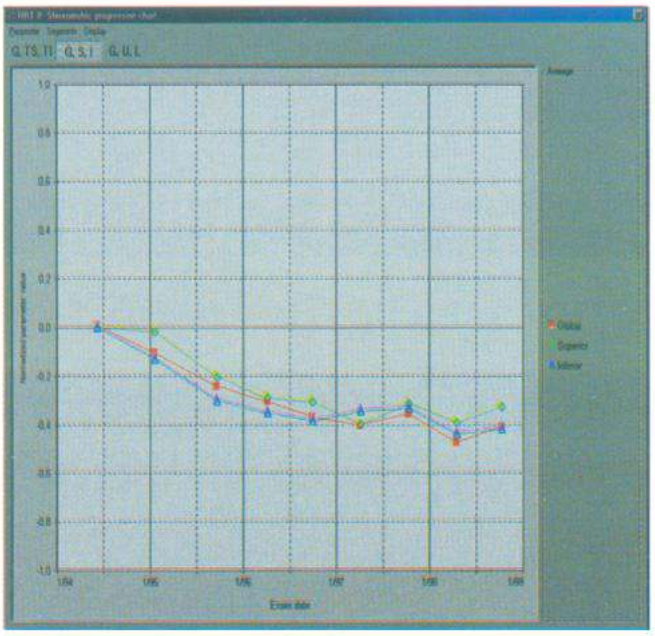


Fig. 12.84 *Parametric changes.*

computes a thickness-equivalent map of the retina. This is useful in macular pathologies such as macular oedema or macular cysts. The researchers concluded that this analysis offers non-invasive, objective, topographic and reproducible index of macular retinal thickening. The scanning laser thickness analyser using HRT II uses 147,456 points while in OCT only 600–768 points are used.

SPECTRALIS HRA PLUS OCT

The Spectralis OCT and the Spectralis HRA + OCT use spectral domain OCT (SD-OCT) technology, also referred to as Fourier domain OCT (FDOCT). The beam of a super luminescence diode scans across the retina to produce a cross-sectional B-scan image. To create 3D images of the retina, up to 768 equally spaced B-scans can be sequentially acquired. The infrared beam of the SLO has an average wavelength of 870 nm.

It is a ***confocal laser scanning ophthalmoscopy (CSLO)*** based multi-modality system in which the images single or in sequence are acquired and stored. It offers the following imaging modes:

- FA,
- ICGA,
- Infrared reflectance imaging (IRI),
- Blue- or red-free reflectance imaging (RF),
- FAF,
- Simultaneous FA and ICGA,
- Simultaneous FA and IRI,
- Simultaneous ICGA and IR and
- Simultaneous AF and IR.

Spectralis OCT is an SD-OCT system that allows high-speed, high-resolution cross-sectional imaging of the retina, offering the simultaneous OCT and infrared reflectance imaging and infrared reflectance imaging alone. OCT imaging can be single cross-sections of the retina (B-scans), patterns of single cross-sections or complete 3D images.

Principle

A laser beam is focused on the retina. It is deflected periodically by means of oscillating mirrors to sequentially scan a 2D sections of the retina. The intensity of the reflected light or of the emitted fluorescent light at each point is measured with a light-sensitive detector. In confocal optical system, light reflected or emitted outside of the adjusted focal plane is suppressed, resulting in high-contrast images. This system produces good quality images in poorly or non-dilating pupils.

Laser sources of the Spectralis HRA emit laser light with three different wavelengths:

- *For excitation of fluorescein*, a blue solid state laser (wavelength 488 nm) is used. A barrier filter at 500 nm separates excitation and fluorescence light. The same wavelength (but without the barrier filter) is used to create blue reflectance images (also called red-free images). Furthermore, the Spectralis HRA is capable of high-quality autofluorescence (488 nm) imaging.
- *For excitation of indocyanine green*, a diode laser at 790 nm wavelength is used, together with a barrier filter at 830 nm to separate excitation and fluorescence light.
- *A second diode laser* at 820 nm wavelength serves to produce infrared reflectance (IR) images.

In the simultaneous imaging modes, each image line is scanned twice subsequently with

alternating lasers. For example, during simultaneous fluorescein and indocyanine green angiography, only the 488 nm laser is switched on for the first scan of a line, while during the second scan only the 790 nm laser is switched on.

RETINAL THICKNESS ANALYSER

Retinal Thickness Analyzer (RTA) (Fig. 12.85A) is an ophthalmic imaging device for the mapping and quantitative measurement of optimal thickness and disc topography (Fig. 12.85B). It uses a computerized laser slit-lamp to measure retinal thickness at the central 20 degree of the macula and overlaps a map of measurements on the patient's retinal image.

A vertical narrow green He–Ne (543.3 nm) laser slit-beam is projected at an angle on the retina while a CCD camera records the backscattered light. Due to the oblique projection of the beam and the transparency of the retina, the backscattered light returns two peaks corresponding to the vitreoretinal and the chorioretinal interfaces. A 3 × 3 mm scan consisting of 16 optical cross-sections is acquired within 0.3 s. Five such scans are obtained at the macula, three scans at the disc and additional five scans cover the peripapillary area (Fig. 12.86).

Clinical Applications

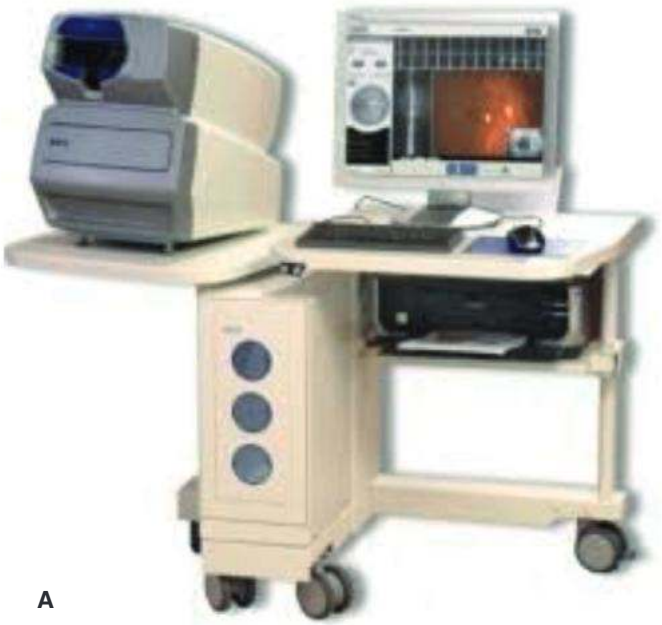
Retinal Thickness Analysis

As the CCD camera records the reflected image of the retinal cross-sections, a thickness algorithm identifies the location of the anterior and posterior retinal borders (Fig. 12.87).

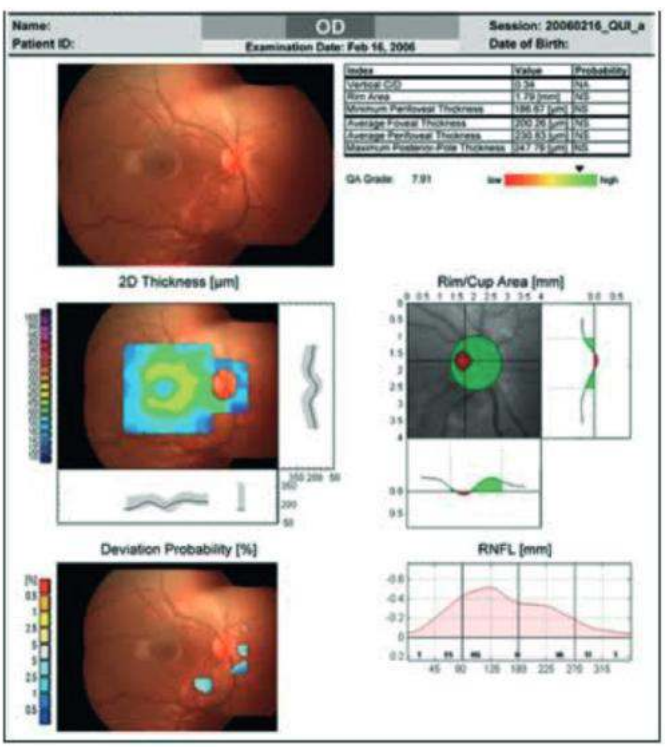
The calculated distance between the two light peaks determines the retinal thickness at a given point. The algorithm measures 16 data points on each slit, 187.5 μm apart, totalling 2560 thickness measurement points.

Indications of RTA include:

- Diabetic macular oedema,
- ARMD,
- Cystoid macular oedema,
- Macular holes and
- Epiretinal membrane.



A



B

Fig. 12.85 *Retinal thickness analyser (RTA): A, Machine; B, Report print out.*

ONH Topography Analysis

The RTA acquires three scans over the disc covering a 3 × 3 mm area. Each of the 16 slit images represents the disc topography along a vertical line. Using edge detection analysis, the topography algorithm identifies the left border of the

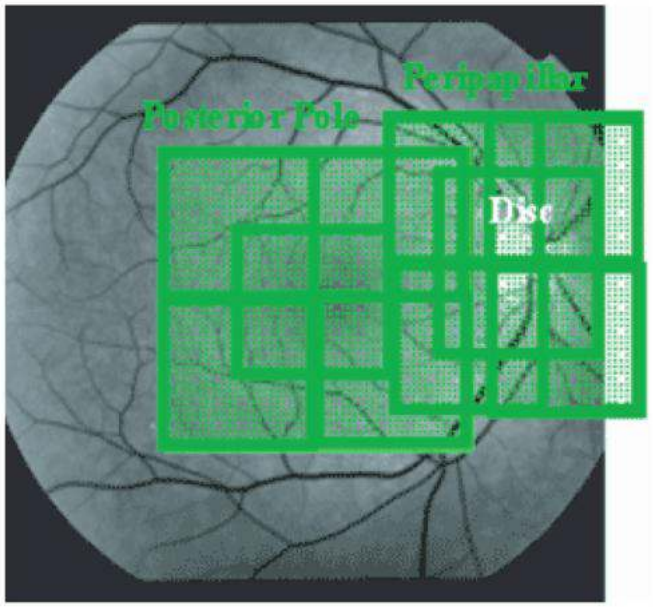


Fig. 12.86 *Thirteen RTA-scanned areas.*

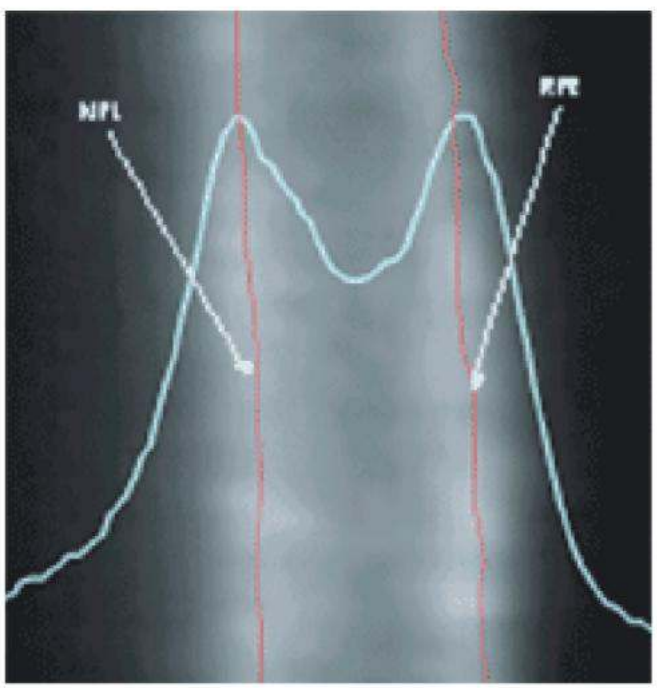


Fig. 12.87 *Light intensity profile as detected by the RTA's thickness algorithm.*

light, corresponding to the vitreoretinal surface, and calculates the disc topography (Fig. 12.88).

In order to obtain quantitative stereometric measurements, the operator is required to draw a contour line along the disc edge. The same contour line is used in follow-up visits to ensure accurate monitoring of subtle changes. The disc topography report displays a rim/cup area

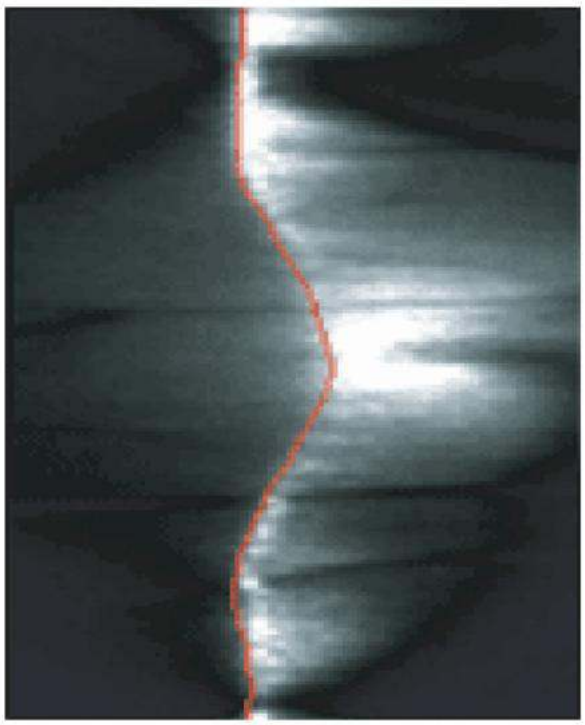


Fig. 12.88 *The vitreoretinal surface as detected by the RTA's topography algorithm.*

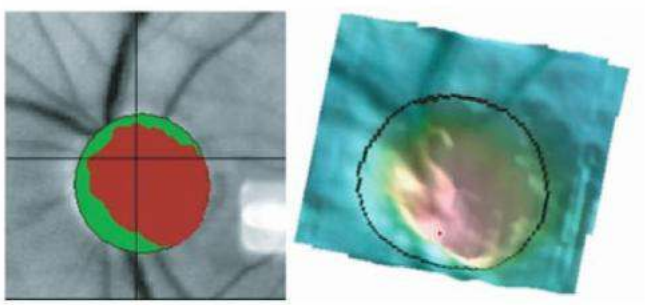


Fig. 12.89 *RTA – disc topography map: A, rim/cup area map and B, pseudo-3D representation.*

map (Fig. 12.89A) and a pseudo-3D representation of the disc topography (Fig. 12.89B).

Thus, the RTA may be used to assess the optic nerve in terms of the cup to disc (C:D) ratio as well as other ONH parameters. It is also able to monitor progression of nerve fibre layer thinning in glaucoma. Findings are presented in numerical values and may be shown in 2D or 3D representation.

RTA: clinical applicability in glaucoma. Early detection of glaucomatous damage is critical for successful treatment. Glaucoma is associated

with ganglion cell and nerve fibre layer loss. Today we know that up to 50% of the total number of ganglion cells are located in the macula. The loss of these two layers is directly reflected in retinal thickness.

None of the other automated imaging tools has emerged as a new gold standard for early glaucoma diagnosis and monitoring. The RTA, however, in addition to imaging the optic disc cupping, identifies and quantifies the anatomical damage in the macula and the peripapillary region even before the symptoms appear.

The RTA is the only tool that provides objective assessment of all three key components of glaucoma-associated changes in the fundus of the eye: macula, peripapillary region and disc area.

Anatomy imager 3D rendering. Recently, the RTA has incorporated an anatomy imager into the device. The anatomy imager allows 3D rendering of retinal thickness measurements over the fundus photo captured by the device. Alternatively, the program allows easy importation of an external image (such as a fluorescein angiography study). The 3D block may be rotated and cleaved as necessary to appreciate the relationship between abnormalities in retinal thickness and pathologies seen on fluorescein angiography.

SCANNING LASER POLARIMETRY

SLP provides on objective quantitative assessment of the peripapillary RNFL and thus is also called *RNFL analyser* GDx; the commercially available RNFL analyser has two models: the GDx FCC (old model) and GDx VCC (new model). RNFL analyser with variable corneal compensation (available as GDx VCC) is the most appropriate structural test for early detection of glaucomatous damage as it quantifies the morphology of RNFL.

PRINCIPLE AND OPTICS

The RNFL analyser works on the principle of SLP. The operating principle of SLP by which it determines the RNFL thickness is the measurement of the *retardation* of a polarized laser light passing through tissues possessing the physical property of *form birefringence* (explained below).

Form birefringence refers to splitting of a light wave by a polar material into two components. These components travel at different velocities, which creates a relative *phase shift*, also termed as retardation. The amount of phase shift or retardation is proportional to the thickness of polar tissue. The polar tissues are composed of parallel structures, each of which is of smaller diameter than the wavelength of the light used to image it. The RNFL behaves as a polar tissue because of the microtubules (with diameters smaller than the wavelength of light) present in the highly ordered parallel axon bundles. The greater the number of microtubules, the greater the retardation of the polarized laser light, indicating the presence of more tissue, thus giving an assessment of RNFL.

Optics. Figure 12.90 depicts the optics of SLP. The near-infrared laser light (780 nm) enters the eye at specific orientation. As the laser double passes the RNFL, it is split into two parallel rays by the birefringent microtubules (present in the axons forming RNFL). The two rays travel at different speeds, and this difference (called retardation) is measured.

Total Birefringence, Anterior Segment Birefringence and RNFL Birefringence

Total birefringence-associated retardation is the sum of anterior segment birefringence (from cornea and lens) and RNFL birefringence.

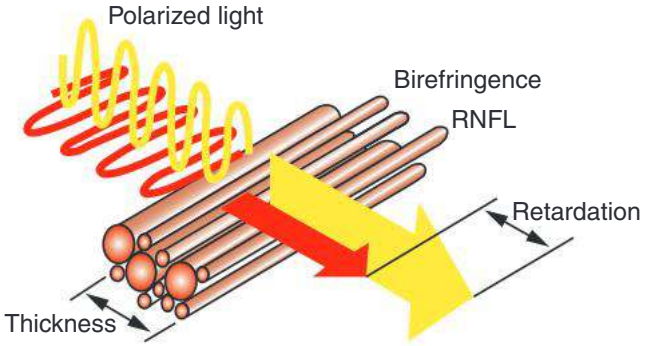


Fig. 12.90 *Optical principle of scanning laser polarimeter (SLP) (nerve fibre layer analyser).*

RNFL birefringence can be isolated from the total birefringence by compensating for the anterior segment birefringence.

Fixed Versus Variable Corneal Compensation

- *Fixed corneal compensation (FCC)* was employed in the earlier models of nerve fibre layer analysers (e.g. RNFLA), ensuring that all individuals had a slow axis of corneal birefringence (corneal polarization axis) 15 degrees nasally downward with a magnitude of 60 nm (corneal polarization magnitude). However, recently it has been shown that there exists a wide variation in the axis and magnitude of corneal polarization in healthy and glaucomatous eyes.
- ***Variable Corneal Compensation*** *(VCC)* is required to exactly measure the RNFL birefringence. The modified version of nerve fibre layer analyser (RNFLA) measures and individually compensates for anterior segment birefringence for each eye and thus allows the exact measurement of RNFL birefringence.

■ NERVE FIBRE LAYER ANALYSER

The Nerve Fibre Layer Analyser (NFLA) (Fig. 12.91) is an SLP, which basically consists of a CSLO with an integrated ellipsometer to measure retardation.

Procedure of Measurement

The measurement is performed with an undilated pupil of at least 2 mm diameter. A 780 nm infrared laser is used to scan the parapapillary area to give the RNFL measurements. Time taken is about 0.7 s. Total chair time is less than 3 min for both eyes. First, the eye is imaged without compensation. The uncompensated image presents total retardation from the eye. The macular region of this image is then analysed to determine the axis and magnitude of the anterior segment birefringence. The macular region birefringence is uniform and symmetric due to radial distribution of Henle's fibre layer.

Fig. 12.91 *Nerve Fibre Layer Analyser.*

Interpretation of the RNFLA Printout

The measurements are compared to a *normative database* (from healthy volunteers of different races) to determine any significant deviations from normal limits which are flagged as abnormal with a *p* value. Most of the parameters on RNFLA printout are calculated from the calculation circle. This is the area of 8 pixels between two concentric circles centred around the optic disc. The RNFLA printout is interpreted as below (Fig. 12.92):

1. ***Colour fundus image*** is seen at the top of the printout. It is depicted as 20 degree × 20 degree image of the disc and parapapillary area (Fig. 12.92A). It is produced by more than 16,000 data points from the scanned area.
2. ***Thickness (polarization) map*** shows the RNFL thickness in a colour-coded format in the 20 degree × 20 degree parapapillary area as below (Fig. 12.92B):
   - *Thick RNFL areas* are indicated by bright colours: yellow, orange and red.
   - *Thin RNFL areas* are indicated by dark colour (dark blue, blue and green).
   - *Typical normal pattern* is characterized by bright yellow and red colours (thicker areas) in the superior and inferior sectors,

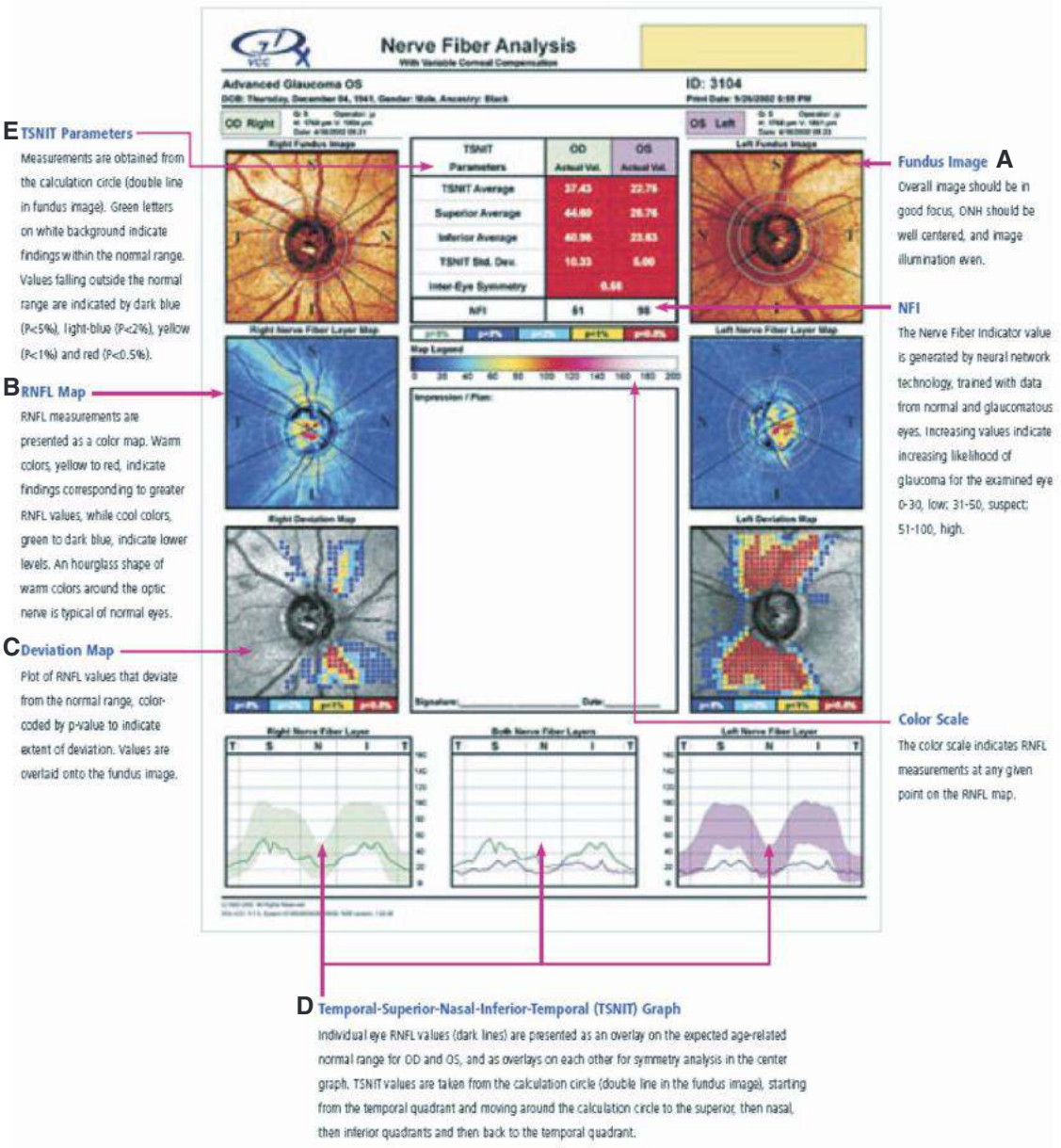


Fig. 12.92 *A representation printout of GDx VCC Retinal Nerve Fibre Layer Analyser.*

and dark blue and green (i.e. thinner areas) in the nasal and temporal sectors.

Abnormal patterns of thickness map include:

- *Diffuse loss of RNFL* leads to its decreased thickness, seen as yellow instead of red.
- *Focal defects* are seen as concentrated dark areas.
- *Asymmetry* between superior and inferior quadrants of RNFL.
- *Asymmetry* between the RNFL of two eyes.
- *Increased thickness* of RNFL in nasal and temporal quadrants of RNFL (seen as red and yellow instead of blue).

3. *Deviation map.* It shows the location and magnitude of RNFL defects over the entire thickness map. It tells how the patient's RNFL thickness compares to values derived from the normative database in a 128 × 128 pixel (20 degree × 20 degree) region centred on the optic disc. Small colour-coded squares indicate the amount of deviation from normal at

each given location and are presented over a black and white fundus image to provide a visual form of reference (Fig. 12.92C). Dark blue squares represent areas where the RNFL thickness is below the fifth percentile of the normative database; i.e. there is only 5% probability that the RNFL thickness in this area is within the normal range. Light blue squares represent deviation below the 2% level, yellow represents deviation below 1% and red represents deviation below 0.5%. Thus, a quick look at the deviation map gives an idea of the wedge defects of RNFL and the pattern of defects.

4. ***The TSNIT graphs*** (Fig. 12.92D). The TSNIT, i.e. 'temporal-superior, nasal-inferior-temporal' graph displays the range and the patient's values of RNFL thickness along the calculation ellipse in TSNIT order separately for right (OD) and left (OS) eyes.

- In a normal eye, the typical TSNIT graph shows a typical 'double-hump' pattern.
- A flat TSNIT graph indicates loss of RNFL.
- *TSNIT symmetry graph* is obtained by displaying the graphs of two eyes together. Normally, the curves from two eyes overlap. However, in glaucoma, one eye often has more advanced RNFL loss and, therefore, the two curves will have less overlap. A dip in the curve of one eye relative to another is indicative of RNFL loss.

TSNIT serial analysis graph and deviation from reference map for a given eye, for analysis of serial changes between visits can also be obtained from RNFLA. This is very useful to demonstrate progression over a period of time.

5. ***TSNIT parameters.*** These are displayed in a table on the centre of printout (Fig. 12.92E). The TSNIT parameters are summary measures based on RNFL thickness values within the calculation ellipse and include TSNIT average, superior average, inferior average, TSNIT standard deviation, inter-eye symmetry and the nerve fibre indicator (NFI).

- *TSNIT average* refers to average RNFL thickness around the entire calculation ellipse.
- *Superior average* is the average RNFL thickness in the superior 12 degree region of calculation ellipse.
- *Inferior average* is the average RNFL thickness in the inferior 120 degree region of calculation ellipse.
- *TSNIT standard deviation* indicates the modulation (peak to trough difference) of the double-hump pattern. A normal eye has high and a glaucoma eye has low modulation in the double-hump pattern.
- *Inter-eye symmetry* measures the degree of symmetry between the right and left eyes. Normal eyes have good symmetry with values around 0.9.
- *NFI.* It is the most important parameter, since it is an indicator of the likelihood that an eye has glaucoma. NFI is generated from the patient's scanned data obtained from within and outside the calculation circle.

The output of NFI is a single value that ranges from 1 to 100 and indicates the overall integrity of the RNFL. The higher the NFI, the more likely that the patient has glaucoma. The values of NFI are generally interpreted as follows:

- Normal: 1–30 (less likelihood of glaucoma)
- Glaucoma suspect: 30–50
- Abnormal: >50 (high likelihood of glaucoma)

Normal Versus Abnormal Values of TSNIT Parameters

Normal values of TSNIT parameters reported from Indian population are as follows:

- TSNIT average: 54.8 ± 4.1 (45.6–66.8) μm
- Superior average: 66.8 ± 6.70 (55.1–85) μm
- Inferior average: 62.1 ± 6.6 (38.9–74.3) μm
- NFI: 17.2 ± 6.9 (4–35) μm

Abnormal values. Although there is no consensus on definition of abnormal scan, the following guidelines have been recommended for TSNIT average, superior average, inferior average, TSNIT standard deviation, inter-eye symmetry and NFI:

- Abnormal at $p < 1\%$ level
- Borderline at $p < 5\%$ level

Additional Diagnostic Parameters

Additional diagnostic parameters available in the machine for an extended analysis include the following:

- *Symmetry*. It is the ratio of the average of the 1500 thickest pixels each in the superior and inferior quadrants. The values closer to 1 indicate more symmetry and thus more chances of normal scan.
- *Superior ratio.* It is the ratio of superior quadrant thickness (average of 1500 thickest pixels) and temporal quadrant thickness (average of 1500 median pixels).
- *Inferior ratio.* It is the ratio of inferior quadrant thickness (average of 1500 thickest pixels) and temporal quadrant thickness (average of 1500 median pixels).
- *Superior nasal.* It is the ratio of superior quadrant thickness (average of 1500 thickest pixels) and nasal quadrant thickness (average of 1500 median pixels).
- *Maximum modulation.* It is ratio of thickest quadrant versus thinnest quadrant. Normally the maximum modulation is more than 1, since superior and inferior quadrants are thicker than nasal and temporal quadrants. Value of 1 or less indicates RNFL loss.
- *Superior maximum.* It is the average of the 1500 thickest pixels in the superior quadrant.
- *Inferior maximum.* It is the average of the 1500 thickest pixels in the inferior quadrant.
- *Ellipse modulation.* It is the ratio of the thickest quadrant and the thinnest quadrant within the ellipse area.
- *Ellipse average.* It is the average thickness (in microns) of RNFL in the ellipse surrounding the ONH.

Advantages and Limitations of RNFLA

Advantages

- Easy to operate.
- Does not require pupillary dilation.
- Good reproducibility.
- Does not require a reference plane.
- Can detect glaucoma on the first examination.
- Early detection before standard visual field.
- Comparison with age-matched normative database.

Limitations

- Does not measure actual RNFL thickness (inferred value).
- Low sensitivity and specificity for detection of pre-perimetric glaucoma in clinical studies.
- Does not differentiate true biological change from variability.
- Limited use in moderate and advanced glaucoma.
- No database from Indian population.
- Affected by anterior and posterior segment lesions such as:
  Ocular surface disorders,
  Macular pathology,
  Cataract and refractive surgery,
  Refractive errors and
  Peripapillary atrophy (scleral birefringence interferes with RNFL measurement).

OPTICAL COHERENCE TOMOGRAPHY

OCT is a diagnostic tool that can perform cross-sectional images of biological tissues within less than 10 μm axial resolution using light waves. Since retina is easily accessible to external light, hence it is especially suited for retinal disorders. The information provided by OCT is akin to in vivo histopathology of the retina.

BASIC PRINCIPLE AND OCT MACHINE

BASIC PRINCIPLE OF OCT

It is a diagnostic imaging technology that utilizes interferometry and low-coherence light in near-infrared range. A broadband width near-infrared light beam (820 nm) is projected. The beam is split to the tissue of interest (say retina), called as probe beam, and to a reference mirror at a known variable position (reference beam) (Fig. 12.93). The light is reflected back from the boundaries between the microstructures and is also scattered differently from tissues with different optical properties. The echo time delay of the light reflected from various layers of retina is compared to echo time delay of light reflected from the reference mirror (Fig. 12.93). A positive interference is produced when light reflected from the retina

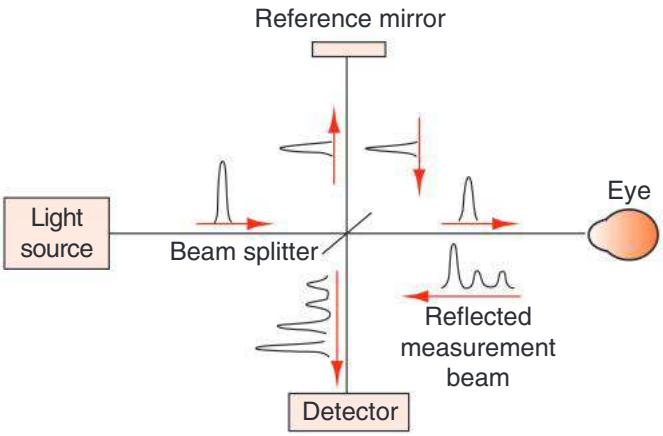


Fig. 12.93 *Basic principle of optical coherence tomography (OCT).*

and the reference mirror arrives simultaneously or within short coherence length of each other. This interference is measured by a photodetector which finally produces a range of time delays for comparison.

The interferometer integrates several data points over 2 mm of depth to construct a tomogram of retinal structures. It is a real-time tomogram using false colour scale. Different colours represent light backscattering from different depths of the retina. The low-coherence light source determines the axial resolution. The axial resolution, as mentioned earlier, is 10 μm for OCT 1 and OCT 2, and about 7–8 μm for OCT 3. The transverse resolution depends on the probe beam diameter and is 20 μm.

THE OCT MACHINE

The OCT system comprises (Fig. 12.94) the following:

- Fundus viewing unit,
- Interferometric unit,
- Computer display,
- Control panel and
- Colour inkjet printer.

Generations of commercially available OCT machine include:

- *OCT 1*, i.e. first-generation of OCT machine has a transverse and axial resolution of 20 and 10 μm, respectively.
- *OCT 2*, i.e. second-generation of OCT machine has a resolution similar to OCT 1 but with an improved user interface.
- Both OCT 1 and OCT 2 acquire 100 vertical scans in a standard OCT scan in an acquisition time of approximately 1.2 s.

Fig. 12.94 *The OCT machine.*

- *OCT 3*, i.e. third-generation OCT unit has improved axial resolution of 7–8 μm and acquires 512 vertical scans.

Commercially available OCT machines are now available as following:

- OCT for posterior segment imaging (e.g. Zeiss Stratus OCT) and spectral OCT (Optopol)
- OCT for posterior segment imaging combined with a non-mydriatic retinal camera (e.g. Topcon 3D OCT-1000)
- OCT for anterior segment imaging and biometry (e.g. Zeiss Visante OCT and SL-OCT, i.e. slit-lamp-OCT, Heidelberg Engineering)
- Dual channel OCT/SLO posterior segment mapping device with adjustable depth resolution (e.g. OTI, OCT/SLO)
- Swept source OCT (DRI OCT, Topcon, Japan)

OCT FOR POSTERIOR SEGMENT IMAGING

PROCEDURE

- *Activation* of the machine and entering of patient data is the first step.
- *Patient position*. The patient's pupils are dilated and the patient is asked to look into the internal fixation target light in the ocular lens.
- *Protocol for scan acquisition* is selected as per the case requirement. The scanning beam is placed on the area of interest and scans are obtained. The Zeiss Stratus OCT machine provides 19 scan acquisition protocols designed for examination of retina and ONH.
- *Production and display of image.* On z-axis, 1024 points are captured over a 2-mm depth to create a tissue density profile, with resolution of 10 μm. On x–y axis, tissue density profile is repeated up to 512 times every 5–60 μm to generate a cross-sectional image. Several data points over 2 mm of depth are integrated by the interferometer to construct a tomogram of retinal structures. Image thus produced has an axial resolution of 10 μm and a transverse resolution of 20 μm. The tomogram is displayed in either grey scale or false colour on a high-resolution computer screen.

NORMAL OCT SCAN OF RETINA

The OCT scan of retina allows cross-sectional study of the macular, peripapillary region including RNFL and ONH region.

COLOUR CODING IN THE OCT SCAN

- *Red–yellow* represent areas of maximal optical reflection and backscattering.
- *Blue–black* represent areas of minimal signals.

INTERPRETATION OF RETINAL SCAN

Vitreous anterior to the retina is non-reflective and is seen as a dark space.

Vitreoretinal interface is well defined due to the contrast between the non-reflective vitreous and the backscattering retina.

Retinal layers are represented as below (Fig. 12.95B):

- *Anterior boundary of retina* formed by highly reflective RNFL is seen as a red layer due to bright backscattering.
- *Posterior boundary of retina* is also seen as a red layer representing highly reflective retinal pigment epithelium (RPE) and choriocapillaris.
- *Outer segments of retinal photoreceptors*, being minimally reflective are represented by a dark layer just anterior to RPE–choriocapillaris complex.
- *Different intermediate layers of neurosensory retina* between the dark layer of photoreceptors and red layer of RNFL are seen an alternating layers of moderate and low reflectivity.

The Macular Scan

OCT Scan Protocols in Macula

- *Line scan*: It gives an option of acquiring multiple line scans without returning to main window. Default angle is 0 degree and length of scan is 5 mm. The length of the scan and angle can be altered to acquire multiple scans of different parameter.
- *Radial line*: It consists of 6–24 equally spaced line scans that pass through a central common axis; the length of these line scans can be changed by adjusting the size of aiming circle. The radial lines are useful for acquiring

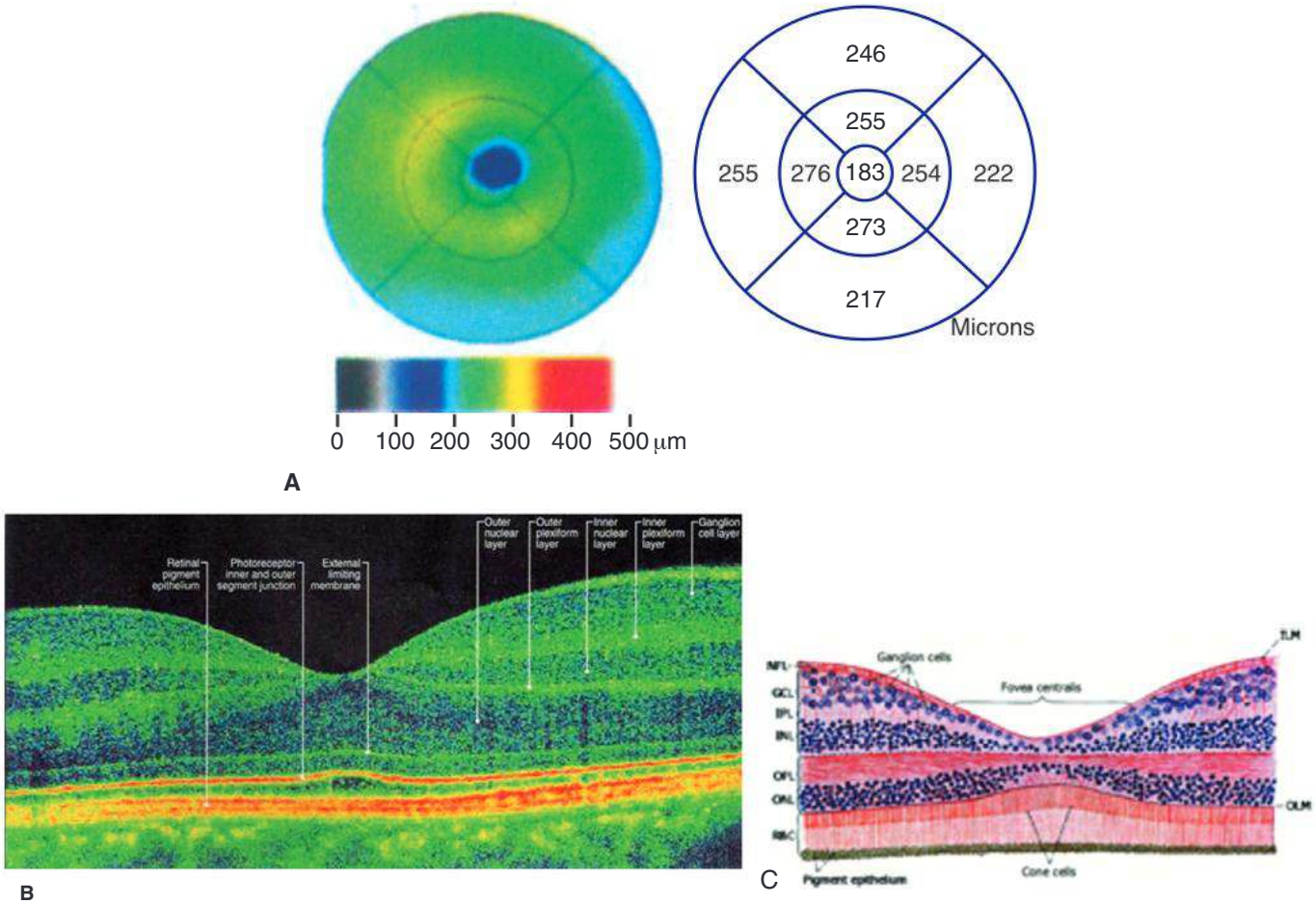


Fig. 12.95 *Lines for macular scan (A), the normal OCT scan in macular area (B) vis-à-vis histopathology (C).*

macular scan and retinal thickness/volume analysis.

- *Macular thickness map*: This is same as radial lines except that the aiming circle has a fixed diameter of 6 mm. This protocol helps in measuring macular thickness.
- *Fast macular thickness map*: It is a quick protocol that takes only 1.92 s to acquire six scans of 6 mm length each, when done in both the eyes. It can be used for comparative retinal thickness/volume analysis.
- *Raster lines*: It provides options of acquiring series of lines that are parallel, equally spaced and are 6–24 in number. These multiple line scans are placed over a rectangular region, the area of which can be adjusted so as to cover the entire area of pathology. This scan is especially useful in choroidal neovascular membrane where one wishes to obtain scan at multiple level.
- *Repeat*: This protocol enables one to repeat any of previously saved protocols, using some of set of parameters that include scan size, angle, placement of fixation LED (light-emitting diode) and landmark.
- Macular scan (Fig. 12.95) is composed from six linear scans in a spoke pattern configuration equally spaced 30 degrees apart (Fig. 12.95A). In the colour-coded macular thickness map, blue colour represents thinner retina and yellow-green represents thicker retina. The fovea is identified by its characteristic depression in the inner retinal border secondary to the lateral displacement of tissues anterior to Henle's layer (Fig. 12.95B).

Optic Disc Scan

Optic disc scan consists of equally placed line scans 4 mm in length, at 30 degree intervals and

centred on the optic disc (Fig. 12.96). Characteristic description of an optic disc scan is as below (Fig. 12.97):

- *Optic disc boundaries and diameter.* The point at which choriocapillaris terminates at lamina cribrosa determines the disc boundaries. Extrapolation of these points to retinal surface defines a line segment which measures optic disc diameter.
- *Optic cup* is determined by the points at which nerve fibre layer terminates.

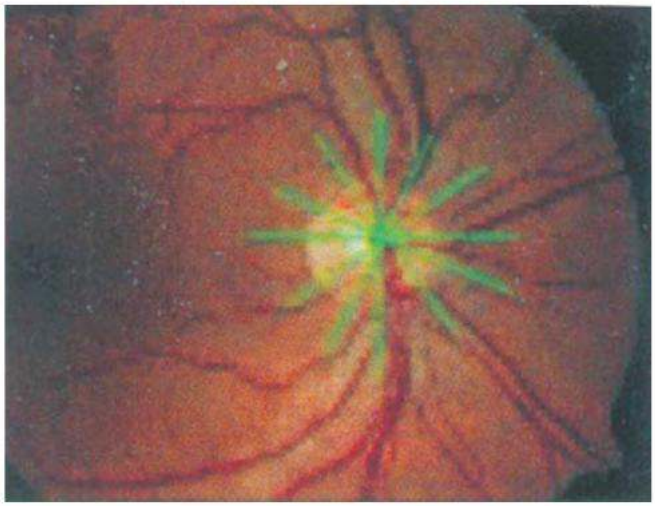


Fig. 12.96 *Equally placed lines, centred on the optic disc for optic disc scan.*

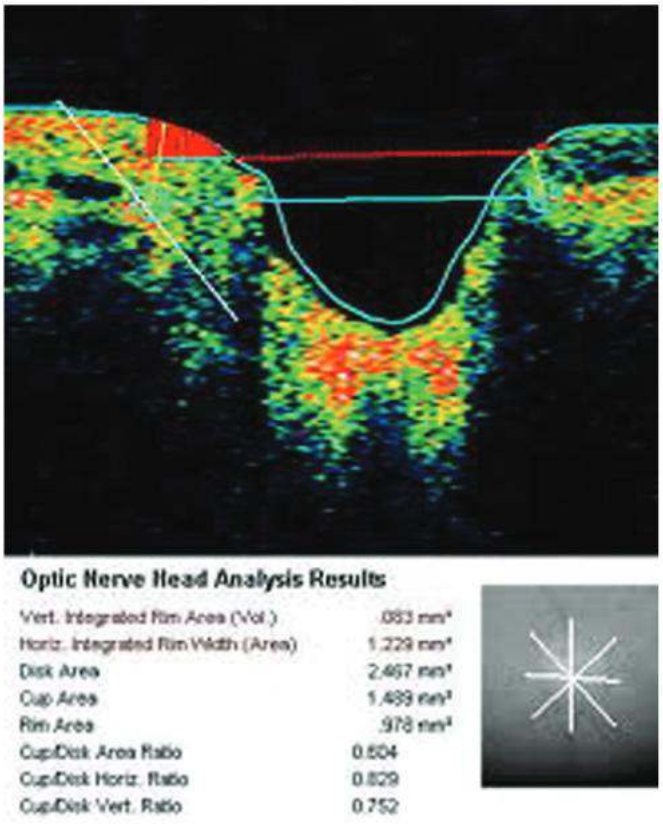


Fig. 12.97 *Optic disc OCT scan for optic nerve head analysis.*

Note. The high-resolution imaging of the optic disc with OCT allows an accurate assessment of the size of the optic cup, disc area, C:D ratio, volume of the cup and thickness of RNFL. Serial measurement records are very useful to monitor glaucoma changes.

RNFL Assessment With OCT

RNFL is highly reflective and its thickness increases from macula to the optic disc margin. OCT 3 offers a variety of RNFL thickness measurement and analysis protocols like RNFL thickness circle scan, fast circle scan, concentric three-ring protocol, RNFL map and proportional circles.

Circular scan of 1.34 mm radius centred on the ONH has been shown to exhibit maximum reproducibility for RNFL measurement. The mean RNFL thickness is calculated using age-adjusted RNFL thickness average analysis protocol (Fig. 12.98).

CLINICAL APPLICATIONS OF POSTERIOR OCT SCAN

I. MACULAR DISORDERS

The OCT is very useful in confirming macular pathologies which are not apparent clinically. OCT picture of some of the important macular lesions is as below:

1. ***Macular hole***. OCT allows confirmation of diagnosis of macular hole (Fig. 12.99) and differentiates it from the clinically simulating condition such as a lamellar hole, foveal pseudocyst (Fig. 12.100). It is also useful in monitoring the course of the disease and the response to surgical intervention (Fig. 12.99C).
2. ***Macular oedema***. In an OCT scan, the macular oedema is characterized by the intra-retinal areas of decreased reflectivity and retinal thickening (Fig. 12.101). Round, optically clear regions within the neurosensory retina are

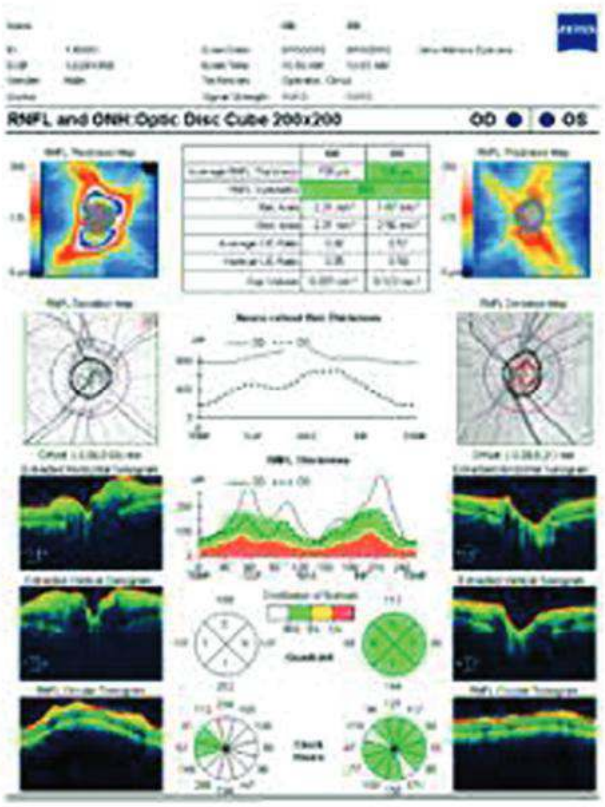


Fig. 12.98 *OCT scan to measure RNFL thickness.*

noted in cystoid macular oedema. Measurement of retinal thickness is performed between two well-defined highly reflective red layers of the nerve fibre layer and the RPE/choriocapillaris layer. Quantitative measurement of retinal thickness can be used to monitor the course of macular oedema secondary to diabetes, vascular occlusions, uveitis and post-cataract surgery.

3. ***ARMD***. OCT, because of its high-resolution capability is able to image

- Morphological changes in the non-exudative ARMD.
- Sub-retinal fluid, intra-retinal thickening and, sometimes, choroidal neovascularization in exudative ARMD (Fig. 12.102). This is especially useful when visualization of choroidal neovascularization is obscured on fluorescein angiography by a thin layer of fluid or haemorrhage.

4. ***Central serous chorioretinopathy***. In an OCT scan, the central serous chorioretinopathy (detachment of neurosensory retina) is characterized

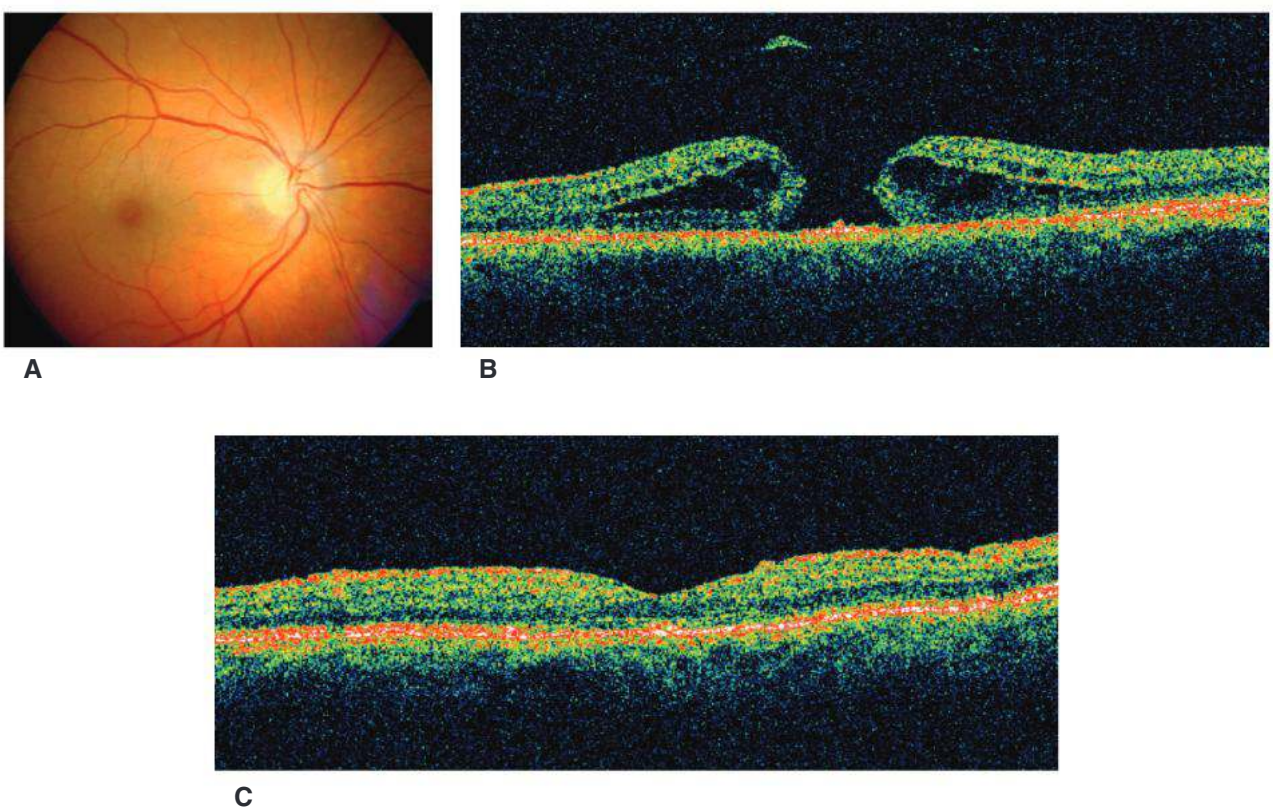


Fig. 12.99 *Clinical fundus photograph (A) and OCT scan of full thickness macular hole before (B) and after surgery (C).*

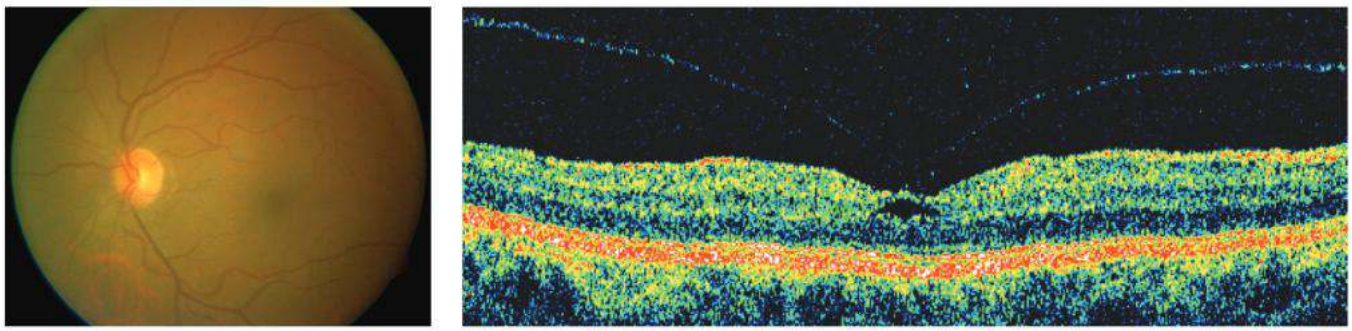


Fig. 12.100 *Clinical fundus photograph (A) and OCT scan (B) depicting foveal pseudocyst.*

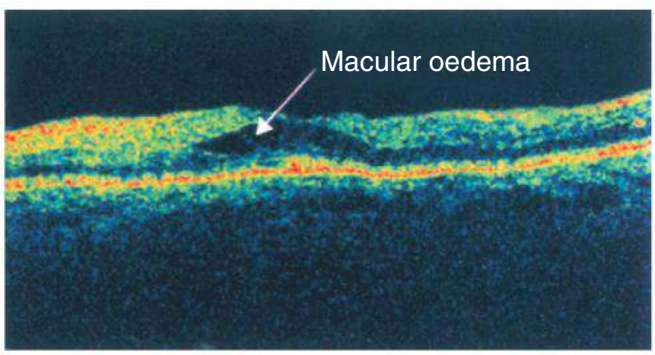


Fig. 12.101 *OCT scan depicting macular oedema.*

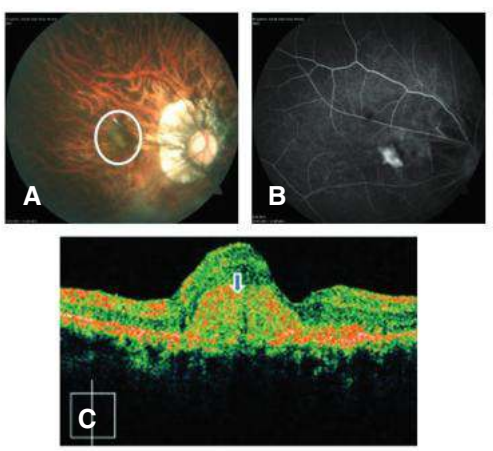


Fig. 12.102 *Clinical photograph (A), fluorescein angiography (B) and OCT scan in a patient with ARMD showing choroidal neovascularization with sub-retinal fluid (C).*

by an area of decreased reflectivity (black area) between the two highly reflective layers – the neurosensory retina and RPE/choriocapillaris (Fig. 12.103). An associated pigment epithelium detachment may be present (Fig. 12.103).

5. ***Epiretinal membrane*** is diagnosed on OCT by the presence of a highly reflective diaphanous membrane over the surface of retina (Fig. 12.104). The OCT provides information about membrane thickness, cystic changes and its adherence to retinal surface.

6. ***Solar retinopathy*** on OCT scan is characterized by formation of an outer retinal hole (Fig. 12.105).

II. OCT IN GLAUCOMA

- *Glaucoma diagnosis*. As mentioned earlier, the optic disc scan is very useful in diagnosing and monitoring the glaucomatous change (page 526, Fig. 12.97). It is also useful in evaluating the RNFL for early (pre-perimetric) glaucoma detection (Fig. 12.98).

Other uses of OCT in glaucoma include:

- Detection, study and follow-up of the macular changes in hypotony-induced maculopathy after glaucoma and
- Evaluation of cystoid macular oedema after combined cataract and glaucoma surgery.

III. ENHANCED DEPTH OCT: IMAGING FOR CHOROID

Enhanced depth OCT (ED-OCT) is a new investigative modality with deeper penetration, which helps in the study of deep retinal tissue and choroid. Choroidal thickness plays a vital role in the determination of the pathogenesis of various disorder.

Technique: Choroidal imaging can be obtained with a slight modification in conventional OCT systems with an improved high-quality eye tracking ability, a longer wavelength of light giving a low signal-to-noise ratio and better

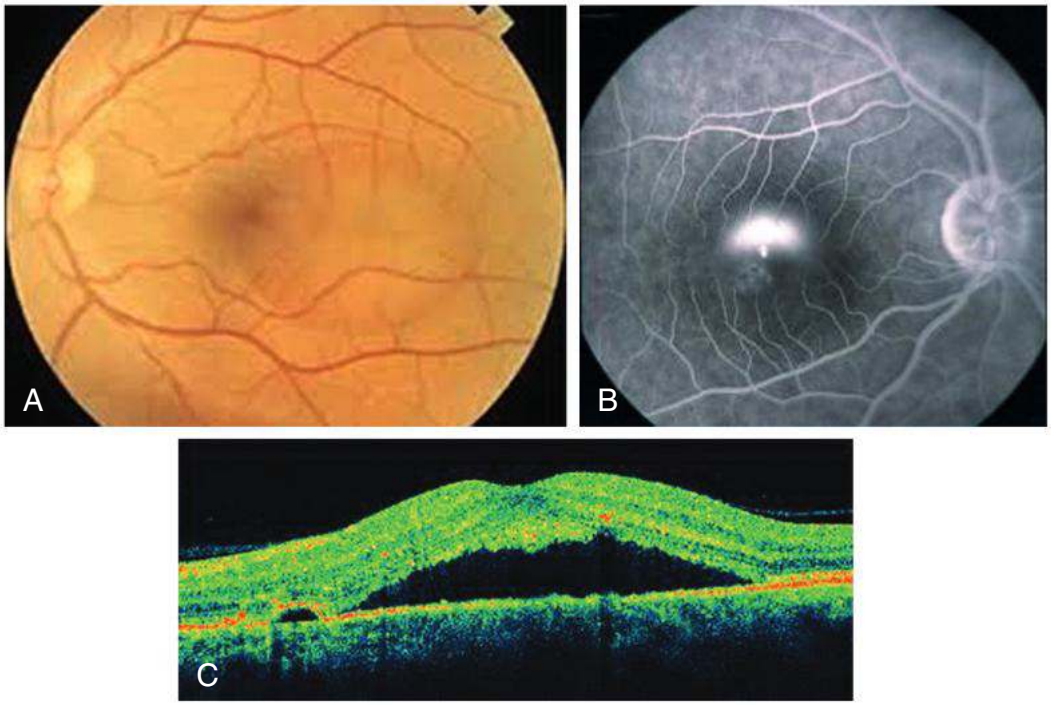


Fig. 12.103 *Clinical photograph (A), fluorescein angiography (B) and OCT scan depicting central serous chorioretinopathy (CSR) and pigment epithelium detachment (PED) (C).*

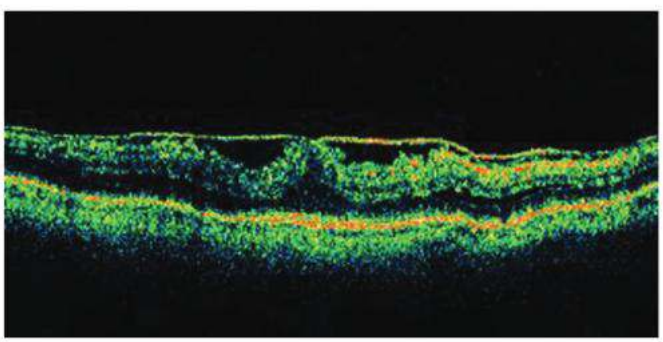
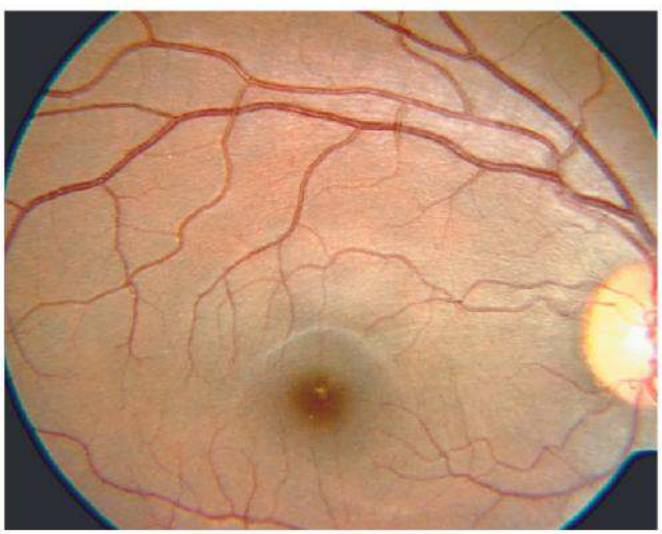


Fig. 12.104 *Epiretinal membrane.*

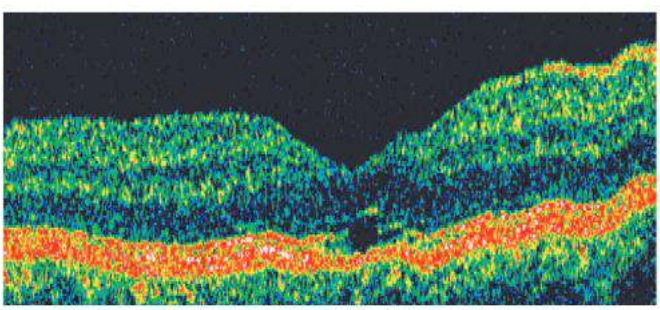
image averaging capability. Currently, the Heidelberg Spectralis OCT (Heidelberg Engineering, Heidelberg, Germany) and the Cirrus HD-OCT (Carl Zeiss Meditec Inc., Dublin, CA) have been described to be capable of performing ED-OCT. ED-OCT has a wide variety of implications in the diagnosis of a large number of retinal and uveal pathologies.

Uses of ED-OCT

- *Diseases with choroidal hyper-permeability* like CSCR (Fig. 12.106A), PCV and VKH syndrome show increased choroidal thickness.
- *Diseases with chorioretinal atrophy* like myopia, macular hole, ARMD (Fig. 12.106B), age-related



A



B

Fig. 12.105 *Clinical fundus photograph (A) and OCT scan depicting outer retinal hole (B) in a patient with solar retinopathy.*

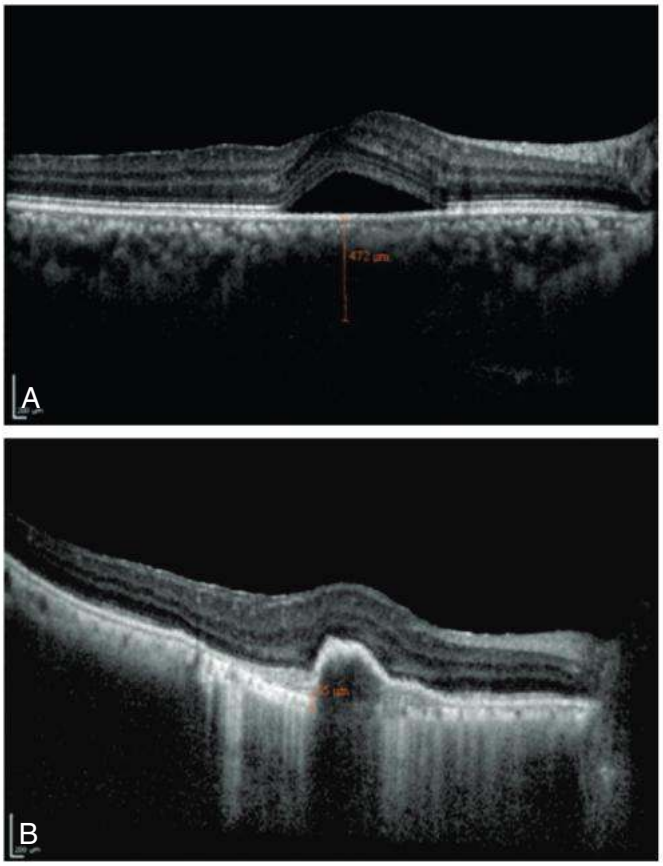


Fig. 12.106 *A, An ED-OCT images of a patient with CSCR demonstrating the thickened choroid. B, An ED-OCT image of a case of ARMD showing a thinned out choroid.*

choroidal atrophy and inherited retinal dystrophies show reduced choroidal thickness.

- *Choroidal thickness measurement* aids in differentiation of ARMD from PCV and CSCR.
- *Choroidal thickness has an important role* in judging response to different treatment modalities like PDT, lasers and anti-VEGF agents.
- *Tumours* which are posteriorly located and small and undetectable by ultrasonography can be easily visualized with the help of this technique.

IV. OCT WITH SURGICAL MICROSCOPE

OCT imaging with surgical microscopes is helpful in intra-operative anatomical assessment, especially in macular surgeries, for instance for the macular hole and epiretinal membrane. Surgeons can, therefore, assess the anatomical details intra-operatively and predict the surgical success rates.

SWEPT-SOURCE OCT

The swept-source OCT (SS-OCT; DRI-OCT, Topcon Japan), the third-generation OCT, is the latest milestone in retinal and choroidal imaging. To overcome scattering by the RPE, which disabled visualization of deeper lying structures, a longer wavelength was adopted for this machine (1050 nm vs 840 nm in SD-OCT), and photodetectors instead of CCD cameras led to a further increase in resolution (1 μm). The scan speed in swept-source instruments is twice that of SD-OCT devices (100,000 A-scans/s compared to 50,000 A-scans/s), enabling faster acquisition of B-scans, thus allowing us to obtain wide-field B-scans (12 vs 6–9 mm with conventional SD-OCT) and more accurate 3D imaging of the vitreous, retina and choroid wide scans make it possible to present the optic nerve and macula on the same scan. Simultaneous high-quality visualization of the vitreous, retina and choroid is possible. Choroidal layers that are hardly distinguishable in conventional SD-OCT become visible. Using a longer wavelength also overcomes cataractous lens opacities and allows visualization of the macula in eyes with disabled fundus view.

The multi-modal approach using SS-OCT is expected to advance the understanding of retinal pathologies such as ARMD, diabetic maculopathy, central serous chorioretinopathy, the pachychoroid spectrum and macular telangiectasia. The 12 × 9 mm scan comprises 256 B-scans, each comprising 512 A-scans with a total acquisition time of 1.3 s. SS-OCT has also the enhanced vitreous imaging where the image can be seen in different logarithmic scales, or windows, for better visualization of the vitreous structures. Structures such as bursa pre-macularis, or the posterior pre-cortical vitreous pockets (PPVP), the Maregiani area (Clocquet's canal), posterior cortical vitreous, posterior hyaloid and vitreous opacities of different aetiologies are more properly viewed with SS-OCT.

SS-OCT uses a wavelength-tunable laser and a dual-balanced photo detector instead of

a broadband super-luminescent diode, spectrometer and high-speed line-scan camera that are used in SD-OCT. SS-OCT offers higher imaging speeds, higher detection efficiencies, improved imaging range and improved depth with reduced sensitivity roll-off. Those features are a fundamental advantage in comparison with SD-OCT and contributed to the improved image quality, including of the choroid, using SS-OCT.

EN FACE OCT

En face OCT is one of the OCT visualization approaches that has significantly benefitted from technical advancements in OCT technology. It takes a different approach in which a software is used to reconstruct C-scan images on the coronal plane. This helps in the precise localization of the lesion within specific subretinal layers using their axial location on OCT cross-sections as well as the ability to register projected OCT images to other fundus imaging modalities using retinal vessels as landmarks. In 1997, Podoleanu et al. first suggested using OCT to generate en face images. Of the retina, en face OCT is currently being applied to various specialized areas including the anterior segment, glaucoma, infectious diseases and retina.

OCT ANGIOGRAPHY

It is a non-invasive imaging technique used to visualize the vasculature of retina, choriocapillaris and the choroid without the intravenous injection of coloured and contrast substance.

Principle. It is mainly based on two principles:

- Phase-based system called phase-variance OCT.
- Amplitude-based system which includes split spectrum–decorrelation angiography (SSADA). Its advantage lies in the algorithm that creates a digital volume of isotropic coherence before calculating the correlation. The devices based on this is the AngioVue software of the RT Vue XR Anamti (Optovue, Inc., Fremont, CA).

Commercially available OCT angiography systems include Zeiss Angioplex, Topcon DRI OCT and Heidelberg Spectralis OCT2.

Characteristic features

- It is a novel technology for in vivo imaging of vascular network.
- It uses moving erythrocyte as contrasting mechanism and avoids the use of IV dyes. A depth resolved 3D image set can be generated within 6 s. The enface image obtained can then be scrolled to visualize individual vascular plexuses and segment the inner retina, outer retina, choriocapillaries and the area of interest.
- It helps quantify vascular compromise depending upon the severity of diabetic retinopathy.

CONVENTIONAL OCT VERSUS OCT–SLO

Conventional OCT provides very good cross-sectional images of the posterior segment and has become a vital investigative modality in the management of macular diseases. However, the exact site of pathology cannot be localized in terms of anteroposterior relationship. OCT-SLO is a new imaging modality, made commercially available by OTI technologies (Canada), that combines the abilities of SLO and OCT and provides coronal images along various depths. Hence, images with this combo machine seem to have better resolution and localization and an ability to demonstrate subtle lesions.

OCT–SLO has a longitudinal resolution of approximately 8 μm and transverse resolution of 20 μm with a maximum scanning field size of 25 degrees. The scanning depth can be varied from 0.5 to 6.0 mm for both transverse and longitudinal scanning. It can also be used to detect ONH and RNFL characteristics.

OCT–SLO produces confocal SLO and OCT images simultaneously and displays them in cross-sectional (B-scan) and coronal (C-scan) sections. With pixel-to-pixel correlation of the two images, a true 3D characteristic of the pathology can be obtained. This allows more precise localization of the lesion.

LIMITATIONS OF OCT

- Being purely dependent on optical principles, it requires a minimal pupillary diameter of 4 mm to obtain a high-quality image.
- OCT has limited applications in patients with poor media clarity due to corneal oedema, dense cataracts, vitreous haemorrhage and asteroid hyalosis.
- High astigmatism, decentred IOL can compromise quality of OCT scan.
- Limited transverse sampling.
- Commercially available instruments are bulky, not portable and tabletop mounted. So, it becomes challenging with paediatric patients, mentally disabled patients and elderly bed-ridden patients.

OCT MACHINE FOR ANTERIOR SEGMENT IMAGING AND BIOMETRY

Anterior Segment Imaging OCT machine is useful for following applications:

1. ***Anterior segment imaging.*** The anterior segment can be evaluated and measured pre- and post-operatively after image acquisition, using the analysis mode of the system's software. Practical tools enable planning and measurement of anterior segment ocular structures, including anterior chamber depth, anterior chamber angles and anterior chamber diameter (commonly referred to as angle-to-angle distance). Anterior chamber angle measurement results provide quick and reliable data for narrow-angle evaluation. Anterior segment images can be printed with or without measurement tools and results (Fig. 12.107A).

2. ***Corneal imaging and pachymetry.*** The OCT provides high-resolution corneal images and documentation for the anterior segment specialist to support the evaluation of ocular health. Rapid acquisition during the pachymetry scan ensures an accurate and repeatable pachymetry map result for application in refractive and glaucoma care (Fig. 12.107B).

3. ***New LASIK information***. In addition to providing a full-thickness pachymetry map prior to laser surgery, OCT is the first non-contact device to image, measure and document both corneal flap thickness and residual stromal thickness immediately following LASIK surgery (Fig. 12.108A). A unique flap tool in the analysis mode enables quick measurements of flap and residual stromal thickness at any location, documented on a colour-coded plot that includes tabular results (Fig. 12.108B). And because OCT is a completely non-contact system, the stability and safety of LASIK flaps will not be compromised.

4. ***IOL and implant imaging***. OCT may also aid post-operative evaluation by allowing imaging and visualization of IOLs and implants in the eye. A simple adjustment to the integrated optometer enables visualization of anterior segment changes due to accommodation. The result can then be saved and printed for addition to the patient record.

OPTICAL DEVICES FOR EYE SURGERY

OPERATING MICROSCOPE

Operating microscope is perhaps the single most important equipment without which the present day modern eye surgery is impossible. The minimum demands for a magnifying system are formation of an enlarged, upright and unreversed image at the approximate working distance. These conditions are fulfilled by prism binocular loupes. But with the increasing sophistication of microsurgical techniques and instrumentation, many more additional features are desirable in an ideal magnifying system, which have been possibly made available in the modern operating microscopes (Fig. 12.109).

COMPONENTS OF OPERATING MICROSCOPE

An operating microscope is composed of three basic systems:

I. Observation system (microscope)
II. Illumination system
III. Mechanical support system (body of operating microscope)

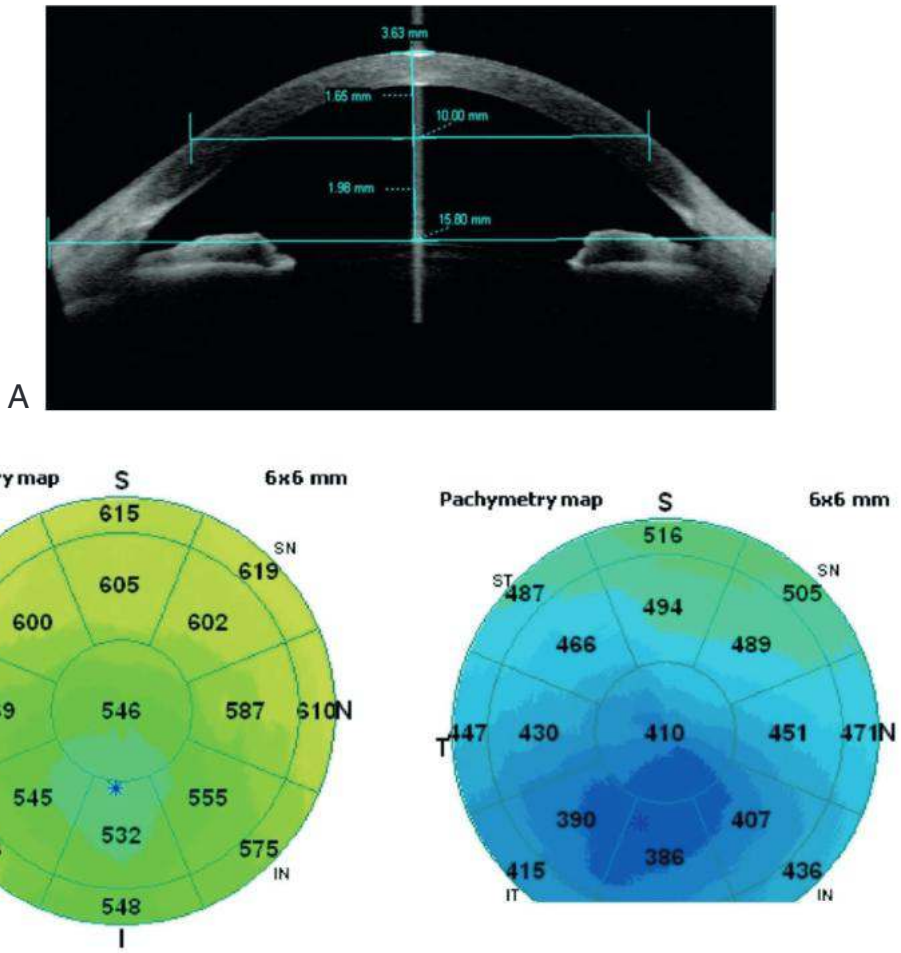


Fig. 12.107 *OCT: A, Anterior segment imaging scan and B, corneal pachymetry – different map report.*

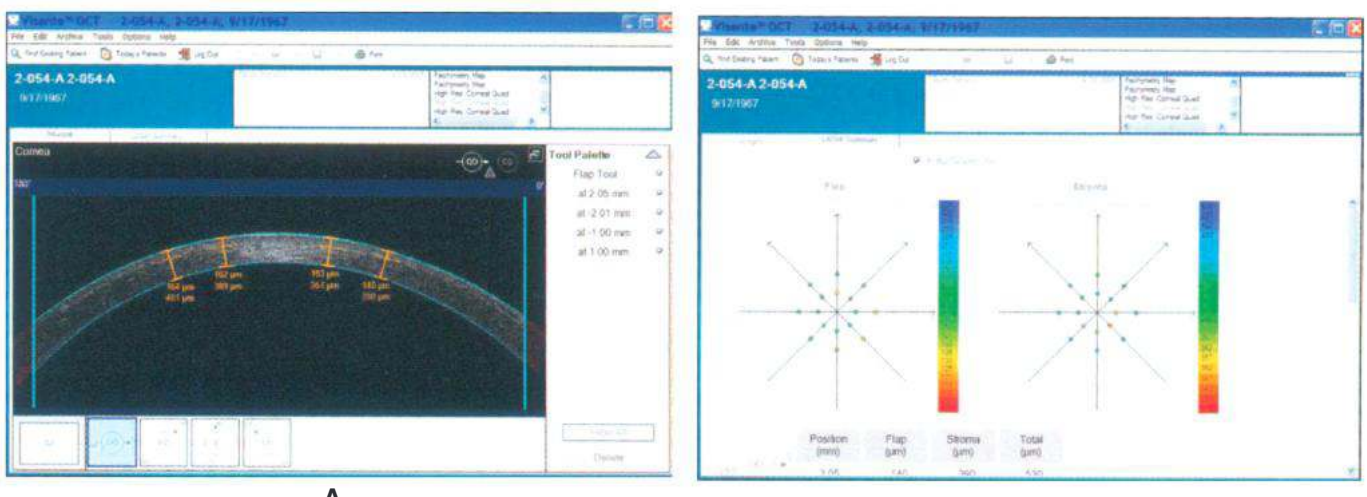


Fig. 12.108 *OCT scan: one-week-post-LASIK image analysis (A) and measurement of flap and residual stromal thickness (B).*

Fig. 12.109 *An operating microscope.*

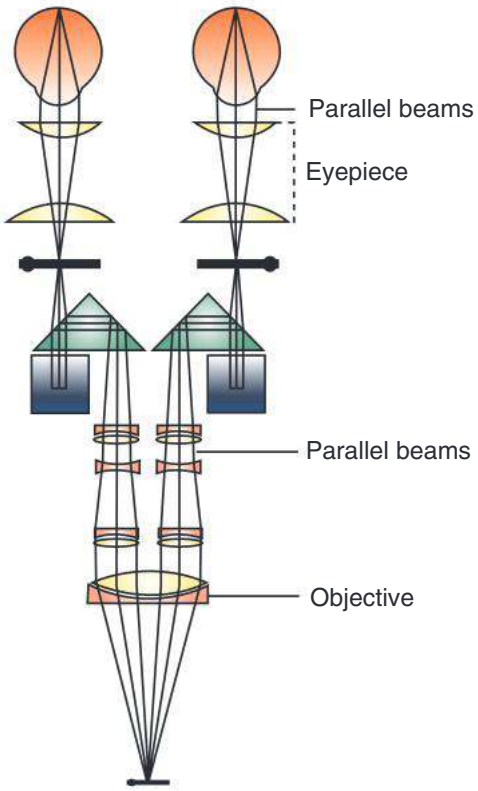


Fig. 12.110 *Schematic diagram depicting components of the observation system of an operating microscope.*

I. OBSERVATION SYSTEM

Components of Observation System

The observation system of an operating microscope consists of the following components (Fig. 12.110):

1. ***Objective lenses.*** The working distance of the microscope (the distance from the objective lens to the patient's eye) is equal to the focal length of the objective lens. Commonly used objective focal lengths in ophthalmic surgery are 150, 175 and 200 mm. An appropriate working distance is very important for microsurgery. A proper working distance can greatly lessen strain especially during lengthy operation. The objective focal length also determines the magnification of a microscope.
2. ***Binocular tubes.*** Straight as well as inclined binocular tubes are available for an operating microscope. For comfortable viewing, inclined tubes are preferred over the straight ones. Binocular tubes that can be tilted to any angle between straight and inclined are also available.

The tube lenses along with the objective lens form the image of the object at the focal plane of the eyepieces. The tube lenses come in two focal lengths of 125 and 160 mm. The focal length of the tube lens determines the overall length of the tube and also affects the magnification system. Size of the image produced by binocular tube lenses is smaller than the original object present at the focal plane of the objective lens. Thus, the main function of binocular tube lenses and the objective lens is to maintain a suitable distance between the eyes of the surgeon and the operating field. This arrangement provides a comfortable posture to the operating surgeon along with an appropriate working distance.

The binocular tubes house the (a) inverting prism system and (b) magnification changer.

a. ***Inverting prism system,*** such as a Porro–Abbe prism to correct for the inverted image produced by the eyepieces.

b. ***Magnification changer.*** The magnification changer systems are incorporated into the observation system of the operating microscope to get the required variable magnification of the image. Two types of magnification changer system available are the Galilean step magnification changer and zoom magnification changer.

i. *Galilean step magnification changer.* It utilizes the Galilean telescope to alter the magnification. The Galilean telescope consists of two optical components, a positive and a negative lens. The step magnification changer incorporates two telescopes; one has a magnification of 2.5× and other of 1.6×. When their optical components are reversed, they cause minification of image by 0.4× and 0.63×, respectively. There is one free path that gives the magnification of 1. So, the magnification changer can magnify 0.4, 0.63, 1.0, 1.6 and 2.5 times. These magnification steps are provided via a turret arrangement which is completely enclosed within the binocular tubes. Older models of the magnification changer indicated total magnification of the microscope, i.e. 6×, 10×, 16×, 25×, 40× on the drum. This, however, is incorrect because total magnification depends on other variables as well, i.e. objective lens focal length, tube lens focal length and eyepiece magnification. So, newer systems bear only the magnification factor of the Galilean telescope.

ii. *Zoom magnification changer.* The zoom magnification changer provides a continuous change in magnification ranging from 0.5× to 2.5×. The zoom system is most advanced and very comfortable and can be operated by a foot control pedal. However, manufacturing of zoom magnifier is more difficult as compared to Galilean step magnification changer and thus the zoom system is expensive.

3. ***Eyepieces.*** The eyepieces of the binocular operating microscopes are constituted by an astronomical telescope system and act as main magnifiers. However, the total magnification of the operating microscope is equal to the product of the magnification of various components of the observation system. Consequently, different focal length objectives, tube lenses and eyepieces are available. The eyepieces are available in different magnifications, which are 10×, 12.5×, 16× and 20×. Choice of the eyepiece depends on the desired magnification and required diameter of the field of view. Eyepieces with 12.5× magnification are considered the best compromise between magnification and field of view. The total resultant magnification varies from 4× to 40×.

Magnification

As described earlier, the magnification of the simple microscope depends upon the objective lens, tube lens and eyepiece lens.

Total magnification = Ft/Fo × Ve, where

Fo is objective lens focal length.

Ft is tube lens focal length.

Ve is magnification due to eyepieces.

Since the magnification changer is nowadays incorporated in the body of the microscope, the magnification can be changed. Therefore, the total magnification will be

$$\frac{\text{Ft}}{\text{Fo}} \times \text{Ve} \times \text{magnification factor}$$

For example, if Ft is 125 mm, Fo is 200 mm, Ve is 12.5× and magnification factor is 1.6, then the total magnification of the operating microscope will be:

$$\frac{125}{200} \times 1.6 \times 12.5 = 12.5 \times$$

Field of View

Field of view is determined by the total magnification used; more is the magnification used, less is the field of vision.

$$\text{Field of view} = \frac{\text{Fo}}{\text{Ve}}, \text{ where}$$

Fo is focal length of the objective tried.

Ve is total magnification of the microscope used.

Therefore, if the Fo is 200 mm and Ve used is 12.5×, then

$$\text{Field of view} = \frac{200}{12.5} = 16 \text{ mm}$$

Parfocality in the Observation System

Nowadays, the operating microscopes are designed to be parfocal (remain in focus) with the change of magnification, but the microscope must be focused properly to begin with, if this feature is to be useful. Up-and-down focusing of the microscope itself should first be performed under highest magnification. This accurately places the object viewed in the focal plane of the objective lens. Then without changing the up-and-down focus of the microscope, the microscope should be changed to the lowest power and each eyepiece should be focused in turn by screwing outwards to fog, and turning inwards until best focus is just attained. Side arm eyepiece should also be focused in the same manner at this time. Parfocality is ensured by this technique.

II. ILLUMINATION SYSTEM

Source of light. Halogen lamps are being preferred as a source of light. Incandescent lamps used earlier are no longer in use now because of their drawback. Incandescent lamps emit a maximum of only about 4% of the fed in electrical energy as visible light. Most of the energy emission is infrared light which is the heat radiation and invisible to human eye. Moreover, these incandescent lamps do not comply with the high demands of documentation equipment (e.g. video recordings).

Halogen lamps were used to offset this drawback. Halogen lamps (12 V, 100 W) are erroneously called as 'cool light' illuminators. They also produce a lot of heat. They are also more sensitive to voltage fluctuations and more expensive. In spite of these drawbacks, they are preferred, not because they emit light of high intensity but because of their high colour temperature. The light emitted by a halogen lamp has high percentage of blue light which increases the contrast of the objects. The light of halogen lamp seems to be 'whiter'.

Fibreoptic versus integral light source. Integral lamp light source is now being replaced with fibreoptic delivery systems, reducing heat near the microscope and allowing easier change of the bulbs during surgery.

Coaxial versus oblique illumination. Various illumination systems are available, but most important for ophthalmic surgery is 'coaxial illumination', especially for visualization of the posterior capsule and for vitreous surgery. In fact, illumination is not exactly coaxial with any microscope. However, as shown in Figure 12.111, it is possible to have almost coaxial system.

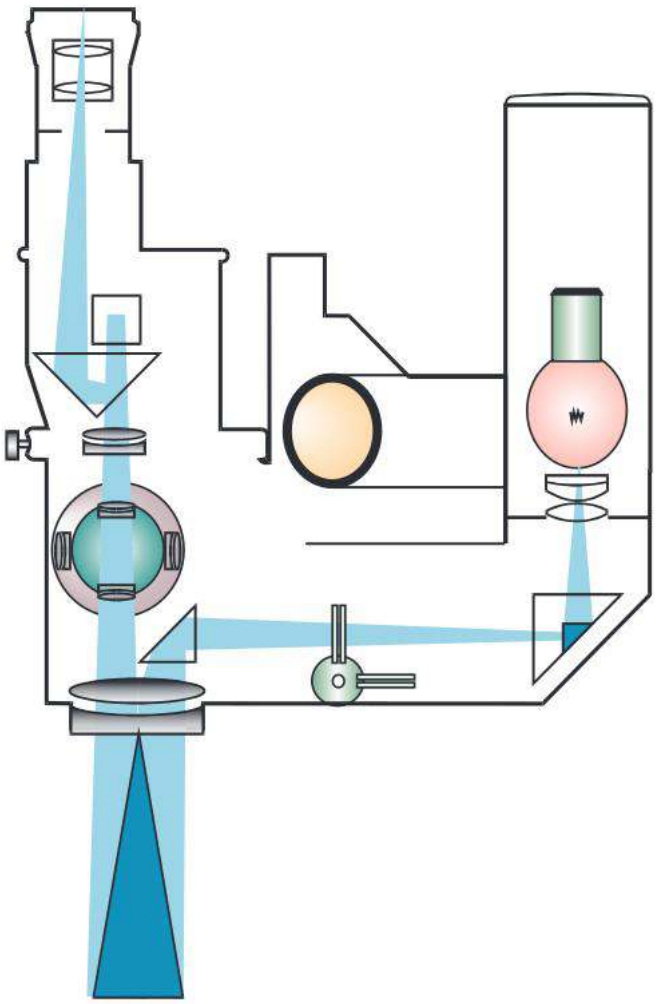


Fig. 12.111 *Schematic diagram showing nearly coaxial illumination system of an operating microscope.*

Parfocality. This term refers to the state of optical configuratues that enable magnification changes to take place without affecting the point of microscope focus.

III. MECHANICAL SUPPORT SYSTEM

The sophistication in the mechanical support system has made the working of operating microscope very convenient. The floor model, table-mounted model and ceiling models of the support system all are in vogue. The fast, controlled x–y coupling, up-and-down focusing and zoom magnifier changers have made the working of ophthalmic surgeons a bit comfortable.

COMMERCIALLY AVAILABLE NEWER OPERATING MICROSCOPES

1. **Luxor LX 3 (Alcon) with Q VUE ophthalmic microscope**. It offers an expanded visual fields a large and stable red reflex and excellent visual details. ILLUMIN-I technology provides a large, stable red reflex zone 'regardless of pupil size, centration, eye tilt or patient movement'.

   True vision allows the surgeon to operate heads up a large manner by 3D viewing on a large screen.

2. **OPMI Lumera 700 (Zeiss)**. It features stereo coaxial illumination for a highly stable and high-contrast red reflex, increased work flow efficiency with markerless toric IOL alignment. Cockpit integrates data from all connected devices, including VISALIS 500 from ZEISS.

3. **Hi-R NEO 900 (Haag Streit)**. This microscope has HD video capabilities for both 2D and 3D integrated OCT (iOCT) and the integrated ophthalmoscope EIBOS 2 system for retinal surgery. It can incorporate the Sony 3D System or the True Vision system.

OPTICAL INSTRUMENTS FOR REFRACTION

- Retinoscopes (see page 133)
- Autorefractors (see page 146)
- Lensmeter

LENSMETER

Lensmeter, an instrument to measure the power of spectacle lenses, is known by various names such as lensometer, focimeter or vertometer. Broadly, two basic types of lensmeters are available, the standard lensmeters and the automatic lensmeters.

TERMINOLOGIES

Before discussing the principle and functioning of the lensmeters, it will be worthwhile to be familiar with certain terminologies associated with the lens power, as depicted in Figure 12.112.

Dioptre is the universally accepted unit of lens power. It is defined as the reciprocal of the focal distance in metres.

Anterior surface power (F_1) refers to the power of a lens incorporated due to curvature of the anterior surface of the lens. For example, let it be +11 D of a particular lens (Fig. 12.112).

Posterior surface power (F_2) refers to the power of a lens incorporated due to curvature of its

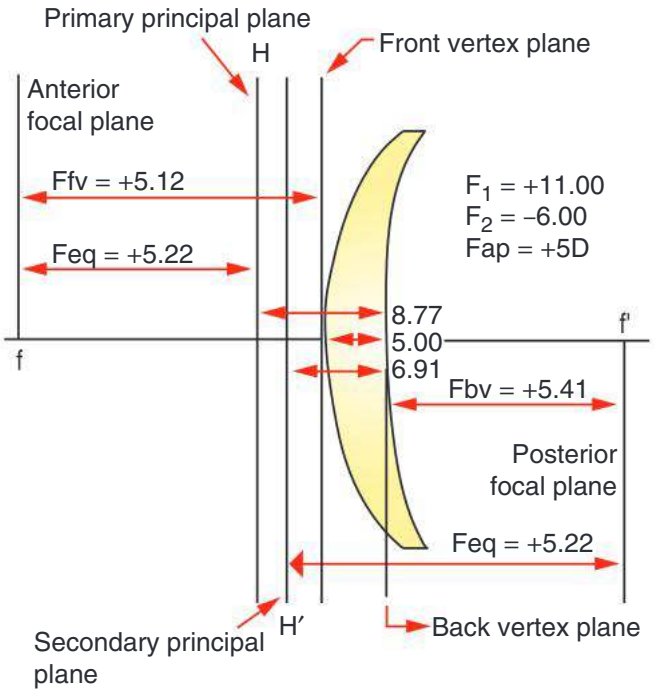


Fig. 12.112 *Terminologies used in relation to lens power.*

posterior surface. For example, let it be –6 D of a particular lens (Fig. 12.112).

Approximate power (Fap) is the sum of anterior surface power and posterior surface power of the lens ($F_1 + F_2$). The Fap of the lens shown in Figure 12.112 will be +5 D (+11 – 6).

Equivalent power (Feq) is defined as the reciprocal of the distance between either the front or back focal point and its corresponding principal plane. It is denoted by the equation

$$Feq = \frac{F_1 + F_2 - tF_1F_2}{n}, \text{ where}$$

F_1 is front surface power (e.g. +11 D).
F_2 is back surface power (e.g. –6 D).
t is centre thickness (e.g. 5 mm).
n is index of refraction (e.g. 1.5232).
In the above example, Feq will be 5.22.

Back vertex power (Fbv) is the reciprocal of the distance to the back focal point as measured from the back vertex of the lens for parallel light incident on the front of the lens. It is the quantity measured by all modern lensmeters. Back vertex power is also referred to as the effective power and is denoted by the equation:

$$Fbv = \frac{F_1}{1 - t/nF_1} + F_2$$
$$= + 5.41 \text{ (in the above example)}$$

Front vertex power **(Ffv)** is the reciprocal of the distance to the front focal point measured from the front vertex of the lens for parallel light incident from the back (eye side) of the lens. Front vertex power is sometimes referred to as *neutralizing power*, because when the power of a spectacle lens is balanced against a trial lens placed in front of it, the resulting power estimated or neutralizing power is actually the front vertex power. The front vertex power is denoted by the equation:

$$Ffv = \frac{F_2}{1 - t/nF_2} + F_1$$
$$= + 5.12 \text{ (in the above example)}$$

STANDARD LENSMETERS

Optics and Basic Structure

Standard lensmeters (Fig. 12.113) are also called the conventional or the manual lensmeters and operate on the principle of optometer. The optical principle of the optometer developed by Badal is preferred over the other non-Badal principle. The schematic diagram of a lensmeter based on the Badal optometer principle is shown in Figure 12.114. Various optical components and their working can be summarized as follows:

1. ***Focusing system***. Its components are as follows:
   - *Illuminated target* (T) which can be moved along the optical axis of the instrument. In some instruments, the target is rotatable and is also used for determination of cylinder.
   - *Collimating lens* or the so-called standard lens (L).
   - *A lens rest* is in the form of a small aperture against which the test lens (TL) can be held

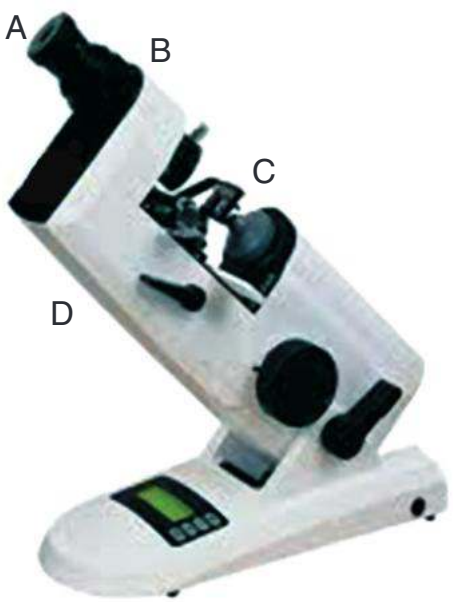


Fig. 12.113 *External features of a manual lensmeter: A, eyepiece; B, eyepiece graticule; C, lens rest and D, housing for illumination lamp, adjustable target graticule and standard lens.*

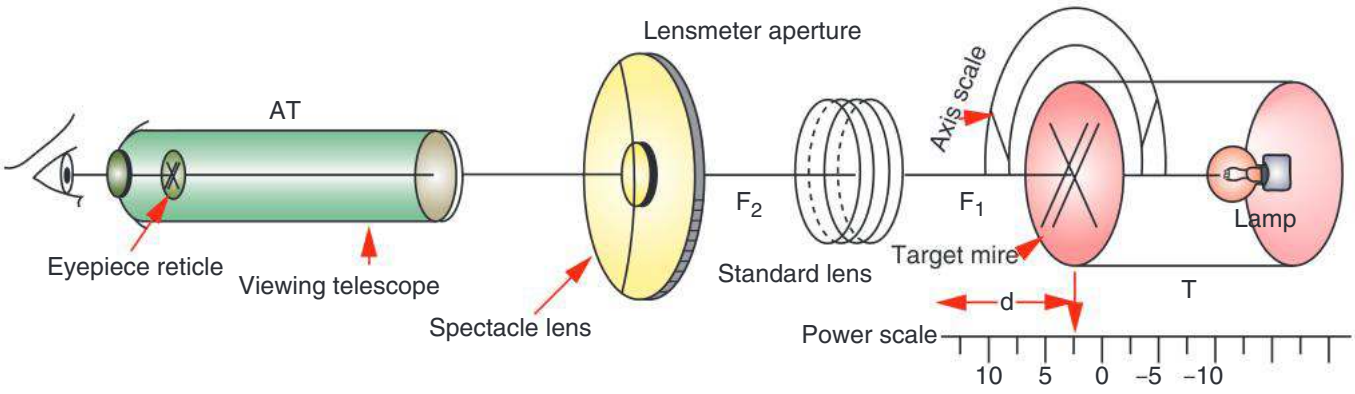


Fig. 12.114 *Schematic diagram of the optics of a typical Badal lensmeter.*

by a clamping device. The lens rest is fixed in such a way that the test lens lies at the front focal plane (F_2) of the collimating lens. This arrangement brings two big advantages:

i. The target always appears of the same size irrespective of the power of the test lens.

ii. The movement of the target required for focusing, measured from the zero point, is directly proportional to the vertex power of the test lens. This means that the dioptre scale recording the power is uniformly graduated.

2. ***Observation system*** by which the target is viewed consists of a focal telescope (AT) with an adjustable eyepiece. When looking through the telescope, one also sees an eyepiece graticule or reticule (R) incorporating a scale for measurement of the prism power. In many instruments, it is also used for the determination of axis direction, in which case it is rotatable or incorporates a protractor scale.

Instrument Designs and Features

All of the available standard lensmeters (conventional non-electronic or the manual lensmeters) incorporate the same Badal-type optical system as described above (Fig. 12.114). However, there are variations in the features and conveniences offered by the various manufacturers. Some of the important features and their variations available are described briefly.

1. ***Target mires.*** Two types of target mires are used.

i. *Star-burst-type* target consists of a ring of very small dots (Fig. 12.115A). When the test lens is cylindrical, the small dots elongate to form focal lines at right angle to the meridian in which the power is being measured. A protractor is usually incorporated into the viewing optics to allow measurement of the axis from the direction of elongation of the dots. This type of graticule has the advantage of requiring no prior alignment. Use of this type of target is more popular in Europe.

ii. *Cross-type target.* In it, the targets themselves can be aligned with the cylinder axis (Fig. 12.115B). It cannot be sharply focused until it has been rotated to correspond with the principal meridians of lens under test. Despite this disadvantage, targets of the crossline type seem to be favoured by American designers. It is probably true that very small cylinders are better measured with the cross-type system.

2. ***Test lens power and axis display system.*** Various methods in use for recording the movement of the target and viewing dioptric scale in different models are as follows:

i. The typical lensmeter has lens power markings along the perimeter of a drum which is attached to a rack and pinion gear

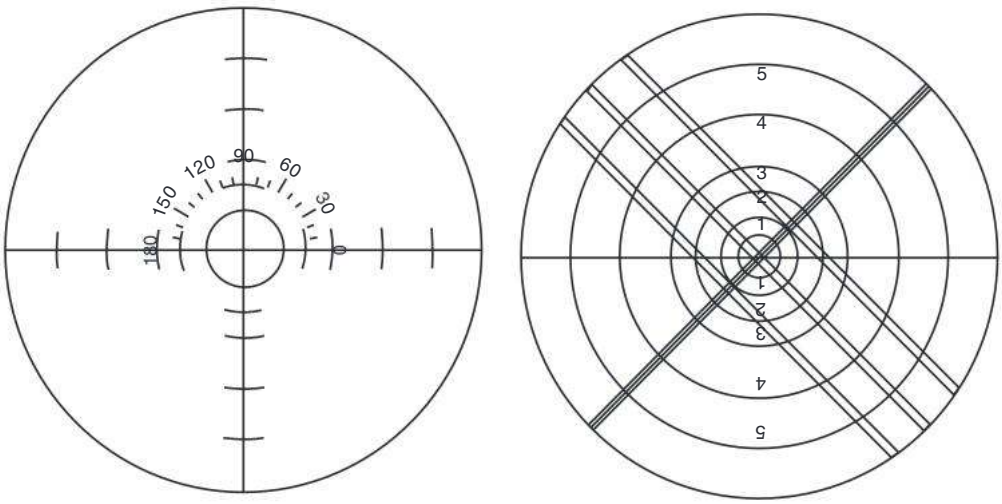


Fig. 12.115 *Lensmeter target mires: A, star-burst type and B, cross type.*

arranged to adjust the axial position of the target mire.

ii. Some manufacturers offer power and axis display within the eyepiece viewing area so that the result can be viewed simultaneously with the properly focused target mires. This feature is sometimes criticized as encouraging a tendency to adjust to an expected measurement value, thereby decreasing the objectivity of the measurement.

iii. *Digital readout* facility is provided by a number of visually focused lensmeters. With some models, there is also the ability to transpose the readout and also round it off to the nearest 0.12 or 0.25 D interval. A hard copy printer may also be incorporated or added. Instruments of this kind should not be confused with the automated type to be described.

3. ***Observation system for target mires.*** As discussed earlier, the standard lensmeter employs *viewing telescope* for observing the focused target mires. However, in some models of the instrument, the viewing telescope is replaced with a projection screen (Fig. 12.116). This arrangement has got following advantages:

i. It eliminates the need to focus on an eyepiece reticule and eliminates concern regarding the influence of operator accommodation on the measurement.

Fig. 12.116 *Lensmeter with projection screen.*

ii. It permits the use of both eyes and is generally more comfortable when in continuous use.

iii. It allows the simultaneous viewing of the target by more than one person which is helpful in discussions of disputed reading. This feature is also useful for teaching purposes.

Disadvantages

i. Projection system is expensive.

ii. There occurs a difficulty in viewing the lensmeter target in unfavourable ambient light condition.

4. ***Tilting facility.*** Some models of lensmeters have facility to be tilted to any desired inclination. This may be a convenience in certain office arrangements.

Determination of Lens Power

While using manual lensmeter to determine the lens power, following routine should be followed:

1. ***Adjustment of lensmeter***. Before using a lensmeter, it is essential to ensure that the eyepiece is adjusted to suit oneself. Someone else may have altered the setting.

First set the dioptre scale at zero and withdraw the eyepiece to its fullest extent. Then move it slowly inwards, stopping as soon as the target is seen in sharp focus. When this setting is reached, the eyepiece graticule should also be in focus. If it is not, the instrument is not fit for use.

2. ***Placing and adjustment of spectacle***. A lensmeter measures the vertex power corresponding to the surface in contact with the lens rest. Hence, to measure the back vertex power, one should place the back vertex of the lens against the rest. Before final focusing adjustment is made, the platform and position of the spectacles should be adjusted so as to centralize the target with reference to the eyepiece graticule or projection screen.

3. ***Determination of spherical lenses power***. It presents no difficulty because the target is in focus in only one position and the power is given directly by the reading on dioptre scale.

4. ***Determination of cylindrical lens power and axis***. Following routine should be adopted:

i. Bring either set of lines into focus and record the first reading as the spherical power, e.g. +2.00 D.

ii. Focus the other set of lines, this time recording their direction as well as the power reading, e.g. +1.5 D at 90 degrees.

iii. To find the cylinder power, subtract the first reading from the second, taking signs into account. In this instance, we should have (+1.5) – (+2.0) = –0.50 D. The prescription is, therefore as below:

+2.0 DS/–0.5 DC at 90 degrees. If the +1.5 D reading had been taken first, the result would have been:

+1.5 DS/+0.5 DC at 180 degrees which is, of course, the plus cylinder transposition of the first prescription.

5. ***Determination of prism power***. When the optical centre of the test lens is not centred on the test aperture, the image of the target is decentred relative to the reticule R. The procedure is to mark with a felt-tipped pen the point of interest on the test lens, usually the location of the patient's pupil. With the point of interest centred in the lensmeter aperture, the amount and orientation of the prism are read from the reticule scale.

6. ***Measuring the bifocal add***. The bifocal add is different from the rest of the spectacle lens. The distance portion is designed to deal with essentially parallel light, and that is the basis on which the lensmeter reading is calculated. The bifocal add, however, is designed to work on diverging light, originating, for example, at 40 cm from a +2.50 bifocal add. If one imagines the bifocal add as being an additional lens placed at infinitesimal distance in front of the distance lens, the principle becomes clearer. Diverging light from the near object passes through the bifocal lens and is made parallel. The parallel light then enters the distance lens from its anterior surface and is refracted with the expected optical effects, yielding the back vertex vergence required to give the patient a clear vision. In a sense, the bifocal add exerts its effect on the light before it passes through the rest of the lens (Fig. 12.117).

Correct measurement of the add, therefore, requires that the lens be measured from the front. The front vertex power of the distance portion is measured, and the difference in front vertex power between the distance and near portions specifies the add. The spectacle power itself is still the back vertex power of the distance portion. In the case of a strongly

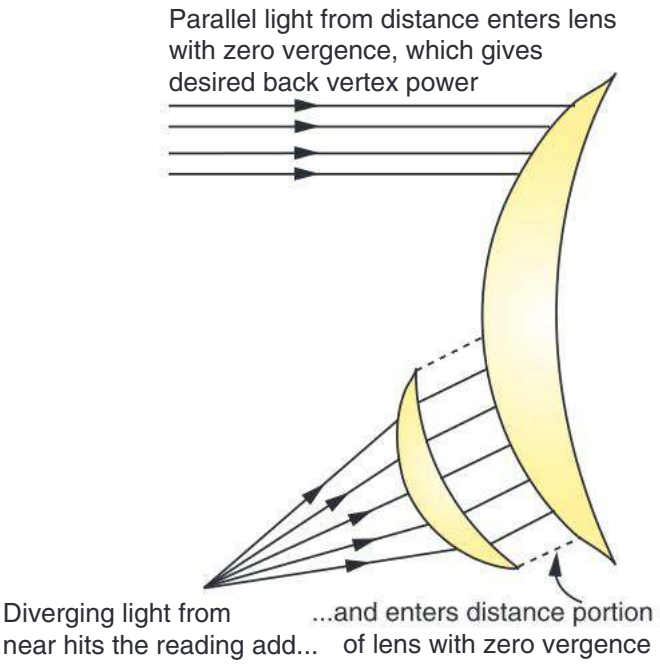


Fig. 12.117 *Arrangement of light rays entering the distance- and near-vision parts of a bifocal lens.*

plus distance lens, there will be a significant difference in the front and back vertex measurements of the add, and therefore there will be a significant error, if the add is not measured from the front. In cases other than a strongly positive distance lens, there is usually little or no clinically significant difference in the measurements.

7. ***Measuring contact lenses power***. While measuring contact lens power using the lensmeter, two problems are encountered:

i. *Large spherical aberrations* due to huge shape factor causes problem in exactly measuring the power. For lenses of power greater than ±5.00 D, an error of 0.40–0.50 D may be seen. In some models of lensmeters, an auxiliary aperture is employed to limit the effects of contact lens spherical aberration.

ii. *Vertex distance error.* The high curvature of a typical contact lens can cause it to arch above the lensmeter's calibrated measuring plane. Some models of the lensmeters have special attachments to hold the contact lenses at the correct vertex height for an accurate back vertex power measurement. An alternative procedure involves measuring the front vertex power by placing the contact lens concave side facing the lensmeter telescope (Fig. 12.118A). Except for high-plus lenses, a careful front vertex power measurement is generally within a few tenths of a dioptre of the back vertex power and can be expected to be smaller in magnitude.

Tests for Accuracy

A lensmeter, like any other measuring device, is capable of errors and should be checked from time to time.

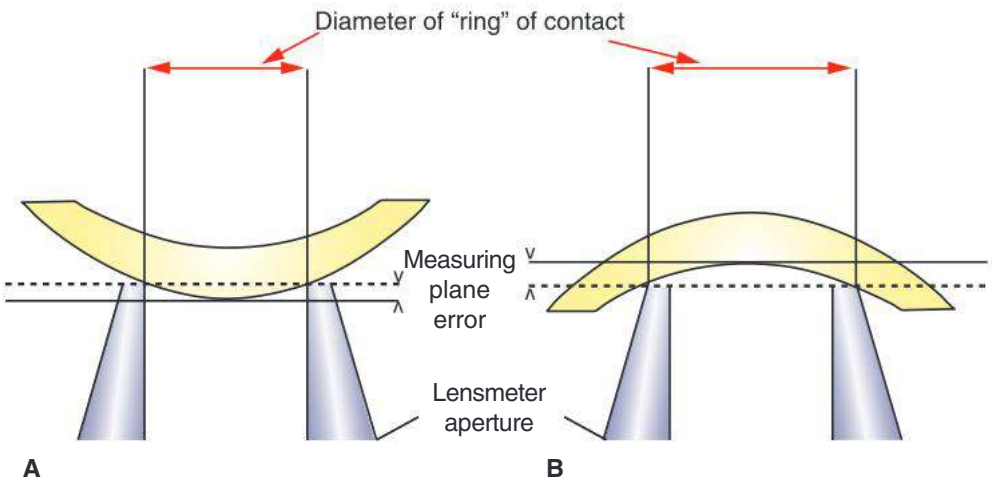


Fig. 12.118 *Measuring front vertex power in a contact lens (A) decreases error in power determination as compared to measuring back vertex power (B).*

1. ***Accuracy of power reading*** can be checked by means of a master set of lenses of known power. A well-calibrated lensmeter should read accurately at zero (no lens) and at a high-plus and high-minus power lens (e.g. +12.00 and –12.00 D). Following errors may be detected:

- *A zero setting error* is usually associated with a misadjustment of the drum scale.
- *A vertex plane error* is indicative of an incorrect location of the measuring head aperture. In it, both strong plus lenses and strong minus lenses read towards the plus (or towards the minus).
- *An incorrect power of the standard lens* is indicated when both strong plus lenses and strong minus lenses read too high or too low in magnitude.

Except for zero setting error, other calibration errors can be corrected by the lensmeter operator.

2. ***Accuracy of axis readings.*** The 0–180 degree line of the axis scale should be parallel to the platform. A simple method of test is to take a strong flat edge planocylinder and grind one edge so as to form a flat edge exactly parallel to the cylinder axis, as shown in Figure 12.119. When this prepared edge is resting on the platform, the direction of the focal lines should be recorded as exactly 90 or 180 degrees. Before use, the test cylinder can itself be checked by taking two axis readings, one with the lens turned back to front. If the flat edge on the test lens has been accurately ground, the two readings – whatever they are – will be the same.

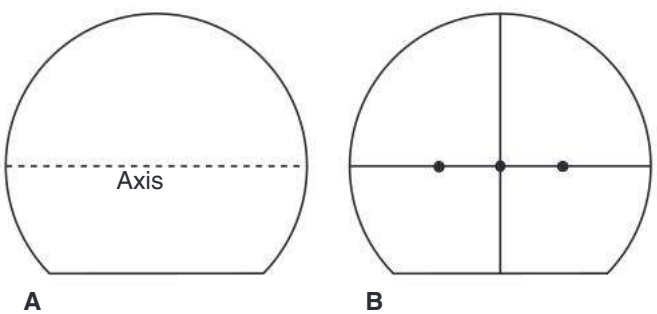


Fig. 12.119 *Test lens: A, for axis scale and B, for marking device.*

3. ***Accuracy of centration.*** Two different types of centration error may occur. Firstly, when the eyepiece graticule is rotated, its central point should remain in the same position relative to the image of the target. If it traces out a circular path, the graticule itself is not correctly centred in its housing. Secondly, the target itself should be centrally placed in relation to the eyepiece graticule. As this is a very critical adjustment which may become disturbed in transit, some models provide a readily accessible means of readjusting the centration of the target.

Either of these errors can lead to faulty estimation of prism power and errors in optical centration when the focimeter is used as a marking device.

4. ***Accuracy of marking device.*** Two different errors, either alone or in combination, can impair the accuracy of the marking device. Firstly, the central point may, in fact, be decentred from its true position. Secondly, the line on which the three marking points are situated may not be parallel to the 0–180 degree meridian of the axis scale.

Marking devices can easily be checked with the aid of a specially prepared spherical lens of fairly high power, as depicted in Figure 12.119. Crosslines are accurately etched on one surface so that their centre coincides with the optical centre of the lens, and a flat edge is ground on the lens accurately parallel to one of the lines. The flat edge is then placed on the platform, the height of which is carefully adjusted until the target appears exactly centralized. The marking device is operated, and if it is in perfect adjustment, the three dots will be marked on the lens in the position shown in the diagram.

AUTOMATED LENSMETER

Basic Instrument Design and Working

Automatic lensmeters (Fig. 12.120) have been designed to calculate lens power from the bending of light beam produced by the lenses. Microcomputers are built into these instruments to mathematically process the data associated with lens measurement, to control displays

Fig. 12.120 *External features of an automated lensmeter.*

and, in some models, to print the results of measurements.

The various automatic lensmeters differ in the detailed method used to measure the deflection of light over the lens surface and thus vary greatly in their internal design, but a typical mode of use can be indicated. The instrument is first switched on and allowed to reset itself in the zero adjustment. The lens is then placed on an annular rest similar in design to those of conventional lensmeters. When a read switch is activated, the power of the lens together with any prismatic effect (measured at the point directly in line with the centre of lens rest aperture) are visually displayed.

Optics and Working Principle

Optics of the Humphrey automatic electronic lensmeter is discussed here briefly.

Humphrey Lens Analyser

To understand how the Humphrey lens analyser operates, we must first consider what happens to an off-axis beam of light when it passes through a spherical spectacle lens. As can be seen from Figure 12.121, the beam will be deviated by an extent dependent upon the power of the lens. If we were to place a scale at X, the amount of deviation could be converted into a measure of the lens power. A problem arises with this technique, if the lens is not centred correctly, as the amount of deviation will vary with the degree of decentration. This problem can be overcome by the use of two beams, as shown in Figure 12.121C and D. The difference in the deviation of the two beams gives a measure of the lens power, independent of any decentration. As a bonus, the midpoint of the two beams will

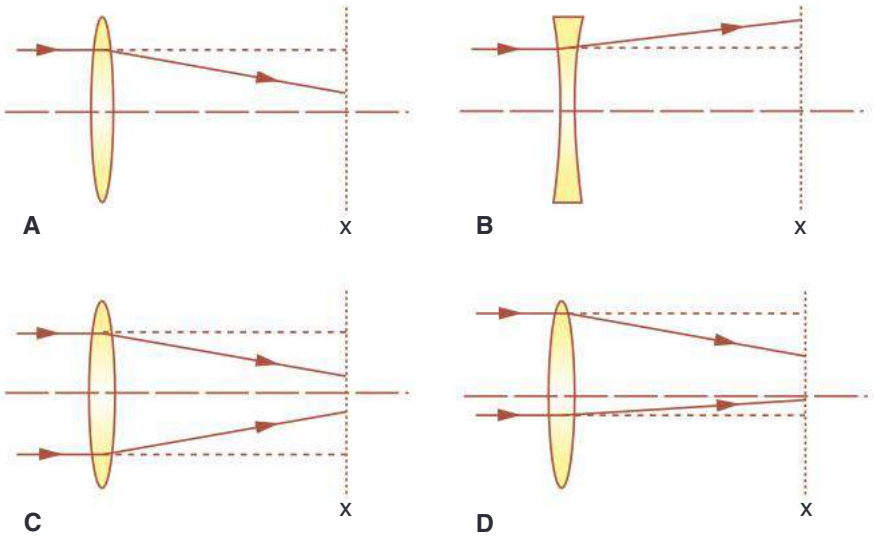


Fig. 12.121 *The deviation of a beam of light as it passes through a lens.*

give a measure of any prismatic component of the lens at the point being tested.

In order to be able to measure the cylindrical powers, it is necessary to use at least four beams of light. The resultant pattern will be elliptical – the major and minor axes of which will coincide with the axes of the cylinder under test. The Humphrey lens analyser (Fig. 12.122) utilizes four beams of light which are alternately flashed on by the rotation of a sector disc in front of a quad prism. The deviation of each beam is measured by a four-quadrant photodetector. This detector will respond to an incident spot of light by giving an electrical signal, the magnitude of which is dependent upon the position of the spot. These detectors can typically resolve the position of the spot to within 1/1000 of an inch. The output of the detector is fed into a small computer which processes the information and then displays the spherical, cylindrical and prismatic powers of the lens on a calculator-type display. The computer can also store the information about a particular lens. This is used when checking glazed spectacles to give a measure of both the horizontal and vertical prisms at the specified centration distance.

Some Commercially Available Automated Lensmeters

1. ***CL-300 (Topcon).*** It is computerized and has mono-and multi-focal lens detection and measurement, a tiltable colour LCD screen with a 5.7-inch touch panel and dynamic graphics, a green light reading beam to enhance measurement precision, and UV transmittance measurement function.
2. ***LM-1800 PD (Nidek).*** It has a Hartmann sensor with 10 and multiple measurement points within the nosepiece to provide rapid measurement of the reading point with greater accuracy and reliability.
3. ***AL700 (Reichert).*** It quickly and accurately measures all type of lenses (i.e. single vision,

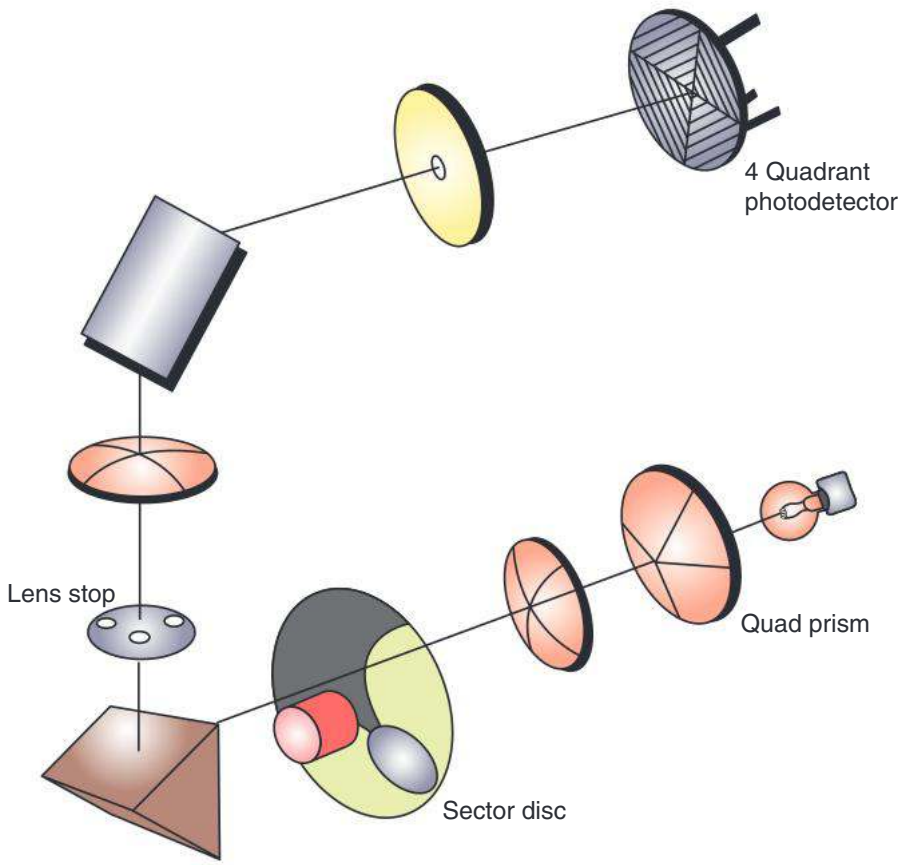


Fig. 12.122 *Optics of Humphrey lens analyser (automatic electronic lensmeter).*

bifocal, progressive and prism). Progressive lenses are automatically recognized and measured, and the rate of addition and dioptre changes are displayed graphically.

4. ***TL-5000 (Tomey)***. This instrument features customizable colour touch panel, a power map that indicates different lens powers in different colours which make measurement of the reading point easier, an auto table lock function when the optical centre of the lens is aligned, simultaneous measurement of UV transmissivity and customizable shortcut buttons for the most frequently used functions.

SMART PHONES IN OPHTHALMOLOGY

A smart phone is a multi-functional electronic device – mobile phone with advanced computing capability and connectivity. In the last few years, clinicians, including ophthalmologists, have started adopting smart phone technology with some innovative modifications in their routine clinical practice. So, it will not be out of place to include 'smart-phone and its application in ophthalmology in the chapter on optical instruments and techniques'.

Operating system platforms that are now available on mobile phones include:

- Android operating system by Google,
- iOS by Apple,
- BlackBerry by RIM,
- Symbian and
- Windows Mobile and Windows Phone.

Some useful APPs for ophthalmic practices:

- The EHB,
- EyeRoute ophthalmic image management system,
- PubMed on tap,
- Dragon dictation,
- Flash card,
- Skyscape medical resources,
- IKONION and
- Personalized Physician Apps.

Uses of smart phones in ophthalmology can be broadly classified as follows:

A: Patient assessment tools
B: Smart phone ophthalmic imaging
C: Patient education tools
D: Education and reference tools for ophthalmologists
E: Smart phone-based calculators in ophthalmology
F: Office tools for patient record and administration
G: Tools for the vision researchers

A. PATIENT ASSESSMENT TOOLS

- *Smart phones have an interface* that provides the commonly used clinical evaluation tools.
- *Testing tools* constitute Amsler grid, colour vision plates, contrast sensitivity charts, near vision cards for adults and children, paediatric fixation targets, Worth 4 Dot test and an OKN drum simulator (Fig. 12.123). These applications are extremely helpful in situations when it is not possible to carry all the standard equipment, such as bedside calls and community eye visits.
- *Eye Hand Book* which is available for free for android and iPhone users is one of the most widely used application (Fig. 12.124). It has all the above-mentioned tools. In addition, other popular applications it has are one iSight test, Vision test, Macular tester and Colour blind test.
- *PEEK Acuity*, a logMAR style smart phone visual acuity tester was evaluated and was found to be as accurate and repeatable as the standard Snellen visual acuity testing among adults in rural Africa.
- *Snellen by Dr Bloggs* (2011) is the most accurate application available for free with an average line inaccuracy of 6.6%.
- *Eye Test by Bokan Technologies* (2009) has been found the most accurate application with an average line inaccuracy of 4.4% compared to standard Snellen optotype.
- *Fluorescein light and pen light.* These tools will have most of their utility in non-ideal patient examination settings. The physician will have

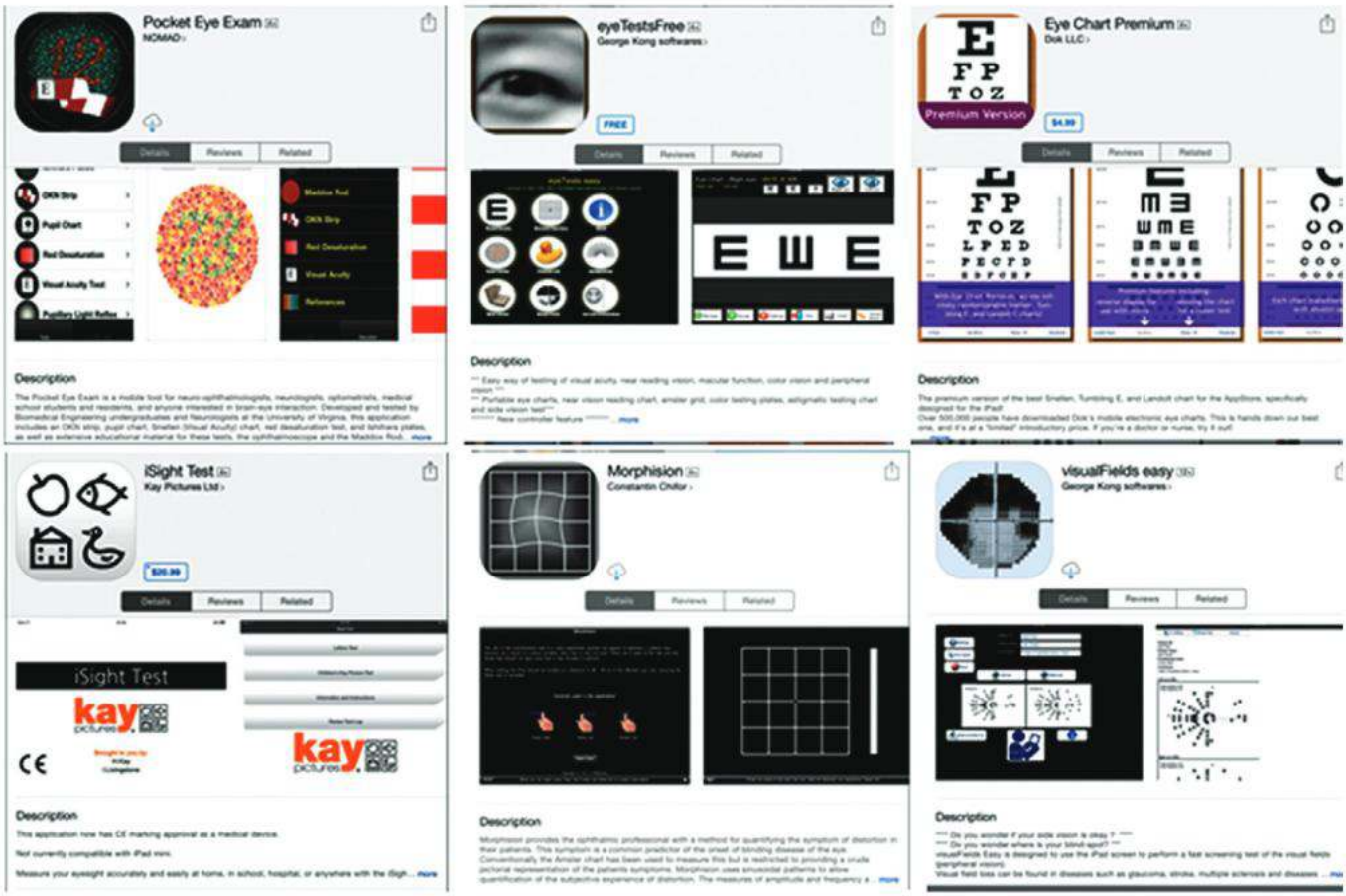


Fig. 12.123 *List of various patient assessment tools available on a smart phone app.*

to increase the screen brightness to its maximum and reduce the surrounding light to its minimum.

- *Paediatric fixation targets.* Smart phones can be used as paediatric fixation targets that are bright and have motion and sound to entertain paediatric patients. These tools on the smart phone engage the paediatric patient very well during the examination.

B. SMART PHONE OPHTHALMIC IMAGING

Smart phones are being increasingly used for ophthalmic imaging; some of the uses include the following:

1. Image Transfer and Display Device

- *Image from a conventional fundus camera is transferred to the smart phone* and sent to another site. In addition, smart phones will display suitable images of magnetic resonance imaging and computed tomography scans directly from an LCD computer monitor. The transfer of images to these devices is readily available through Bluetooth or Wi-Fi. These images can then be easily sent for remote expert consultation, to be reviewed in a traditional office workstation or on another smart phone.
- *Use in telemedicine*. The availability of smart phones and their extensive mobile-phone networks make these devices ideal for telemedicine.
- *OsiriX and Meditech* applications enable use of information from hospitals. Picture archiving and communication system (PACS), secure transfer from one physician to another and from one location to another.

2. As Digital Camera

Taking pictures of ocular pathologies is not an uncommon practice in an ophthalmology clinic.

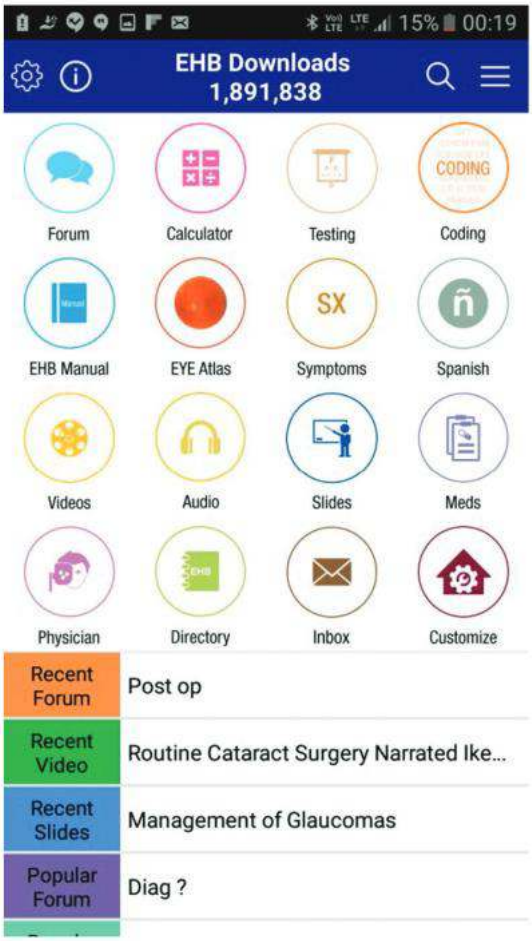


Fig. 12.124 *A screenshot of the Eye Health Book app.*

Fig. 12.125 *A third-party macro lens attachment to a smart phone turns the iphone into a magnifier.*

Fig. 12.126 *A, Smart phone with adapters used as a handy and portable slit-lamp camera. B, Slit-lamp smart phoneography is done by latching the phone to the eyepiece.*

Not many hospitals are fortunate to have anterior segment camera and fundus photographic units. Smart phones play an important role in this field. Most smart phones come equipped with a high-megapixel camera (13–20 MP) and high-resolution video capabilities (1080 pixels). These cameras can be used for anterior segment photography and fundus photography.

I. Anterior segment imaging: The anterior segment and the adnexa are photographed using digital magnification and the camera flash (Fig. 12.125). A small third-party macro lens can also be used. Recently adapters (Fig. 12.126A) have been developed to latch the smart phones to the eyepiece of a slit-lamp (Fig. 12.126B). In this, the camera sensor is held at a distance of nearly 1 cm from the eyepiece, which fills the view on the camera screen. Sometimes a small amount of vignetting is seen at the image

corners, which can be overcome by digitally magnifying the image. Use of an indigenous solution has been described where a deodorant cap is glued to a camera case. The deodorant cap is slid over the eyepiece of the slit-lamp biomicroscope and the image is captured. These same adapters can also be latched to the assistoscope of an operating microscope and used for recording eye surgery (Figs 12.127 and 12.128).

- The iPhone and other smart phones also have the ability to capture video of eye movements, which is of acceptable quality.

II. **Smart phone fundoscopy**: Initial approaches to smart phone fundoscopy consisted of using a fundus lens, 78 or 90 D, and a smart phone attached to the slit-lamp eyepiece. Although fundus imaging with this technique was successful, the images were of low quality, and acquisition was difficult and cumbersome. Now some better options are available.

- ***iExaminer*** (Welch Allyn, Skaneateles Falls, NY), has been approved by FDA in January 2013, which is a smart phone adaptor system that attaches and aligns an iPhone to Welch Allyn's PanOptic Ophthalmoscope, to use the iPhone's camera to capture images of the retina and optic nerve (Fig. 12.129). This device can capture fundus images without dilation of the pupil with 25 degree field of view. Although good images can be acquired with this device, especially of the optic nerve, fundus imaging is limited by the narrow field of view.
- ***Smart phone assisted video indirect ophthalmoscopy*** is one of the most versatile methods of smart phone fundoscopy. In this technique, the coaxial camera light serves as the source of retinal illumination and camera sensor serves as the 'observer eye'. The camera is kept on the video mode with flash on. Then the red glow of

Fig. 12.127 *Smart phone assisted ophthalmic surgery recording using the DIY adapter attached to the assistoscope of operating microscope.*

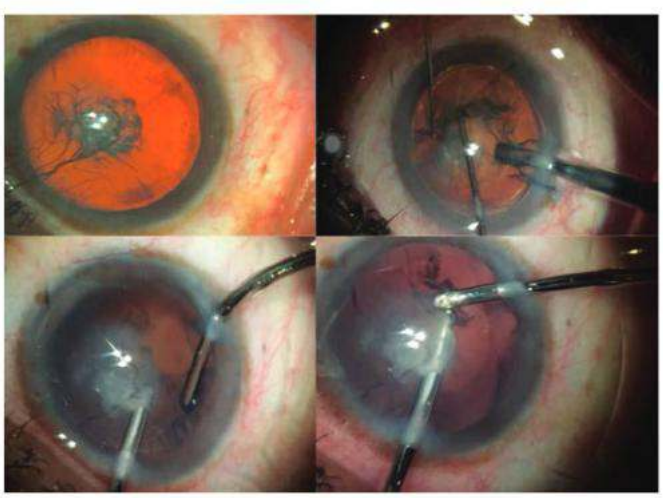


Fig. 12.128 *A collage of stills captured using DIY smart phone ophthalmic surgery recording.*

Fig. 12.129 *Iphone attached to the PanOptic monocular indirect ophthalmoscope.*

the fundus is visualized on the screen of the phone held at 25 cm from the eye. A 20 D lens is interposed between the camera and the eye as in indirect ophthalmoscopy and the fundus image is brought to focus (Fig. 12.130). Smart phone video indirect ophthalmoscopy can be done bimanually or by using devices such as those given below.

- ***MII – RetCAM***, i.e. Make In India Retinal CAMera (Fig. 12.131), designed by Sharma et al. in 2015 is a device and imaging technique that can image entire fundus, central and peripheral. This device is patent pending. The MII – RetCAM holds the 20 D lens and the camera which leaves one hand free and can be used for indentation to visualize and image retinal periphery.
  - *For central fundus imaging*: The user, equipped with a smart phone and 20 D lens, holds the device close to the eye and once fundus glow is visualized through the dilated pupil, slowly brings it back (similar to standard indirect ophthalmoscopy) until a clear image can be visualized in the smart phone camera.
  - *For peripheral imaging*: The user holds the indenter in the hand that he or she normally uses during indirect ophthalmoscopy and tries to indent the area of interest and follow a similar focusing technique.
  - *The Filmic Pro app* (Cinegenix LLC, Seattle, WA) can be used to provide control of the light intensity and independent control of focus and exposure, which are required to obtain high-quality fundus images with this technique.
- ***Direct ophthalmoscopy with smart phone***: By placing a LED light source (powered by an external battery source) close to the camera, the mobile phone can effectively be transformed into a direct ophthalmoscope (Fig. 12.132).
- ***Fluorescein angiography*** using an external LED light source and barrier and excitation filters sourced from an old fluorescein angiography can also be performed with

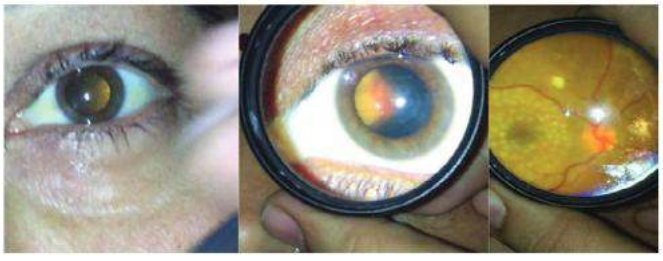


Fig. 12.130 *Smart phone video indirect ophthalmoscopy in progress.*

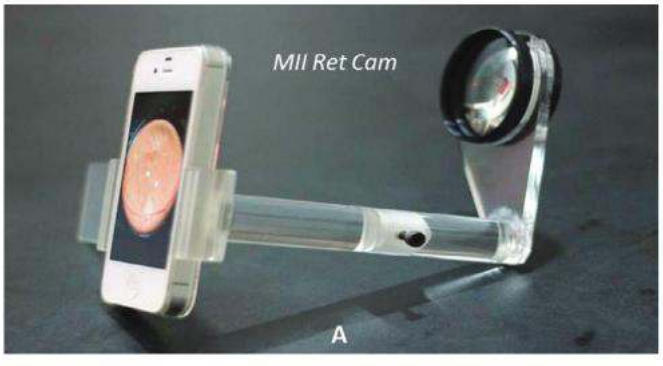


Fig. 12.131 *MII retcam for unimanual video indirect ophthalmoscopy.*

Fig. 12.132 *Modification of the mobile phone camera by affixing a light emitting diode light with external power supply.*

smart phone camera. This technique can be beneficial for bed-ridden patients and patients in poor resource settings.

C. SMART PHONES AS TOOLS OF PATIENT EDUCATION

Patient education is an essential component of medical management. Conventional educational material includes instruction sheets, brochures and flyers, which can be shown or handed over to the patients in the outpatient department.

Applications have been developed to promote patient awareness of ophthalmic conditions. These include the following:

- *3D applications that introduce anatomy and broad information about signs, symptoms*, management of ophthalmic diseases and surgical procedures. For example, IKONION (IKONION Digitale Medien GmbH) is an application available on the iPhone, which proves to be very useful in patient education. This application may be downloaded by patients wanting more information about their disease process. It provides patients with a brief description of eye diseases along with high-resolution pictures, videos and animations, which facilitate a better understanding of common eye conditions (Fig. 12.133).
- *MyEyeDrops*, an app developed by the Singapore National Eye Centre, sends reminders to patients instilling anti-glaucoma medications.

D. EDUCATION AND REFERENCE TOOLS FOR OPHTHALMOLOGISTS

The smart phone provides various physician education modalities available at any time. These include the following:

- Colour-coded retinal drawings are available for use of ophthalmologist.

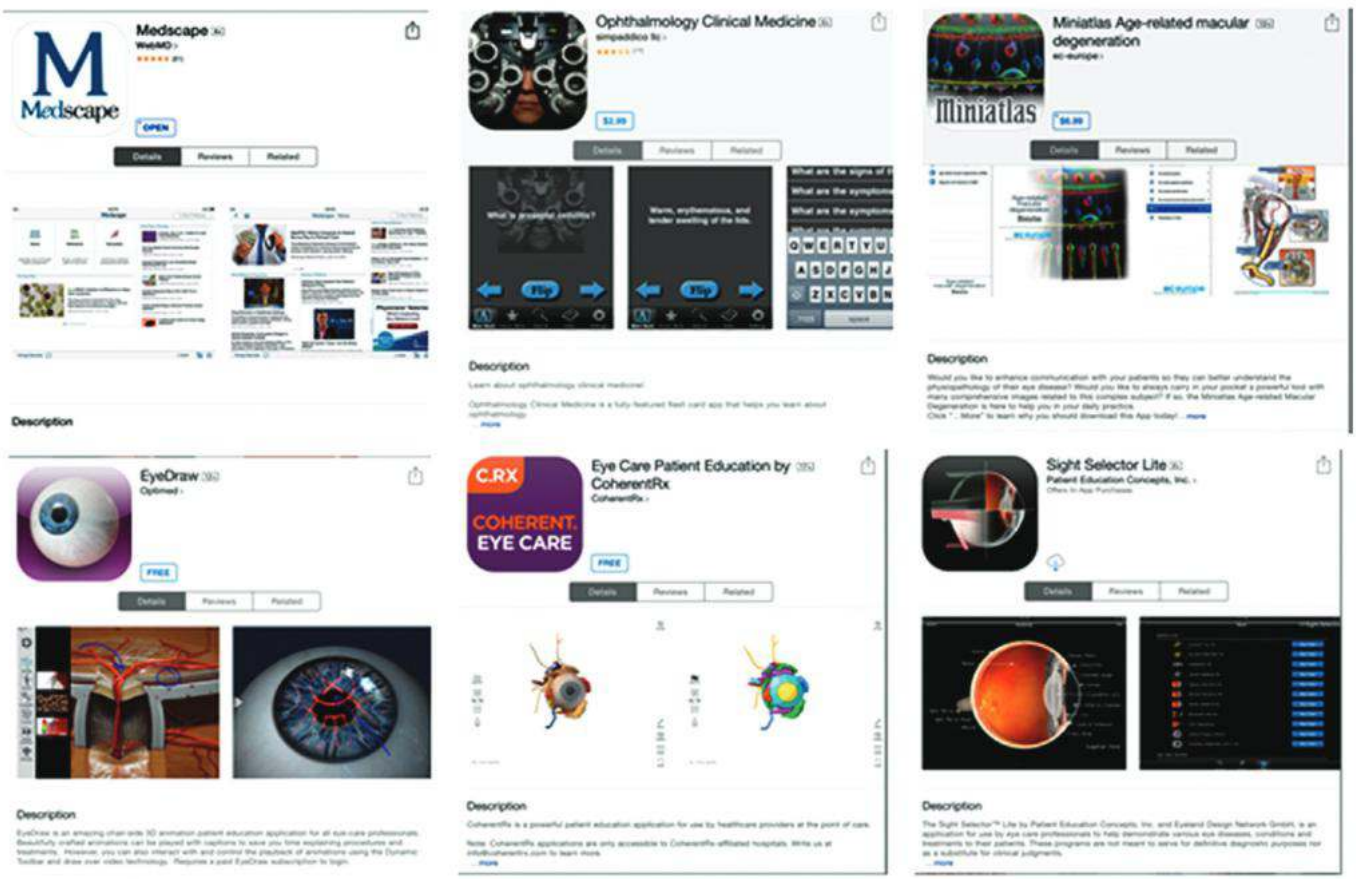


Fig. 12.133 *Some patient education aids in ophthalmology available on smart phone.*

- *Colour atlas of commonly encountered ophthalmic diseases* and a summary of major clinical trials is also very useful.
- *Clinical Trials* (StopWatch Media Inc., Philadelphia, PA, USA) is an app that utilizes databases by the National Library of Medicine and National Institutes of Health to list over 86,000 clinical trials registered with the US government. With similar search options and limiters as in a regular complex web interface, the Clinical Trials app offers advanced search options, including type trial (observational, interventional or expanded access), location, clinical trial phase and enrolment status.
- *All classifications and grading systems* such as angle anatomy, diabetic retinopathy, macular holes, optic nerve oedema and melanoma are easily available.
- *Several applications provide access to database and literature search in biomedical literature databases* such as PubMed/MEDLINE. Most popular database search applications are '*PubSearch*' and *PubMed on Tap*.
- '*Eyetube*', '*UptoDate*', '*Epocrates*' and '*Medscape*' are some applications which are of great use for keeping track of medical advancements and news through videos and articles, and provide most recent information useful for practicing evidence-based medicine.
- '*Normal Lab Values*' or '*Pocket Guide to Diagnostic Tests*', which offer information regarding common laboratory tests, including reference values and interpretation, causes for abnormal values and laboratory unit conversations.
- *Skyscapes RxDrugs* or *SafeMed Pocket* are drug reference apps which offer names of drugs, their indications, dosages, pharmacology, drug–drug interactions, contraindications and costs.
- *MedMath* and *MedCalc* are other applications apps which offer options for calculating various clinical scores, individual drug dosing, etc.

E. SMART PHONE-BASED CALCULATORS IN OPHTHALMOLOGY

- *IOL calculator, Panacea IOL and Toric calculator* are smart phone apps which can be used for IOL power and estimating surgically induced astigmatism.
- *iToric* is an android smart phone camera-based application used for Toric IOL marking and in a study was found to be better than manual marking.
- *Glaucoma risk calculator* based on the Ocular hypertension Treatment Study is a useful app for glaucoma patient.
- *IOP-CCT calculator*, *Transposition calculator*, *Visual acuity calculator*, *cross cylinder calculator* and the *dioptre to radius conversion calculator* and *back-vertex distance calculator* are other tools of day-to-day use.

F. OFFICE TOOLS FOR PATIENT RECORD AND ADMINISTRATION

- *DrChrono EHR/EMR, inpatient care EHR* and *Doctor on GO* Smart phone applications which can be used for generating and maintaining electronic medical records and scheduling appointments. These apps may not be perfect solution for large setups but are suitable for individual or small group practices.
- *Hospital Information Systems (HIS)* applications allow secure access to patient's records from remote locations.
- *OsiriX and Meditech* are applications which enable use of information from hospitals 'PACS'. They ensure secure transfer of data from one physician to another and from one location to another.
- *Coding diseases according to the International Classification of Diseases* (ICD) are also be done with some available applications which can be very helpful and time-saving.
- *Tele-ophthalmology* presents the use of electronic communication and information technologies to provide or support a diverse group of activities related to eye care. Smart phone applications enable true appliance of tele-ophthalmology, while it covers many medical activities, including making diagnoses, treatment, prevention, education and research.

G. TOOLS FOR THE VISION RESEARCHER

- Besides the variety of clinical applications discussed herein, the presence of smart phones in the basic science laboratory has

significantly increased, replacing timers, calculators and other small digital aids.

- Moreover, the number of *specialized basic science applications* has steadily grown over the recent years. However, it is difficult to estimate the total number of scientific apps currently available for iPhone and iPad. The available apps may be categorized as reference, medical, productivity or utility app.
- Many manufacturers now also provide iPhone or Android apps. While some are mere smart phone versions of online catalogues, others include technical references and animated tutorials for a variety of equipment and consumables used in a modern vision research laboratory.
- In addition, a growing number of apps feature basic data viewing, protocol editing and analysis capabilities, sometimes even combined with various degrees of remote protocol features for networked equipment.

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