SFCR Experts Series 2

Stéphane Litrico *Editor*

Surgery for Degenerative Lumbar Spine

Vol.2

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SFCR Experts Series

Volume 2

Spinal surgery has evolved considerably in recent years, making it particularly challenging for the spine surgeon to have the latest and most relevant knowledge in the field of spinal diseases at his disposal. French spine surgeons have always been innovative in the field of spinal treatment, introducing new concepts and breakthrough theories for many years, and some of them, such as Dr. Pierre Stagnara, Professor Raymond Roy-Camille and Professor Jean Dubousset, are considered masters in the field and recognised pioneers throughout the world. This series has been conceived by a group of experts from the French Spine Society with an 'encyclopaedic spirit', and the aim of bringing together the best knowledge, scientific literature, personal experience and expert opinion in all areas of spinal pathologies. It will cover a wide range of topics (trauma/degenerative/tumours), from decision-making and artificial intelligence to surgical strategy, new technologies and complications, as well as specific conditions such as spinal deformities, spinal infections, cranio-vertebral junction, osteoporotic spine or paediatric spine. A unique panel of French experts and of international contributors with extensive experience in the field are involved, ensuring a high quality scientific level of content. The friendly format, with illustrations and tables and concise chapters, undoubtedly makes the books easy and enjoyable to read.

Stéphane Litrico
Editor

Surgery for Degenerative Lumbar Spine

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SFCR Foreword

The French Spine Surgery Society (SFCR) was created in 2004 under the initiative of an orthopedic group (Daniel Chopin, Arnaud Blamoutier, and Pierre Guigui). From 2011 onward, following several joint meetings, French spine neurosurgeons joined the SFCR, which now represents all spine surgeons in France. Over the years, the society has considerably grown organizing many activities not only in scientific and academic fields but also regarding socio-professional and medico-economic aspects. Each year, members have the opportunity to present their scientific work, learn the most recent advances in the field, and share their opinions through interactive discussion sessions during the Annual Meeting of the society. The SFCR is also strongly connected with other spinal societies, especially in Europe, and is regularly involved in international conferences and symposiums.

France has a tradition of innovative concepts in spine surgery, and Professor Raymond Roy-Camille and Professor Jean Dubousset, both from Paris, represent undoubtfully the most world recognized French pioneer surgeons who have revolutionized spine surgery in the 1960s and the 1980s, respectively. More recently, under the impulsion of Madame Duval-Beaupère, the French spine school considerably contributed to a better understanding of sagittal balance concepts by introducing new parameters and developing modern ideas.

To perpetuate the tradition of the French school in the field of spine surgery, the SFCR sought to establish a collaboration with Springer to produce a book series on spinal concepts, adopting an encyclopedic approach. The aim is to address all the features of spinal pathologies through the book collection by publishing 1 to 2 volumes per year. The first volume is dedicated to the fundamentals and basic concepts. Volumes 2 and 3 will discuss lumbar and cervical degenerative diseases, and Volumes 4 and 5 will be focused on thoracolumbar and cervical traumas, respectively.

At the end, it is our great pleasure to contribute to the diffusion of knowledge in spinal disorders, for the next generation of spine surgeons. We assume that the "SFCR Experts Series" collection will provide them with useful tools and decision-making support for their daily practice.

SFCR presidents:

2004/2005: D. Chopin	2010: P. Guigui	2015: J. Beaurain	2020: J. Allain
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For the SFCR,
Prof. Cédric Y. Barrey (SFCR President 2023)

Preface

We are pleased to present the second volume of the "Expert Series" made with the support of the French Spine Surgery Society and dedicated to degenerative lumbar spine disorders.

This volume is the result of a collaborative effort by renowned experts and offers a structured, critical, and thoroughly up-to-date overview of the diagnostic and therapeutic challenges related to lumbar degeneration. From imaging to chronic pain management, including revision surgery and sagittal alignment, each chapter combines up-to-date scientific data and clinical experience.

Readers will find:

A clear review of the principles of evidence-based medicine (EBM) as applied to lumbar spine surgery
A comprehensive overview of imaging modalities adapted to lumbar pathologies
A description of the main lumbar degenerative pathologies and their treatment
A detailed analysis of modern surgical indications, including minimally invasive techniques, disc arthroplasty, and anterior, posterior, or lateral fusion approaches
A practical guidance for managing persistent pain, complications, and failed surgeries

This volume is intended not only as a reference tool for neurosurgeons and orthopedic spine surgeons but also as a resource for training, discussion, and practice improvement.

We hope the richness of these contributions serves as a reminder: the successful management of care still relies on the alliance of knowledge, expertise, and attentive care.

Nice, France — Stéphane Litrico

Contents

1 Evidence-Based Medicine in Lumbar Degenerative Spine Surgery

Bertrand Debono

Low back pain is the leading global cause of years lived with disability and a major contributor to health-related economic burden [1]. Degenerative disorders of the lumbar spine—such as disc herniation, spinal stenosis, and degenerative spondylolisthesis—account for a significant portion of this impact, affecting millions of adults worldwide [2]. While surgery remains a cornerstone of treatment for patients who fail conservative care, the decision to operate, and particularly *how* to operate, is frequently debated [3–5].

Over the past two decades, the field has witnessed a growing emphasis on Evidence-Based Medicine (EBM) to standardize care, improve outcomes, and guide clinical decision-making [6]. The aim of EBM is to integrate the experience of the clinician, the values of the patient, and the best available scientific information to guide decision-making about clinical management [7] (Fig. 1.1).

In parallel, a small but influential number of randomized controlled trials (RCTs) have sought to evaluate surgical versus non-surgical treatment, as well as fusion versus decompression strategies [8]. However, spine surgery—unlike many medical disciplines—has faced substantial methodological, cultural, and logistical obstacles in generating high-level evidence [9].

Heterogeneous pathologies, surgeon, and patient treatment preferences, challenges in randomization and blinding, and the long-time horizon required to assess outcomes have all contributed to a relatively low level of proof supporting many common procedures. As a result, despite increasing data, guidelines remain weakly graded, and considerable practice variation persists [10, 11].

Moreover, even when robust evidence exists, its integration into surgical practice is neither automatic nor uniform. Cognitive biases, statistical illiteracy, professional culture, and financial incentives often outweigh the influence of published data. Thus, the failure to implement EBM is not only a problem of evidence generation—but also one of evidence adoption [12–14].

In this chapter, we aim to explore the barriers to obtaining high-level evidence in degenerative spine surgery, both due to methodological limitations and biases inherent in these pathologies. We will also discuss the human factor and cognitive biases of practitioners. Finally, the chapter explores cognitive, systemic, and educational strategies to enhance both the *production* and *uptake* of high-quality evidence in everyday surgical decision-making.

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Fig. 1.1 Three components of Evidence-Based Medicine (EBM)

1.1 Methodological and Structural Barriers to High-Level Evidence in Lumbar Spine Surgery

Despite an increasing number of trials in spine surgery over the last two decades, the overall level of evidence supporting many common interventions—particularly fusion for degenerative lumbar conditions—remains low [15]. This paradox stems from a convergence of methodological, cultural, financial, and logistical challenges that are both intrinsic to surgery and amplified within the spinal field. As a result, most guideline recommendations remain weakly graded, and surgical decision-making is often based more on tradition or local norms than on high-certainty data [5].

1. *Scientific and Methodological Limitations*

Heterogeneity of Patients and Pathologies

Lumbar spine degeneration encompasses a wide spectrum—disc herniation, stenosis, degenerative spondylolisthesis (DS), facet joint disease—with substantial variation in symptomatology, imaging, and functional impact. Randomized controlled trials (RCTs) that attempt to compare surgical strategies often pool heterogeneous populations (e.g., stable vs unstable DS), diluting treatment effects and compromising subgroup interpretation [16].

Trial Design Challenges

RCTs in spine surgery suffer from high crossover rates, and true clinical equity is hard to achieve: surgeons and patients often enter studies with strong preferences for or against surgical intervention, particularly when surgery promises immediate pain relief, non-operative care has already failed, or when fusion or decompression is viewed as "standard" in that setting.

In the SPORT trials, up to 49% of participants deviated from their allocated arm, undermining the intention-to-treat (ITT) principle [17]. Moreover, blinding is typically impossible, exposing results to performance and expectation bias—particularly when primary outcomes are subjective (ODI, EQ-5D, VAS) [18, 19].

Follow-Up and Attrition

Most RCTs have short-term horizons (12–24 months), insufficient for capturing long-term outcomes such as reoperation, adjacent segment disease, or functional decline [20–22].

Additionally, loss to follow-up is a pervasive problem. Rates of 15–30% are common in 2–5-year studies, particularly when patients change providers or drop out after symptom improvement. These losses are rarely random, and can introduce attrition bias, especially when lost patients differ in outcome trajectory from those who remain [23].

Inconsistent Outcome Measures and Reporting

A wide array of outcomes is used across trials: Function (ODI, Roland-Morris, SF-36 physical functioning), Pain (VAS leg/back, numeric rating scales), Quality of life (EQ-5D, SF-12, PROMIS), and Radiographic outcomes (slip angle, disc height, fusion status).

This lack of standardization complicates meta-analyses and limits comparability across trials [24]. Moreover, important concepts like Minimal Clinically Important Difference (MCID) are not uniformly defined or applied. Some trials report statistically significant improvements that do not meet MCID thresholds, leading to overstatement of clinical impact [25–27].

2. *Structural and Logistical Barriers*

Cost and Resource Intensity

Surgical RCTs are expensive and resource-intensive. They require coordination across surgical teams, operating theaters, and data capture systems—demanding institutional and financial commitment. Public funding often favors preventive or conservative research; industry-funded studies, meanwhile, may carry bias toward devices or implants [9, 28–31].

Logistical and Ethical Hurdles

RCTs in spine surgery face additional challenges:

- Randomizing a patient with neurological symptoms to "no surgery" can raise ethical concerns—even when evidence suggests conservative care is equivalent. Institutional Review Boards (IRBs) may hesitate to approve such designs, especially without strong pilot data.
- Patient recruitment is slow, as both patients and surgeons may be reluctant to relinquish control to a computer-generated allocation.
- Resource demands (OR time, research staff, data monitoring) are high, often discouraging surgeons from participating in trials unless they are externally funded.

Many spinal trials are single-center, underpowered, or industry-sponsored, all of which reduce the generalizability and objectivity of findings [18, 32, 33].

3. *Implications for Levels of Evidence and Establishment of Guidelines*

Because of these barriers, even well-conducted trials in spine surgery frequently receive "Low" or "Very Low" certainty ratings under GRADE [9, 34].

These limitations include:

- Serious risk of bias (non-blinding, high cross-over).
- Inconsistency across studies.
- Indirectness of populations or outcomes.
- Imprecision due to small sample size.
- Potential publication bias.

4. *Limits of Registry-Based Research*

National and institutional registries provide valuable longitudinal data on large patient cohorts. While this helps overcome RCT limitations, they introduce new risks:

Confounding by Indication

Surgeons choose procedures based on clinical nuance not captured in registries. This makes it difficult to compare outcomes fairly between treatment groups.

Data Heterogeneity and Missingness

Even well-maintained registries suffer from variation in coding, definitions, and follow-up completeness. Not all outcomes—such as subtle neurological deficits or quality-adjusted life years (QALYs)—are tracked.

Analytical Complexity

Although methods like propensity score matching, inverse probability weighting, and instrumental variable analysis (see below) attempt to correct for confounding, they cannot eliminate it entirely. As a result, such studies are graded as

"low" certainty in GRADE, even when published in high-impact journals.

The widespread implementation of registers, although promising and the subject of recent publications in high-profile journals, is undoubtedly one of the keys to future research, but strategies need to be developed to address the biases and completeness issues that have been highlighted [35–37].

1.2 Two Examples from Literature!

In order to clarify the various points raised above, we would like to give two examples from recent literature, which have already been critically analyzed by Mattei et al. in an editorial in the NASS journal [9].

Degenerative Spondylolisthesis: The Archetype of a Difficult Generalization

Since the 1990s, there has been a convergence of recommendations toward fusion for degenerative spondylolisthesis that has failed medical treatment. The literature available in high-level journals therefore confirmed this option [38]. In 2016, in the same issue of the New England Journal of Medicine (NEJM), two RCTs were published on this topic, one American [39] and the other Swedish [40] with conclusions that appeared to diverge.

The American article included 66 patients and seemed to show a slight predominance in the physical quality of life score at 2 years for the fusion group (but the values were below the MCID!). The authors reported a high revision rate after decompression alone (34%), which led critics to question the likely aggressiveness of this decompressive surgery. The power of this study was also criticized.

The European article randomized 247 patients and found no difference in scores at 2 and 5 years. It was criticized that this study did not include an assessment of instability in patients, that most fusions were strictly posterolateral and not circumferential, but that, on the other hand, decompressions were performed under minimally invasive conditions. Ultimately, readers may have been left confused by two studies with seemingly flawless methodology, published in one of the most prestigious (but non-specialized) journals, but neither of which was ultimately free from criticism. This highlighted the difficulty of generalizing results and allowed each reader to come away with a conclusion that suited their own biases and beliefs!

In 2021, in the same NEJM, a new RCT on the same subject highlighted a lack of difference in terms of the various progression scores, complications, and average length of stay between the fusion and decompression groups [41]. The conclusion was therefore that decompression was non-inferior after 2 years… a paradigm shift? Ultimately, it seems difficult to conclude, as there is no truly generalizable EBM methodology for determining which patients with degenerative spondylolisthesis could benefit from fusion in addition to decompression.

SPORT and Lumbar Discectomies: The Reality Principle Versus Randomization

Every spine surgeon has come across the sprawling SPORT (Spine Patient Outcomes Research Trial) study, funded by the NIH ($13.5 million), which (among other conditions) compared the results of surgery versus conservative treatment for patients with symptomatic lumbar disc herniation in JAMA [17]. This complexly designed project included a cohort study suggesting superiority of surgery over conservative treatment and an RCT that did not demonstrate a statistically significant difference between the operated and non-operated groups at all follow-up stages. This result can be explained by a major cross-over (50% of patients assigned to the surgical group underwent surgery at 3 months, while 30% of patients assigned to medical treatment underwent surgery during the same period).

Finally, somewhat mocking critics pointed out that, thanks to EBM standards, SPORT was only able to show that patients suffering from severe pain will undergo surgery and do well, while patients with minor disabilities will opt for conservative treatment with comparable long-term results [9]. This is a somewhat frustrating conclu-

sion, considering that this study focused on one of the most performed and well-established procedures in the field of spinal surgery: a daunting challenge for other conditions and other, far more complex techniques.

1.3 From Evidence to Operating Theater: Human Factors

Even when robust evidence exists, its influence on surgical decision-making remains limited. Cognitive biases, statistical misinterpretation, surgical culture, and systemic constraints contribute to a persistent gap between research and practice.

Cognitive Biases in Surgical Thinking
Surgeons, like all clinicians, are prone to mental shortcuts that distort how evidence is processed. These cognitive biases include: Confirmation Bias (Preference for information that supports existing beliefs), Availability Bias (Memorable cases skew perception of risk or benefit), Anchoring (Early impressions (e.g., imaging) dominate reasoning), and Outcome Bias (Good results justify decisions, even when not Evidence-Based). These biases are often subconscious, reinforced by time pressure and high-stakes decisions [14, 42].

Statistical Illiteracy
Many surgeons struggle with the basic uses of biostatistics most often learned during their initial training: interpreting *p*-values, confidence intervals, and effect sizes, applying MCID to clinical outcomes like ODI or VAS, misusing subgroup analyses, especially in underpowered trials. This limits critical appraisal and promotes anecdote-driven decisions [43, 44].

Training and Surgical Culture
Early mentorship shapes how evidence is perceived and applied:

The influence of initial training, mentoring, and the influence of local key opinion leaders can be very influential in decision-making. Hierarchical teams may discourage junior questioning or guideline uptake. Finally, cultural norms often outweigh literature in shaping practice [12, 45].

System-Level Pressures
The design of the healthcare system can influence practitioners' behaviors and decisions: Fee-for-service models favor complex surgeries financially, volume quotas and defensive medicine encourage overtreatment, and public systems may face waitlists or equipment constraints that restrict Evidence-Based options.

These structural incentives can distort guideline adherence [46, 47].

To sum up, biases and systemic pressures lead to decisions that drift from evidence—especially when the literature is neutral or contradictory, the guidelines lack strength and the local culture or patient pressure dominates.

1.4 Patient Preferences and Values

EBM aims to integrate patient preferences and values into clinical decision-making. However, in spine surgery, patient expectations and willingness to accept risks can vary considerably and conflict with what the best available data suggest. It is difficult, but crucial, to strike a balance between the evidence and patient-specific factors [48].

Integrating patient preferences and values into spinal surgery poses several challenges:

Variability in Preferences
Patient preferences can vary greatly depending on individual circumstances, cultural background, pain tolerance, expectations of surgery, and personal values. For example, some patients may prioritize a quick return to work over long-term health outcomes, while others may prefer non-surgical options to avoid the risks associated with surgery, despite a potentially slower or less complete recovery [49].

Barriers to Communication
Language differences, health literacy levels, and patient discomfort discussing personal values or

questioning medical recommendations can impair shared decision-making [48].

Complexity of Information

Spinal surgery options often involve complex information that can be difficult for patients to understand. Decisions may include technical details about surgical risks, potential benefits, alternative treatments, and possible outcomes, making it difficult for patients to fully grasp the implications of their choices [50].

Decision Conflict

Patients often face decision conflict when surgical options are associated with both significant benefits and serious risks. Anxiety about making such an important decision can affect their ability to make choices that truly reflect their personal values and preferences [51].

In order to optimize the integration of these parameters, it is necessary to develop shared decision-making, a process in which clinicians and patients work together to make decisions. This approach uses decision-making tools (brochures, videos, or interactive online formats) and is particularly useful in spinal surgery to clarify complex issues [51].

It might also be a good idea to improve communication skills training for different healthcare providers to help them better understand how to get and understand patients' preferences. Suggesting a second opinion isn't necessarily a bad thing for the doctor-patient relationship and can add some transparency to a complex discussion involving neurological and/or life-threatening risks to resolve functional discomfort [52]. Finally, regular and structured follow-up ensures that treatment remains consistent with the patient's preferences, particularly when circumstances and values change over time.

1.5 Roadmap for Better Evidence and Uptake

Improving evidence in spine surgery requires two parallel efforts: generating more relevant data and ensuring its real-world application.

Pragmatic Trials for Real-World Use

Classic RCTs often lack generalizability. Pragmatic trials, by contrast, reflect clinical reality: broad inclusion criteria, flexible interventions within care standards, comparisons with usual care.

Designs like cluster-randomization (random assignment of treatments is done at the level of clusters of participants, rather than individual participants) or stepped-wedge trials accommodate preferences and promote feasibility [53, 54].

Registry-Based Randomized Trials (R-RCTs)

R-RCTs integrate randomization into routine registry platforms, like SweSpine and NORSpine, offering: Lower costs and high external validity, long-term follow-up capacity, real-world patient diversity and feasibility of adaptive design [55, 56].

A major challenge remains: Data must be complete, standardized, and reliable to draw valid conclusions.

Improving Observational Evidence

When RCTs aren't feasible, observational series can be offered, keeping in mind that observational data remains vulnerable to unmeasured confounding. However, advanced methods can enhance observational studies, including: propensity score techniques, inverse probability of treatment weighting (IPTW) and instrumental variable analysis, sensitivity analyses to test robustness [57–60].

Core outcome sets (e.g., ODI, EQ-5D, reoperation) should therefore be standardized to enhance comparability.

Bridging the Implementation Gap

Even strong evidence often fails to influence practice. Solutions from implementation science include: audit & feedback (benchmarking outcomes vs peers), decision-support tools embedded in electronic health record, shared decision-making via patient education and option grids, EBM leadership & training (from journal clubs to local EBM champions), etc. These approaches shift focus from knowledge to behavior change [61, 62].

Incentive Alignment and Policy Levers

Change is most effective when clinicians and systems are aligned in their goals. Strategies include: pay-for-performance models based on outcomes, not procedure volume, bundled payments that reward high-value care rather than surgical complexity, policy incentives for participation in registries and RCTs (e.g., funding tied to data contribution).

Health systems that reward evidence-concordant care will help accelerate adoption and reduce unwarranted variation in spine surgery [63, 64].

1.6 Conclusion

Over the past two decades, the pursuit of Evidence-Based practice in lumbar degenerative spine surgery has evolved from aspiration to incremental reality.

Yet despite these advances, the field continues to grapple with methodological limitations, cultural inertia, and significant variability in care. High cross-over rates, inconsistent outcome measures, and limited long-term data have prevented many studies from reaching high levels of evidence certainty. Meanwhile, the translation of existing knowledge into practice is hindered by cognitive biases, gaps in statistical literacy, and misaligned incentives.

True Evidence-Based medicine in spine surgery requires more than trials and meta-analyses—it requires a system that embraces critical thinking, values transparency, and empowers both patients and providers to make informed choices. It means training surgeons not only to operate skillfully, but to reason with rigor. It means building infrastructure for pragmatic research and fostering a culture that respects both scientific data and clinical nuance.

The science may tell us what works on average, but wisdom lies in knowing when your patient *is* the average—and when they are not. The next decade must focus not only on generating better evidence, but also on bridging the gap between what we know and what we do.

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2 Imaging of the Degenerative Lumbar Spine

Olivier Hamel and Jean-Marc Vital

The spinal column is a composite whole, comprising a container with the vertebrae made up of compact bone and cancellous bone, linked by Junghanns' mobile intervertebral segment, which includes the intervertebral disc and the intervertebral ligaments. There is also a content including the spinal cord and, in the lumbar region of interest here, the spinal roots, forming the cauda equina, and their meninges.

In the context of lumbar degenerative pathologies, it must be kept in mind that analysis of images must be balanced by knowledge of natural aging, which is perfectly described and often asymptomatic, and by the data from a clinical examination without radiological a priori. As Gérard Morvan says, "without imaging, the clinical examination is blind, but without clinical examination, imaging is crazy."

This chapter on diagnostic radiology is representative of the multiple options available to clinicians when dealing with this multifaceted degenerative lumbar pathologies. The question arises as to which examinations should be chosen to explore which anatomical structure and/or which pathology?

2.1 Which Examinations, Which Indications?

First of all, we need to differentiate between an etiological assessment of pain, which in this degenerative nosological context can be summed up by MRI, and a pre-therapeutic assessment, which should enable us to make the best choice among multiple treatment options, and may call on a wider range of imaging examinations.

(i) It seems more logical to start with *MRI*, even though it is the most costly and least accessible of all radiological examinations. Its final drawback is that it is performed in the decubitus position. Lumbar segment loading systems have been developed but are not widely used. Despite this, MRI is the main examination and the first to be carried out in cases of low back pain or lumboradicular pain resistant to medical treatment, outside a specific context (non-mechanical pain, present at rest or during the night; unexplained weight loss, history of cancer; presence of febrile syndrome; alteration of the general condition) which would lead to a more accessible CT-scan. Nevertheless, in the context of degenerative lumbar pathology, there is an emergency indication for MRI: cauda equina syndrome. MRI analysis of the lumbar spine is quite complete for the container, essential for the neurological content. It

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allows us to answer most etiological questions and make therapeutic decisions in many cases. The examination should include a 3D T2 sequence for reconstruction, a sagittal T1 sequence and a sagittal STIR sequence. The systematic use of a "de Sèze STIR," which explores essentially sacroiliac joints, is questionable, especially if it replaces a sagittal sequence, which is more effective in analyzing intervetebral discs and vertebral endplates. T1 sequences with contrast injection are not necessary in the first instance, but remain indispensable if an intradural lesion is discovered, or a history of disc surgery. MRI analysis of the lumbar spine is virtually complete for the content, and above all essential for the neurological content. It allows us to explore many etiologies and make therapeutic decisions in most cases. *Spectro-MRI* of intervertebral discs is still in progress and may be useful by the detection of some metabolites within the disc, correlated with painful disc.

(ii) *CT-scanner* provides unrivaled bone analysis, particularly of the subchondral bone which is of most interest in degenerative pathology. The degeneration of the various intervertebral joints can be assessed in a similar way to MRI, but the degeneration that results in an aeric density within the joints and intervertebral disc is much better visualized by CT. Both bone and soft tissue filters can be used. The latter are more interesting for content analysis (vertebral canal and intervertebral foramina), but are of inferior quality to MRI, especially in obese patients. It does, however, provide the best possible assessment of any calcification of a compressive tissue process. Limitations of CT-scan are the patient's decubitus position and the radiation exposure, which can be problematic in pregnant women.

(iii) *Lumbar X-rays* are the oldest means of exploration, easily accessible, low-cost but irradiating. Using the same physical principle, they obviously analyze the same densities as CT-scans. Plain X-rays are no longer indicated in the primary assessment of low back pain or lumboradicular pain, but are still of interest in the pre-therapeutic assessment, especially for studying relationships between spinal segments.

- Three types of segmental views can be requested: *Lateral, AP and 3/4 views*, which are less commonly used, but which allow the posterior arch to show the image of La Chapelle's "small dog" (Fig. 2.1) and, in particular, to clearly visualize the isthmus, which corresponds to the neck of the small dog ruptured in the event of isthmic lysis. More specifically, the lumbosacral junction can be explored using the "De Sèze cliché" with ascending beam. This also enables visualization of the coxofemoral and sacroiliac joints, whose pathologies may be interrelated with those of the lumbar spine. All these radiographic images are of particular interest in standing position. Vertebral alignment can be compared between X-rays and lying position examinations, but the search for degenerative instability may require dynamic lumbar X-rays.
- *Dynamic lumbar X-rays*, under load, realized in the sitting or standing position, considered as the gold standard for diagnosing the presence of degenerative instability. Numerous authors describe their techniques. For flexion-extension, which is the most studied sector, we can cite Putto [1], Wood [2], Dupuis [3] and Hayes [4], Putto's technique being the most reproducible. Associated lateral tilt views proposed by Dvorak [5] are less widely used than flexion-extension views. On the latter, we look for signs of instability such as a forward displacement of the posterior wall of more than 3 mm and angles between the vertebral plates greater than 17° in L4–L5 and 11° in L5–S1 (Figs. 2.2, 2.3, and 2.4). In fact,

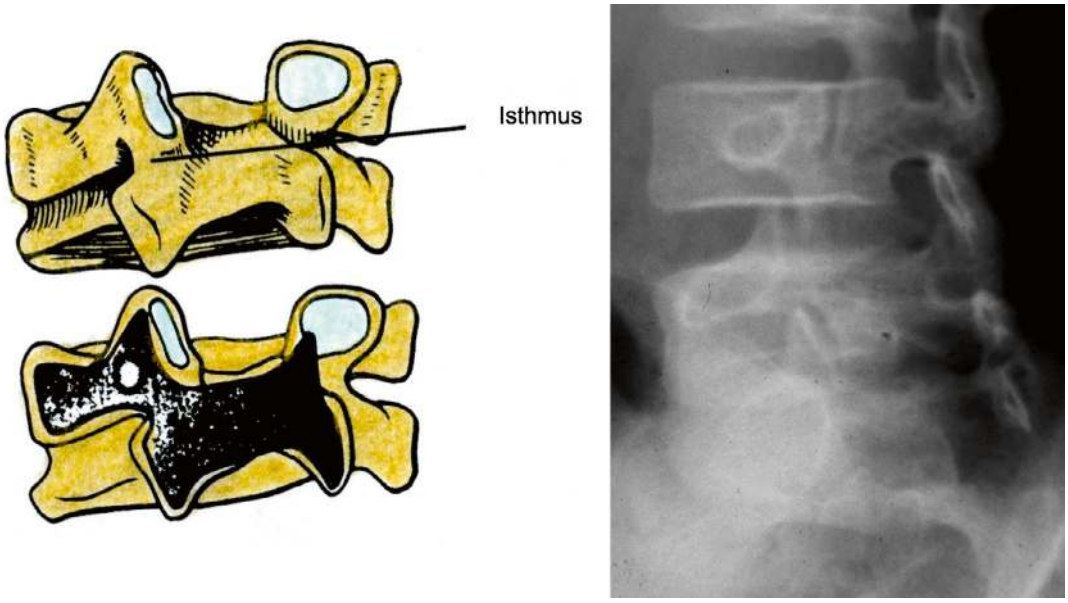

Fig. 2.1 3/4 view X-ray

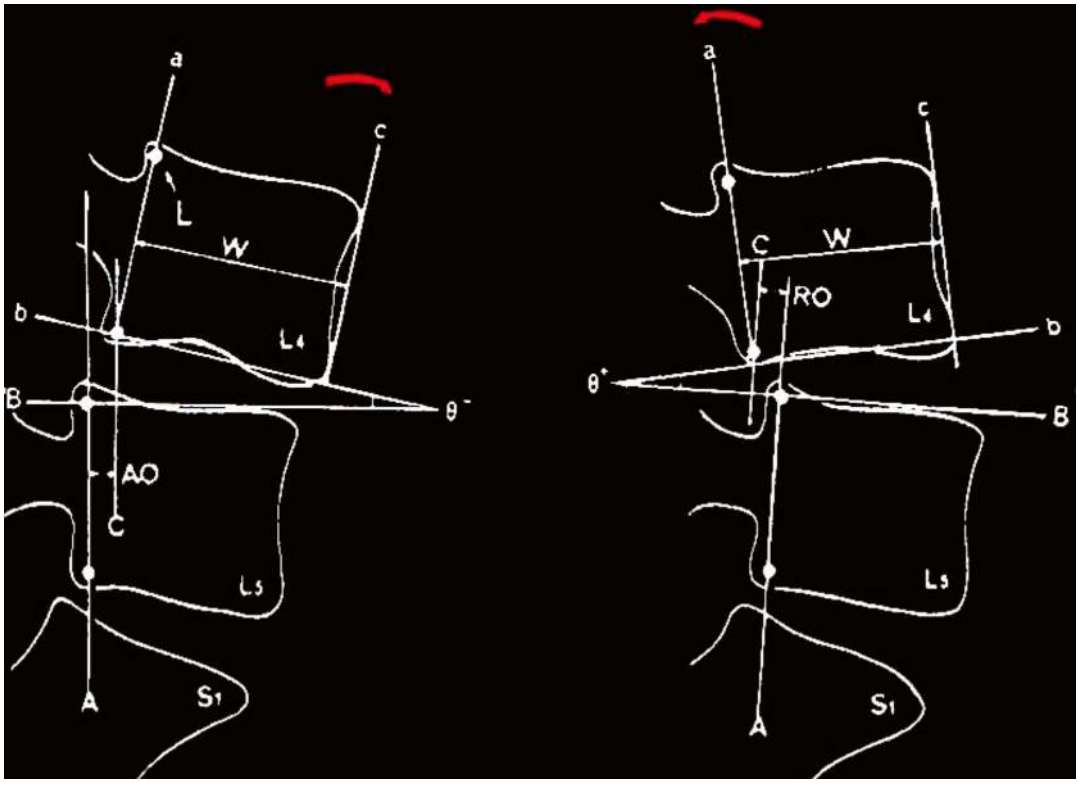

Fig. 2.2 Measurements on dynamic lumbar lateral view

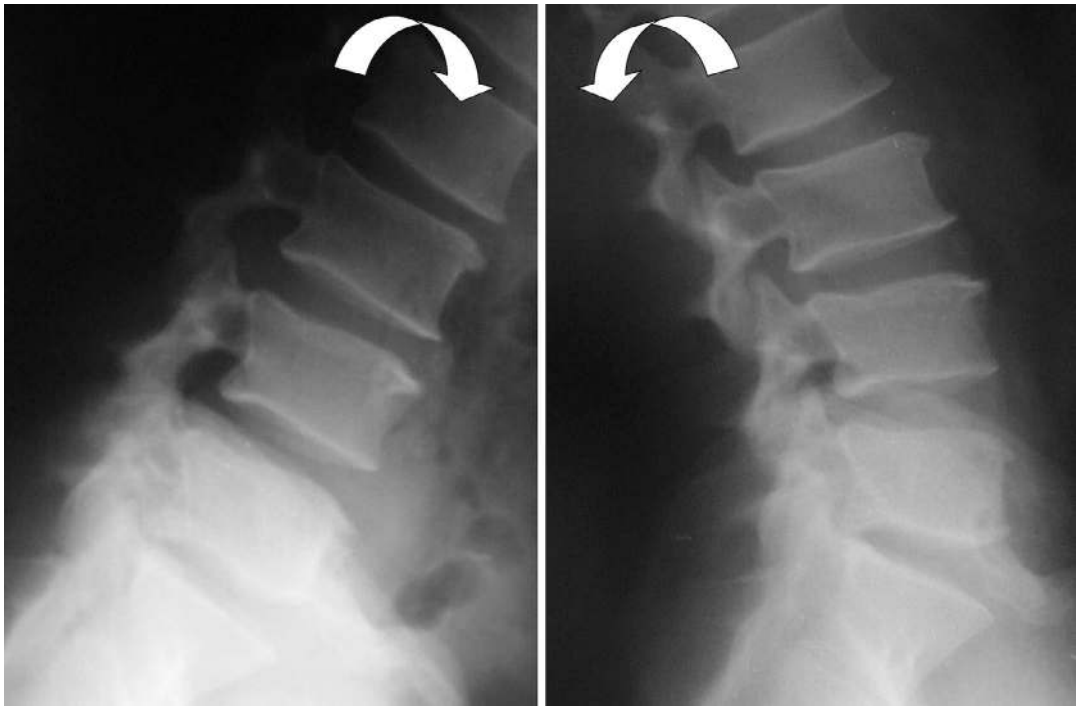

Fig. 2.3 Normal dynamic flexion-extension lateral X-rays

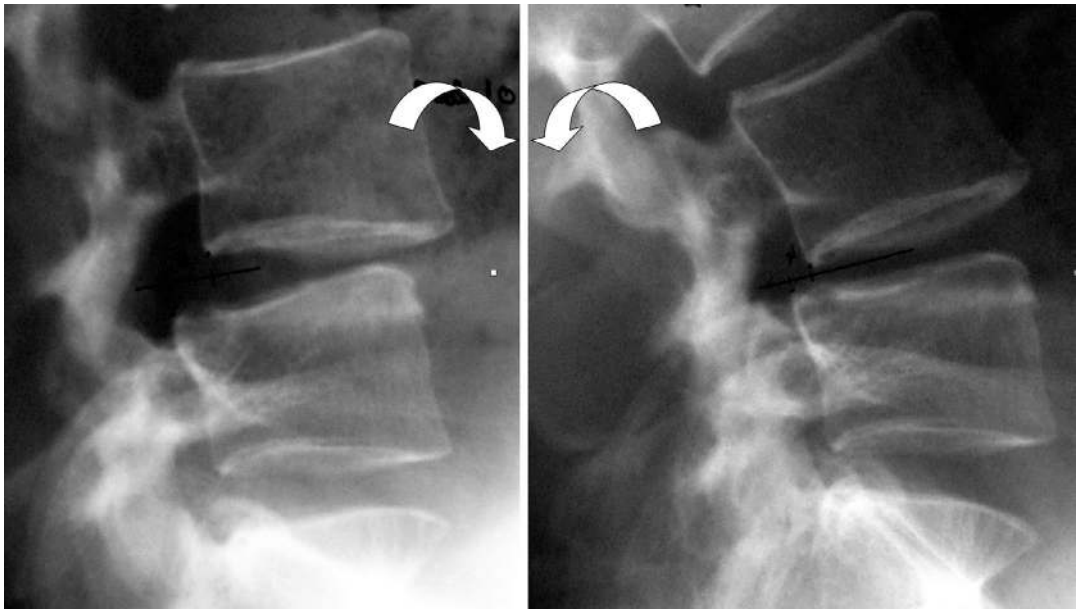

Fig. 2.4 L4–L5 degenerative instability on dynamic X-rays

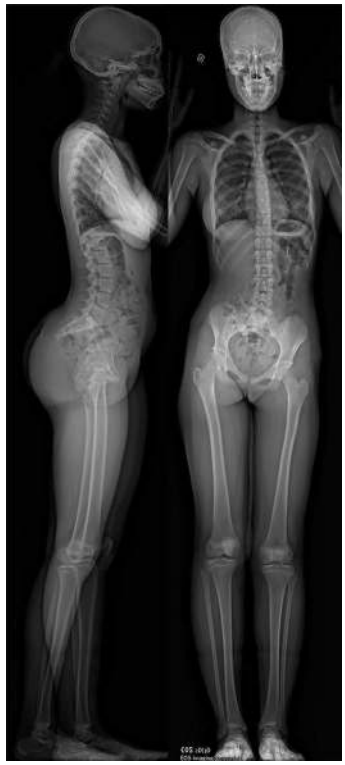

Fig. 2.5 Lateral and AP EOS views

with degeneration, hypomobility is most often observed.

- *Digital tomosynthesis*, developed for breast exploration, is a medical imaging modality with high spatial resolution and radiation levels similar to radiography. Some teams begin the use of tomosynthesis in spinal indications and may be of interest for exploring the foraminal region under load [6].
- Analysis of the entire spinal column may be necessary, even in the case of segmental pathology, using *teleradiography* (also AP and lateral views) to study spinal deformities. This study of frontal and sagittal spinal alignment can now be carried out, with considerably less radiation, by means of images on.
- The *EOS system* (Fig. 2.5), developed by Georges Charpak (Nobel Prize for Physics in 1992) [7]. The physical principle is the wire chamber, which replaces planar sensors with a scan based on the linear gas detector. Despite this, it has two limitations: the 20-s vertical scan, which can result in artificial "moving" deformation images, and the reduced field of view associated with a 50 cm anteroposterior diameter, which can limit the analysis of large anterior imbalances. The EOS system provides not only 2D images, but also 3D images, which make it easier to recognize dislocations, since the subject is once again radiographed standing up, and intervertebral rotations, thanks to the use of vectors described by Illès [8].

(iv) Two additional imaging techniques, combining radiography and scans, are more invasive regarding that they require iodine injections either in the cerebrospinal fluid (saccoradiculography and saccoscanner) or in the disc (discography). Arthrography of the interapophyseal joints in search of synovial cysts is no longer necessary, unless associated with infiltrative therapy.

- *Saccoradiculography* is interesting for its dynamic and weight-bearing nature (Fig. 2.6), but indications must remain rare: contraindication to MRI or MRI analysis made difficult by previous surgery (stainless steel implants, disc prostheses, etc.). The quality of saccoscanner images is close to that obtained with T2-weighted MRI sequences for analysis of the spinal canal.
- *Discography* consists of an intradiscal injection which, coupled with a CT-scan, enables analysis of disc fissures. Its main aim is to reproduce pain through the pressure of the injection, in order to determine whether the disc being tested is actually the source of chronic pain (Fig. 2.7). However, the value and reliability of this technique are still debated, all the more so as MRI provides excellent information on the hydration of discs and subchondral bone.

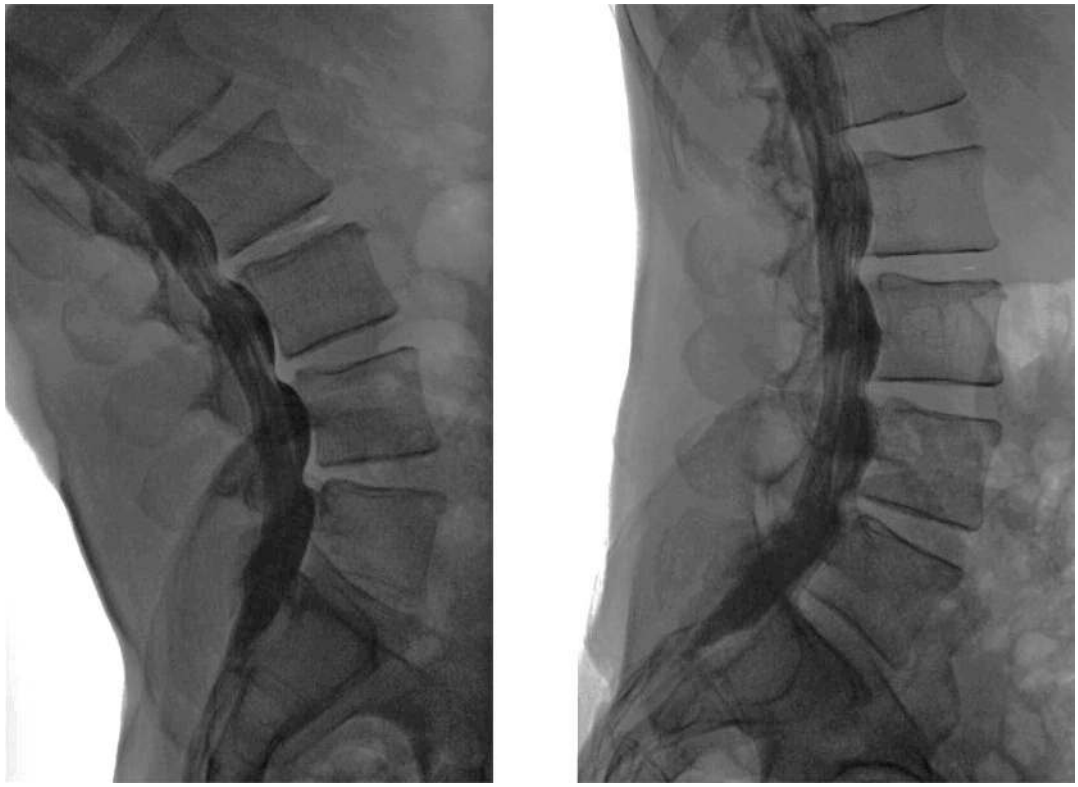

Fig. 2.6 Saccoradiculography in standing position and extension

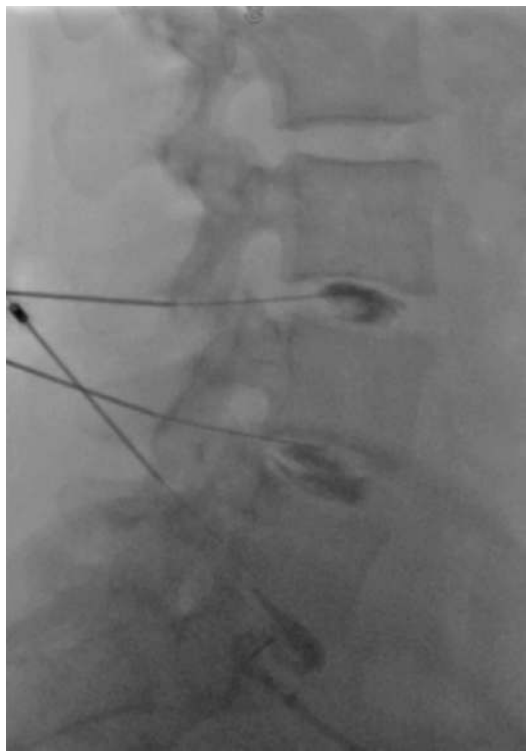

Fig. 2.7 Discography with multiple successive injections in order to reproduce pain

(v) "Non-morphological" imaging techniques are sometimes used in the assessment of degenerative lumbar pathology.

- This is the case with *bone scintigraphy*, which requires the injection of a biphosphonate combined with technetium 99, and enables the identification of bone structures with high osteoblastic activity. The sensitivity of this metabolic imaging is high, but its specificity is low, although improved by coupling with CT scanning. It can be used to detect vertebral areas where degenerative damage predominates. It may also be of interest in postoperative assessment.
- Finally, *osteodensitometry*, a form of X-ray, is used to assess bone density, particularly in the lumbar region. The search for osteopenia or osteoporosis may be necessary prior to surgical management,

including placement of intra-spinal implants.

2.2 Exploration of the Container

(i) The *vertebral body* is the structure that takes up the most space, whatever the examination. X-rays and CT-scans are particularly useful for assessing the shape, normally quadrangular, and bone density of this ventral part of the vertebra. The ratio between height and transverse diameters gives these bodies an almost square appearance (with the exception of the L5 vertebra, which has a body that is higher anteriorly than posteriorly) (Fig. 2.8). Repeated mechanical stress, particularly during growth, gradually makes these vertebral bodies more rectangular. Particular attention should be paid to the subchondral bone immediately nearby the vertebral endplates, which may be marked by an intraspongiosa herniation (Schmorl's nodule) or a condensation reaction to disc degeneration, without any specificity. In axial CT views, they form a clear lacuna, in contact with vertebral endplate, and with a peripheral border of osteosclerosis (Figs. 2.9 and 2.10). The vertebral corners, where the endplates meet the anterior and posterior walls, should be sharp and pointed; their blunting is pathological and often linked to an anomaly of the annular ring. The vertebral endplates may be prolonged by the presence of pressure-reactive osteophytes. These osteophytes, whether anterior or lateral, may lead to spontaneous fusion, with no real pathological character and leading instead to an improvement in pain (Kirkaldy-Willis restabilization [9]) (Fig. 2.11). They should not be confused with Mac Nab enthesophytes, located a few millimeters above or below the anterior corners of the vertebral bodies. They are linked to traction on the ventral longitudinal liga-

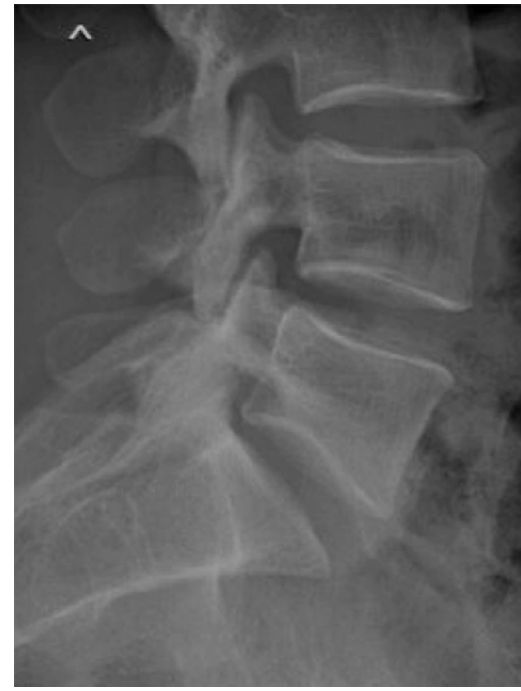

Fig. 2.8 Shapes of vertebral bodies (especially L5) on lateral X-ray

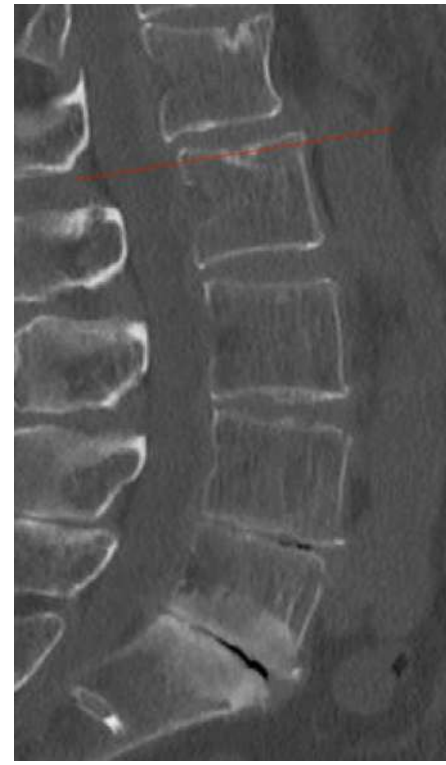

Fig. 2.9 Schmorl's herniation on sagittal CT-scan view

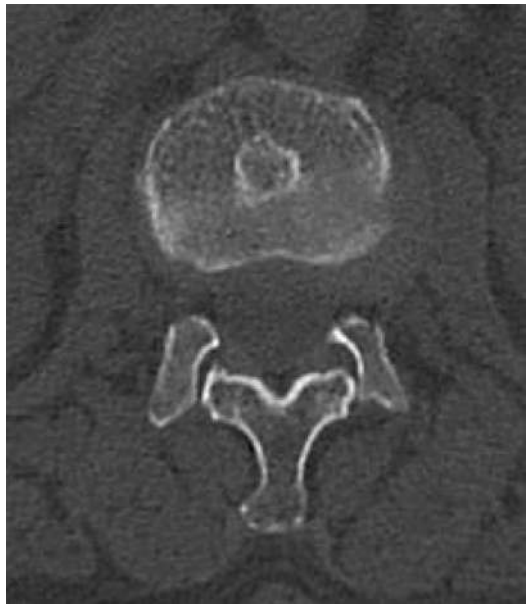

Fig. 2.10 Schmorl's herniation on axial CT-scan view

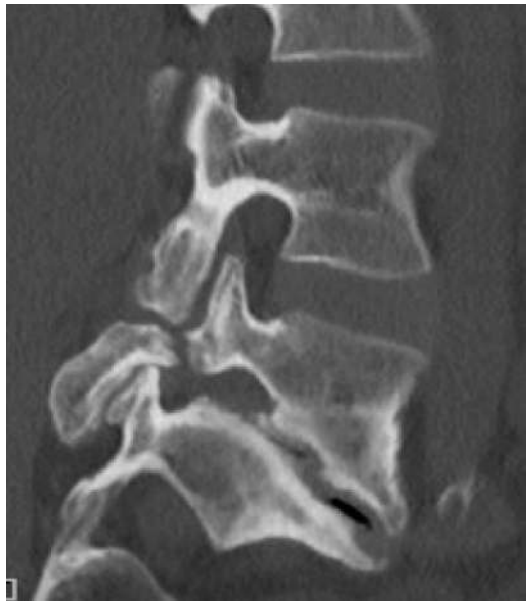

Fig. 2.11 Pressure-reactive osteophytes associated with isthmic spondylolisthesis (Sagittal CT-scan view)

ment, indicating potential segmental instability [10] (Fig. 2.12).

MRI can also be used to assess the degenerative evolution of vertebral bodies by analyzing the subchondral bone reactions

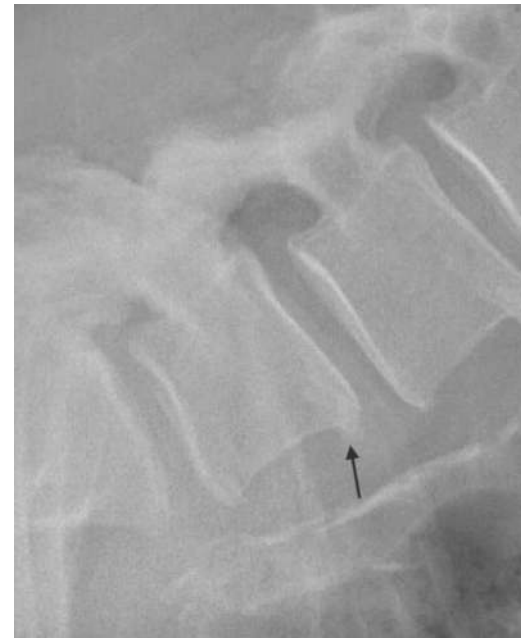

Fig. 2.12 Mac Nab enthesophyte on dynamic lateral X-ray

described by Modic, whose classification [11] is a benchmark for characterizing peridiscal bone, distinguishing:

- An inflammatory stage (stage 1) defined by a T1-weighted hyposignal, a T2-weighted hypersignal (even more pronounced in STIR sequences) and possible contrast after gadolinium injection (Fig. 2.13),
- A fatty involution stage (stage 2), defined by a T1 and T2 hypersignal, most frequently found (Fig. 2.14),
- A sclerotic stage (stage 3) characterized by a T1 and T2 hyposignal, rarer (Fig. 2.15).

There is a continuum between the different stages, with an intermediate stage between Modic 1 and 2. In these situations, the STIR sequence helps to determine the persistence of peridiscal inflammatory phenomena.

The onset of these abnormalities appears to be correlated with age [12], with progression generally from stage 1 to stage 2, and

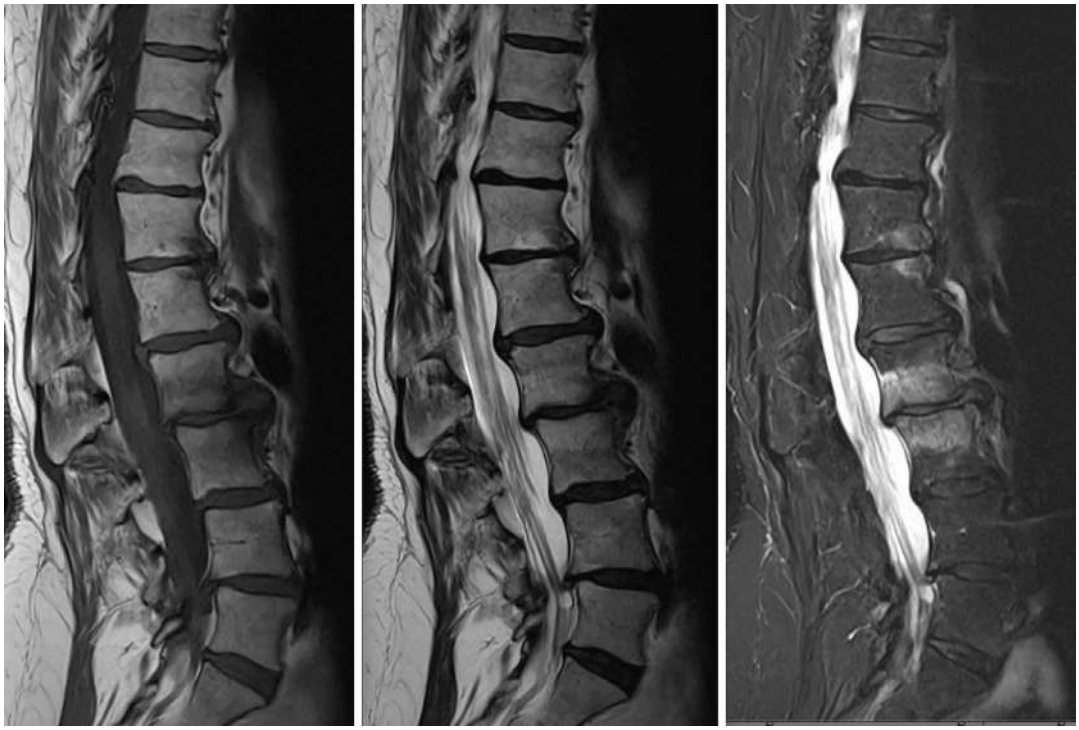

Fig. 2.13 L2–L3 Modic 1 changes on sagittal T1-, T2-, and STIR-weighted images

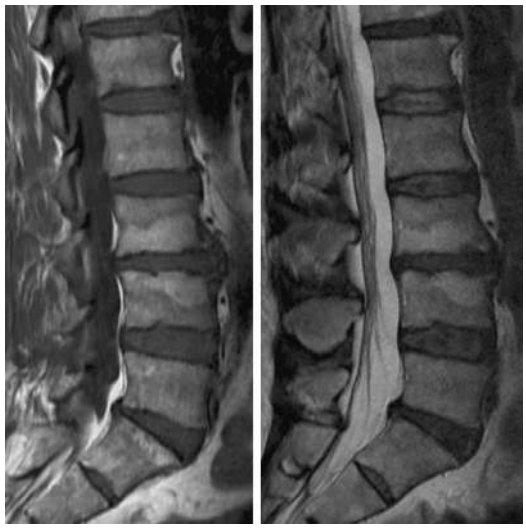

Fig. 2.14 Modic 2 changes on sagittal T1- and T2-weighted images

sometimes to stage 3; however, reverse reconversion has also been reported [13].

However, it is stage 1 that is the focus of most attention. It appears to be associated with histological and biochemical changes, confirming its inflammatory nature with proliferation of nerve endings [14]. It appears to be seven times more frequent in patients with low back pain [15], although this has been called into question. There should be no doubt about the painful nature (not always, of course) of Modic 1 compared with Modic 2, which corresponds to the healing of Modic 1.

(ii) Because of its radiolucency, *the intervertebral disc* is poorly studied by radiography. Apart from disc loss of height, which suggest a loss of lumbar lordosis, lumbar lateral views can sometimes reveal the presence of intra-disc calcifications, which may indicate intervertebral fusion (Fig. 2.16), or, conversely, the presence of air (or nitrogen), which indicates relative intervertebral abnormal mobility. Radiographic classifications of disc degeneration are numerous. In addition to disc height, peridiscal bone reactions are also taken into account.

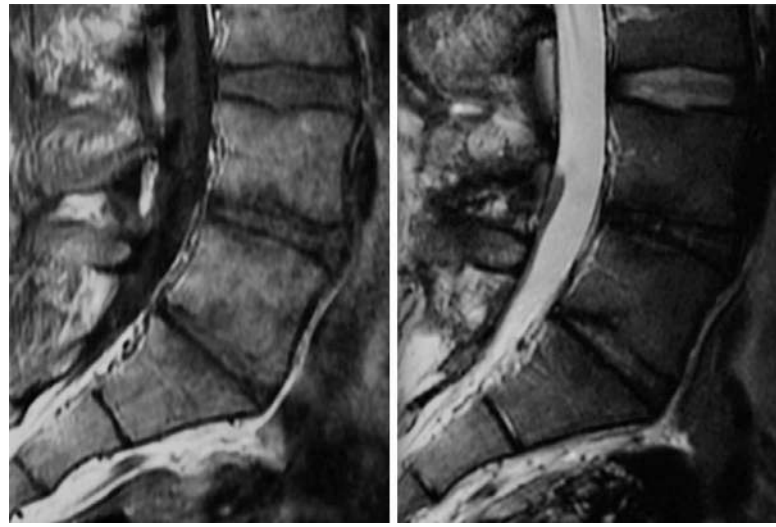

Fig. 2.15 L4–L5 Modic 3 changes on sagittal T1- and T2-weighted images

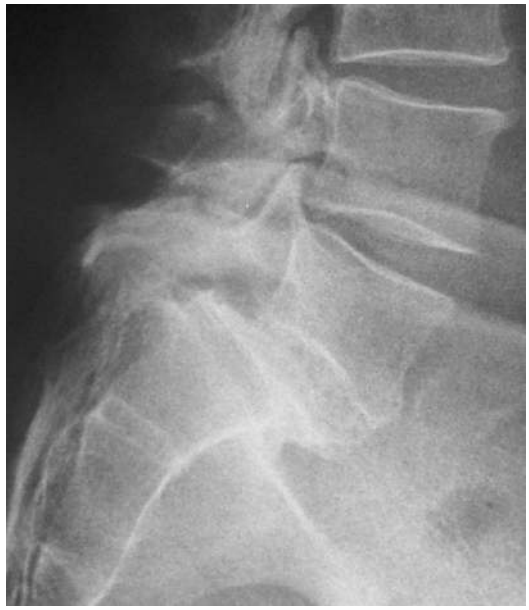

Fig. 2.16 Calcifications of the L5S1 disc showing its fusion

We refer here only to Lane's classification [16], which has proven to be reproducible.

CT-scan offers only a few more than plain radiographs, apart from the possibility of reconstruction and good visualization of intradiscal gas (Fig. 2.17), called vacuum phenomenon, which can sometimes contaminate the canal spaces (Fig. 2.18), and often associated with segmental instability [17]. A spread of the intervertebral disc can be appreciate on axial views, subchondral bone sclerosis is best demonstrated on sagittal reconstructions. CT-scan is also the best examination for disc calcifications, peripheral or central, of no clinical significance (Fig. 2.19).

MRI is the most suitable examination for disc analysis, as it allows us to assess the state of hydration of the disc. Disc degeneration is assessed using Pfirrmann's classification [18] on sagittal T2-weighted or STIR sequences (Fig. 2.20). Grade 1 corresponds to a healthy disc, a situation rarely observed in adulthood. The normal hyperintense signal of the nucleus pulposus is highly correlated with the proteoglycan concentration and signal loss of the disc correlates with progressive degenerative changes [18]. The specifics of the other stages are described in Fig. 2.12. Pfirrmann's grades correspond broadly to Thompson's grades anatomic classification. This classification is perfectly reproducible from one observer to another. The higher stages can be subdivided by the modified Pfirrmann classification [19].

Axial T2-weighted images may show annular tears in the fibers of the annulus fibrosus. A small amount of fluid through these annular tears is responsible for high signal intensity; however, annulus fibrosus

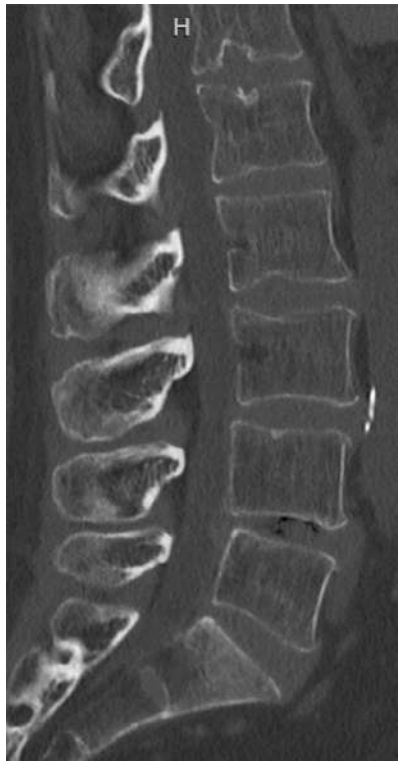

Fig. 2.17 Small amount of intradiscal gas which can only be seen on CT-scan

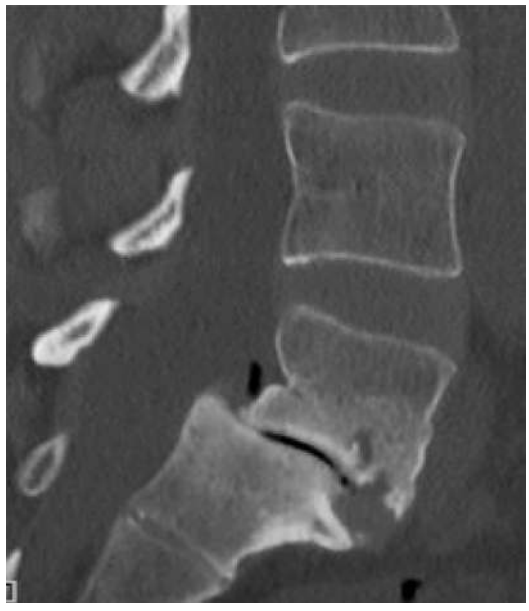

Fig. 2.18 Intradiscal gas contaminating the spinal canal on sagittal CT-scan view

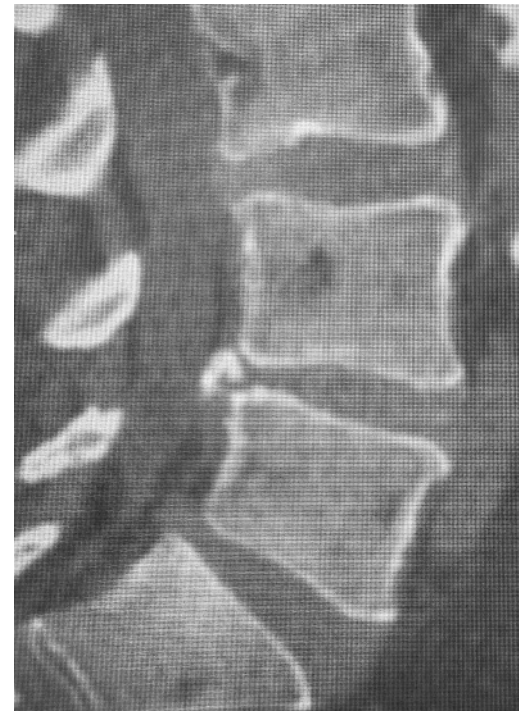

Fig. 2.19 Discal herniation calcification on sagittal CT-scan view

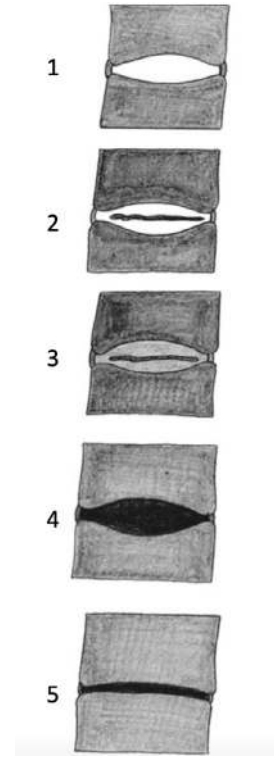

Fig. 2.20 Pfirrmann's grades of intervertebral disc degeneration

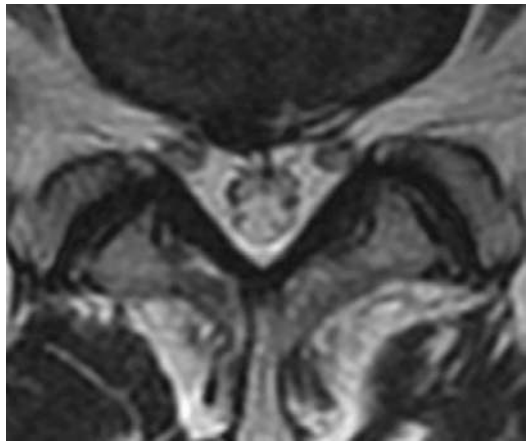

Fig. 2.21 HIZ on T2-weighted axial image

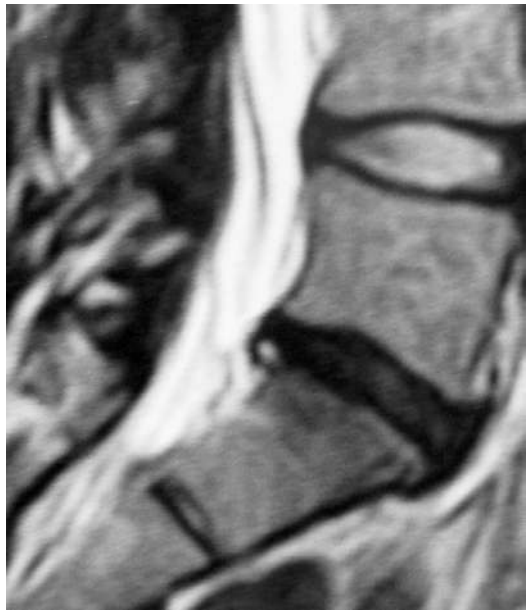

Fig. 2.22 HIZ on T2-weighted sagittal image

material is not displaced [20]. Annular tears can be circumferential, peripheral rim, and radial, and are visualized as a T2-weighted HyperIntense Zone (Figs. 2.21 and 2.22). Fissures do rarely change on MRI over time and therefore cannot indicate the age of the lesion [21].

Intersomatic gas is only visible if abundant, essentially like hyposignal in sagittal T1-weighted images, but this signal is identical to calcifications (Fig. 2.23). Future

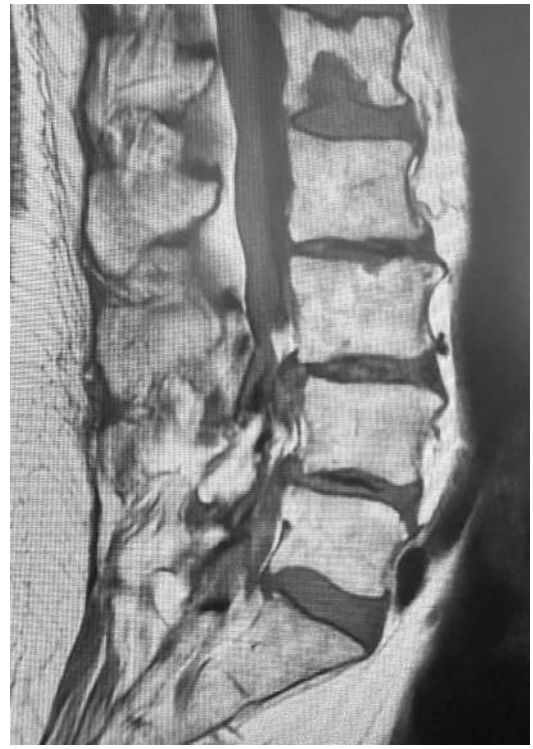

Fig. 2.23 L4–L5 vacuum phenomenon (and L1 Schmorl herniations) on sagittal T1-weighted image

analysis may use MRI spectroscopy and particularly the lactate/proteoglycan ratio which can assess disc degeneration from another angle than hydration status or height [22].

Discography has seen its indications diminish in the face of MRI; there are morphological classifications which are of less value than the phenomenon of pain reproduction on injection [23]. Discography had also been used to diagnose the recurrence of a herniated disc, with opacification of a pocket and typically a cocoon image of the hernia in the pocket (Fig. 2.24), but it is still an examination that has all but disappeared in the face of MRI with gadolinium injection.

The main intervertebral disc pathology, investigated and described, is disc herniation, a generic and over-generalized term defined as "a portion of an intervertebral disc outside the limits of its normal anatom-

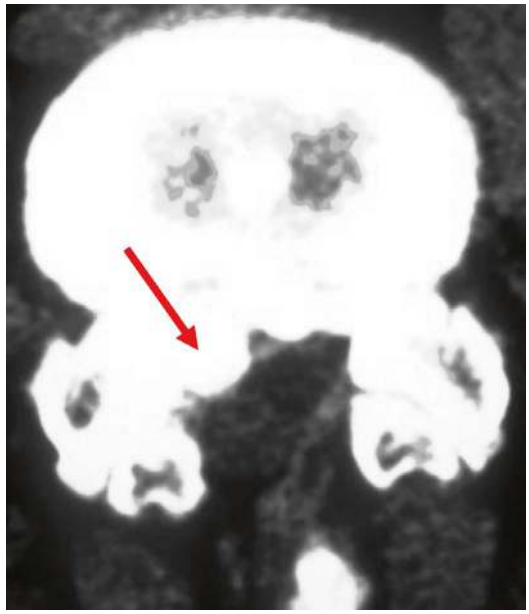

Fig. 2.24 CT-discography image showing a disc pocket in a herniation recurrence assessment

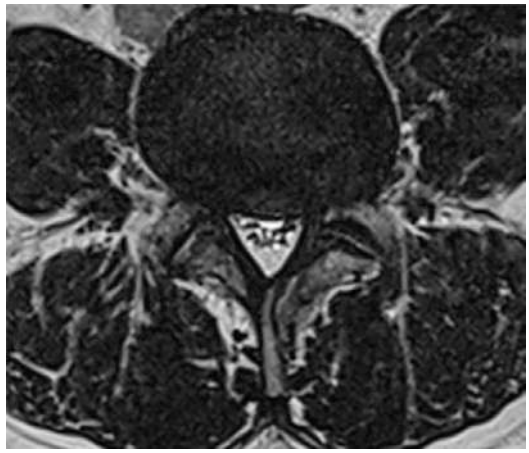

Fig. 2.25 Concentric disc protrusion, on axial T2-weighted view

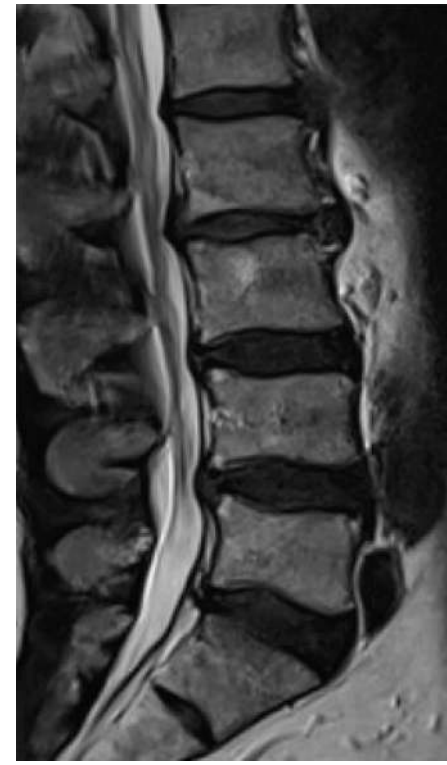

Fig. 2.26 Multiple protrusive disc disease on sagittal T2-weighted view

ical situation." On axial sections, we can describe a global, concentric disc protrusion beyond the limits of the vertebral endplates, without rupture of the disc curvature (Fig. 2.25). In the case of focal protrusion of the posterior disc the term "herniation" is often used. This term is unsuitable, however, as it may include morphological abnormalities that are clinically asymptomatic. Exact description of a herniated disc requires three-dimensional analysis in CT or, even better, in MRI, to determine whether there is a good radioclinical match between the position of this herniation and the radiculopathy defined by the pain described and any sensory, motor or reflex abnormalities.

First, the anteroposterior plane is analyzed to characterize the extent of damage to the posterior part of the annulus fibrosus and the extent of displacement of the nucleus pulposus. On CT or MRI, we can distinguish the disc protrusion (protrusive disc disease) (Fig. 2.26), or a true subligamentary (Fig. 2.27) or excluded herniation (Fig. 2.28), sometimes between the two (transligamentary herniation) (Fig. 2.29) which could be small but painful herniation. In the right-to-left transverse plane, the hernia is described as median or central (10% of cases, often asymptomatic from a radicu-

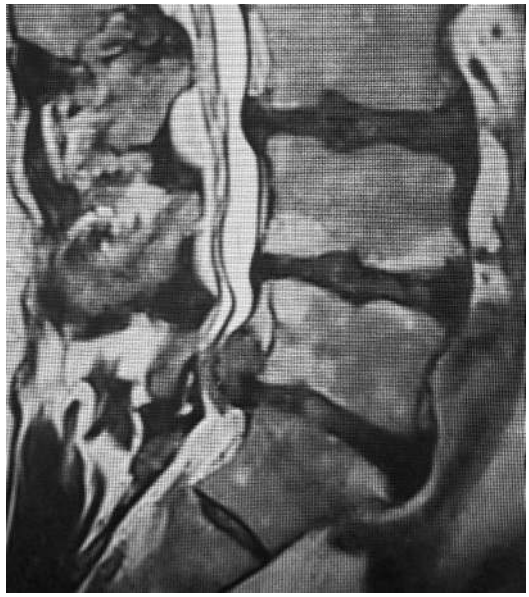

Fig. 2.27 Subligamentary discal herniation on sagittal T2-weighted view

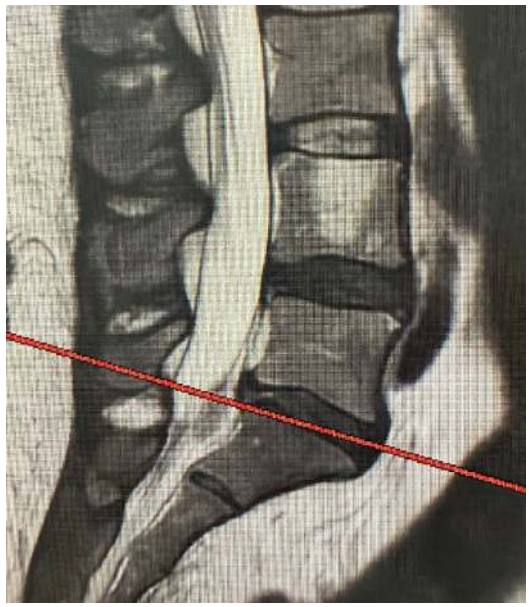

Fig. 2.28 Extruded discal herniation on sagittal T2-weighted view

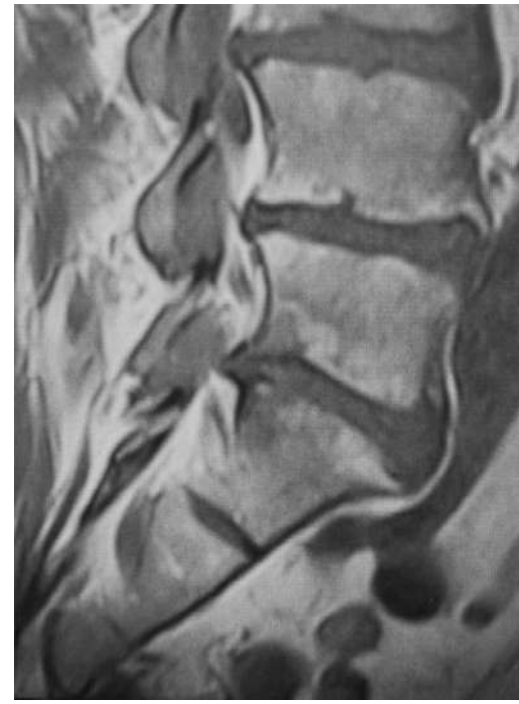

Fig. 2.29 Transligamentary discal herniation on sagittal T2-weighted view

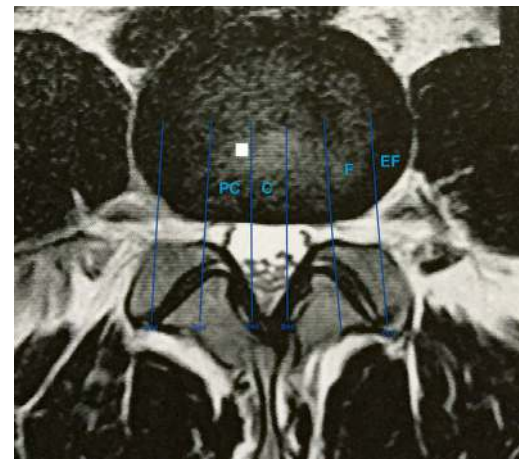

Fig. 2.30 Possible herniation locations on axial T2 (C: central, PC: paracentral, F: foraminal, EF: extraforaminal) which may be associated each other

lar point of view), posterolateral (paracentral), foraminal or extraforaminal (10% of cases) (Fig. 2.30). Large median hernias may be difficult to distinguish from the cul-de-sac on CT-scan, especially in cases of suspected cauda equina syndrome. Finally, in the sagittal plane, possible downward migration within the lateral recess (Fig. 2.31) or upward (in conflict with the root axilla) migration is described (Fig. 2.32). The limit

of sagittal sections is the analysis of the extraforaminal region. The same herniation may have several of these locations, resulting sometimes in a compression of two adjacent spinal nerve roots and hence a biradiculopathy [24]. The calcified nature of the herniation may be related to a history of marginal listel detachment or sometimes intradiscal injections, particularly of hexatrione.68. Some differential diagnoses need to be considered [25]. Migrated herniation may suggest a schwannoma or other epidural tumor, but the contrast enhancement on MRI is discriminating (Fig. 2.33, same case as Fig. 2.28). There is also bone scalloping, with circumferential enlargement of the foramen in the case of schwannoma. It is also, and above all, the clinical history that differentiates these pathologies. The presence of a fibrotic and lateralized arthrosynovial cyst, an epidural venous ectasia (which generally does not exert any mass effect), a radicular cyst on CT-scan (but MRI shows the liquid content), an anomaly of the radicular emergences, especially in L5–S1 (with a common origin of the L5 and S1 roots) is sometimes evoked (Fig. 2.34).

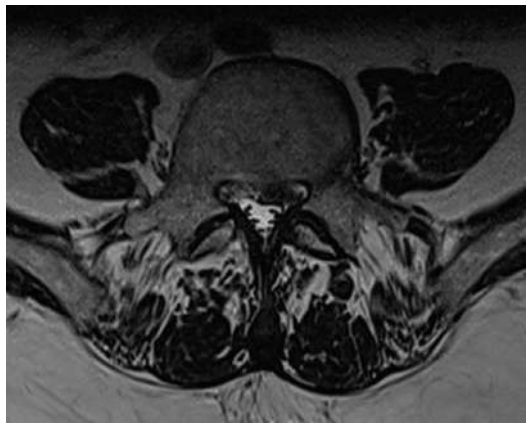

Fig. 2.31 Discal herniation with downward migration within the lateral recess on axial T2-weighted view

As the L5 vertebra, the L5–S1 disc is normally clearly lordotic. Transitional abnormalities of the lumbosacral junction result in the presence of a thin L5–S1 disc, whose vertebral endplates are usually parallel, with no marginal degenerative changes (Fig. 2.35), confirmed by a radiological AP view, or coronal reconstructions, showing fusion of the last lumbar vertebra to the sacrum with mega-transverse processe(s). The fusion may be complete or there may be a transverso-sacral or transverso-iliac joint (Bertolotti syndrome). To determine whether this is a lumbarization of S1 or a sacraliza-

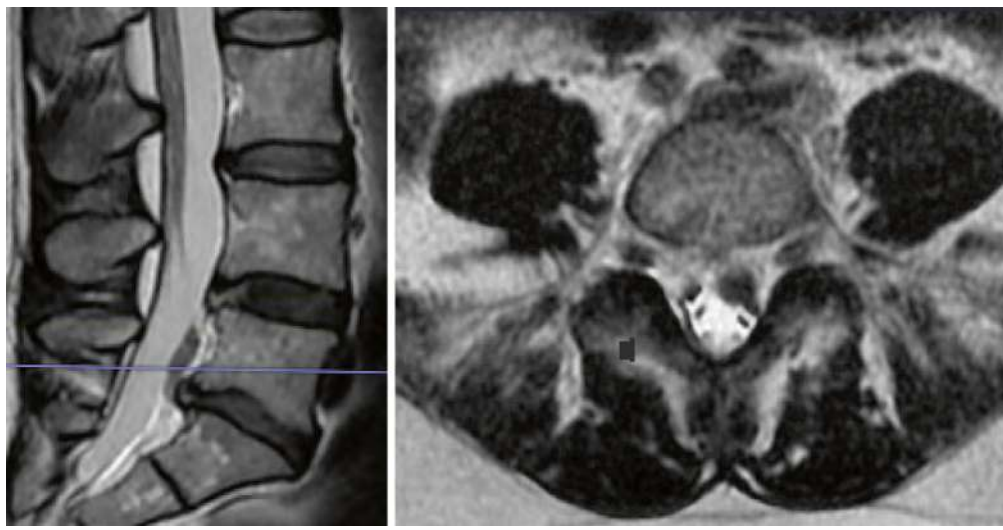

Fig. 2.32 Discal herniation with upward migration on sagittal and axial T2-weighted images

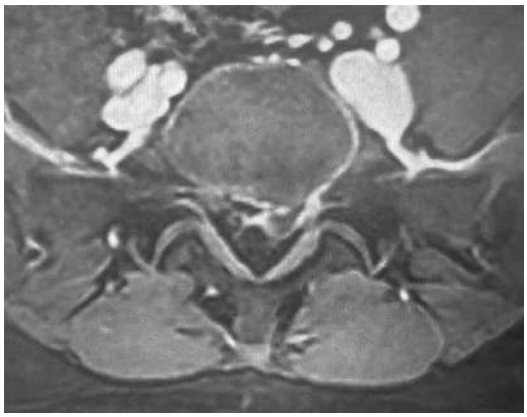

Fig. 2.33 Typical peripheral Gadolinium enhancement around discal herniation (axial T1-weighted)

tion of L5, the longest transverse processes, which are usually those of the L3 vertebra, should be identified on the frontal view.

(iii) *The neural arch* for which the CT-scan is probably the best radiological examination for:

- Precise measurement of the pedicles, short and wide in case of congenital (or constitutional) narrow lumbar canal;
- Highlight presence of tropism, i.e., asymmetry of the interapophyseal joints leading to intervertebral dysfunction [26] (Fig. 2.36);
- Or presence of arthrosis of the interapophyseal joints, which can be classi-

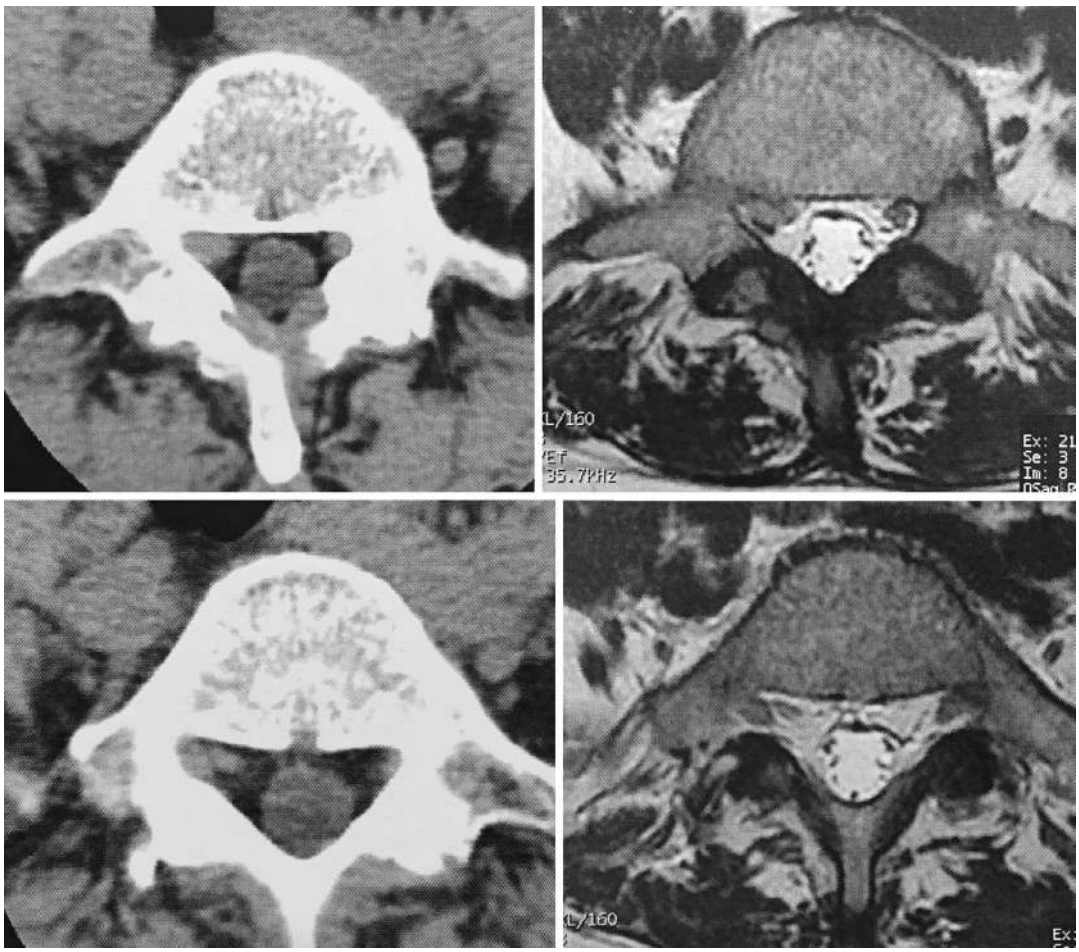

Fig. 2.34 Common origin of the L5 and S1 roots on axial CT-scan and MR T2-weighted images

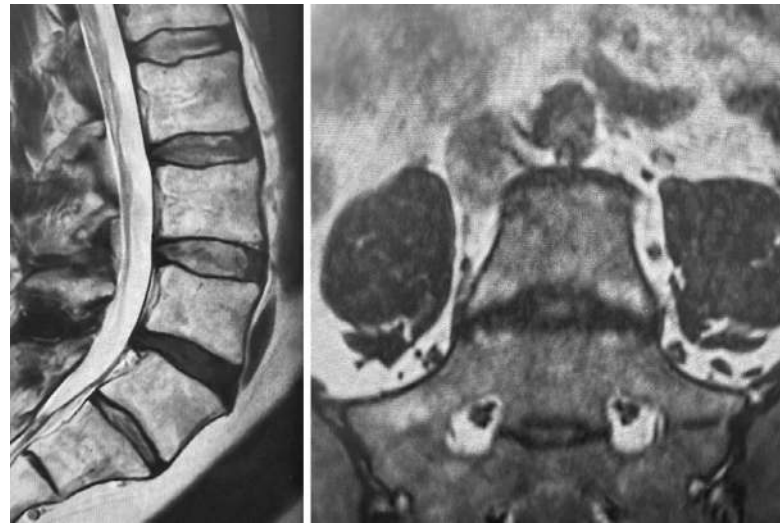

Fig. 2.35 Sacralization of L5 on sagittal and coronal T2-weighted images

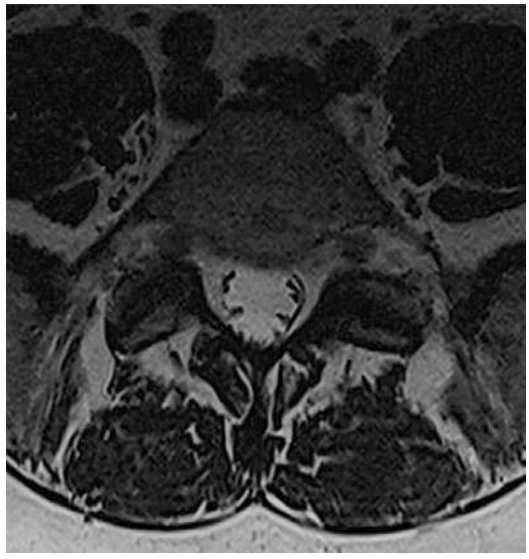

Fig. 2.36 Tropism of the interapophyseal joints

fied according to Weishaupt on CT and MRI [27] (Fig. 2.37). The same "vacuum phenomenon", described for the discs, can be seen within these joints. Interapophyseal osteoarthritis is almost constant after the age of 50, and mainly affects the last three lumbar levels. Arthro-scanner provides a precise diagnosis of synovial cysts, actually only useful if combined with anti-inflammatory infiltration for therapeutic purposes (Fig. 2.38). Many of arthrosynovial cysts are located at the L4–L5 level [28]. On MRI, synovial cysts are hyperintense on T2-weighted slices if there is direct communication with the facet joint (Fig. 2.39) and hyperintense on T1-weighted if there is a hemorrhagic or proteinic component. The presence of an enlarged interapophyseal fluid space, marked by hypersignal T2-weighted images, is an indirect sign of degenerative instability (Fig. 2.40).

- Precise diagnosis of uni- or bilateral, fresh or old isthmic lysis (Fig. 2.41).
- Check the shape of spinous processes (L5 has a smaller spinous process). An interspinous neoarthrosis (Baastrup syndrome) with the appearance of an interspinous bursa may occur in cases of conflict between the spinous processes, most often secondary to the combination of lumbar hyperlordosis and loss of disc height. Bursae and bony erosion are seen on sagittal CT-scan reconstructions (Fig. 2.42), and especially on sagittal MRI slices, where the bursa appears as hyposignal T1 and hypersignal T2, possibly with a bony STIR hypersignal (Fig. 2.43).

(iv) *Intervertebral ligaments*:

- Anterior Longitunal Ligament can normally not be distinguished from the disc on examinations. However, it can be dis-

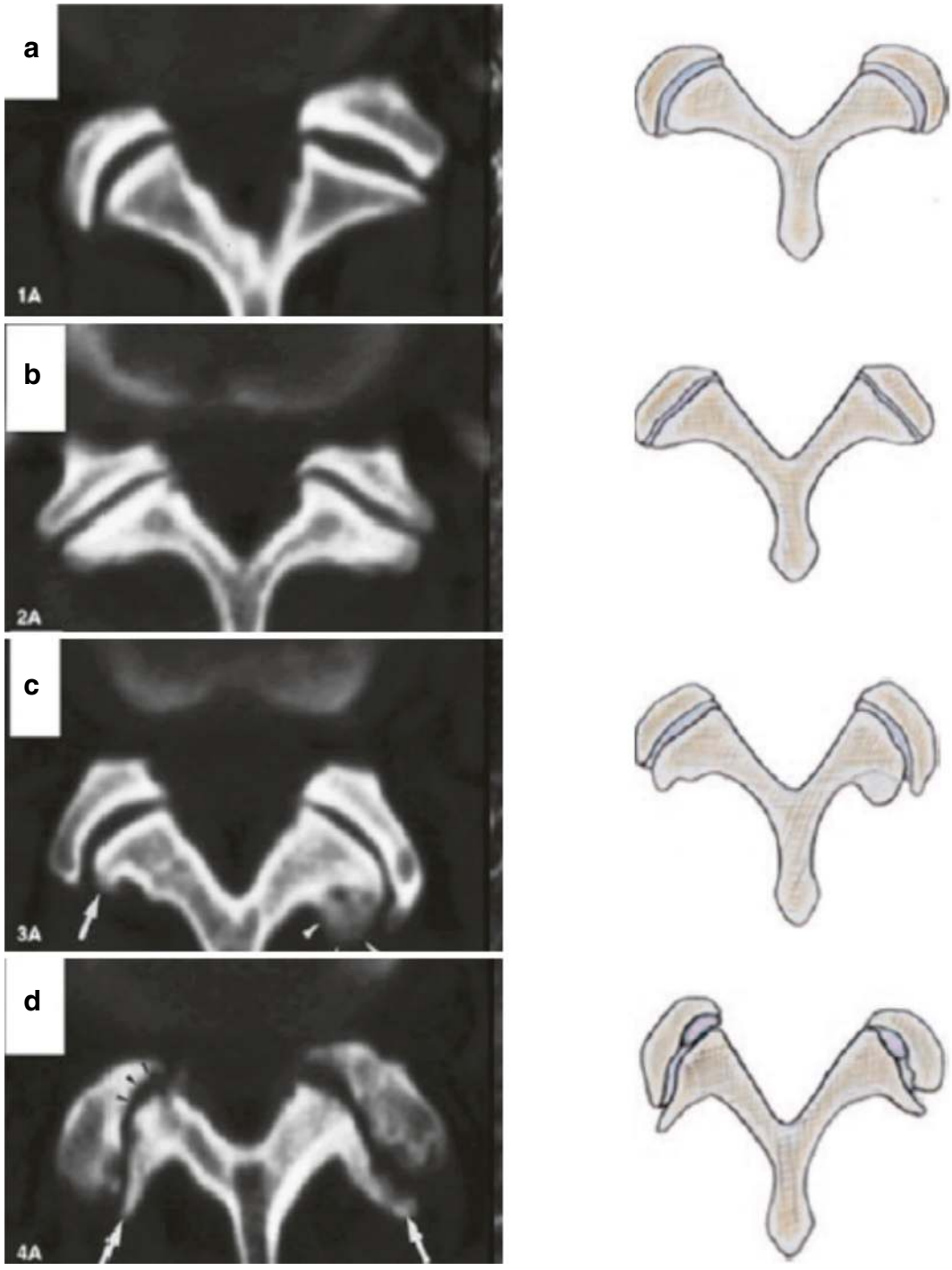

Fig. 2.37 Weinshaupt classification of interapophyseal joints degeneration

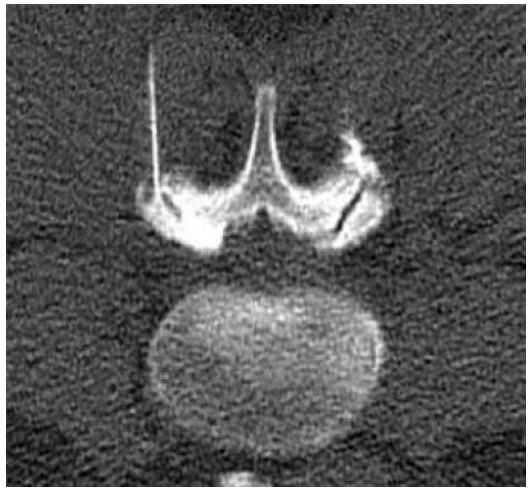

Fig. 2.38 Arthro-scanner for infiltration

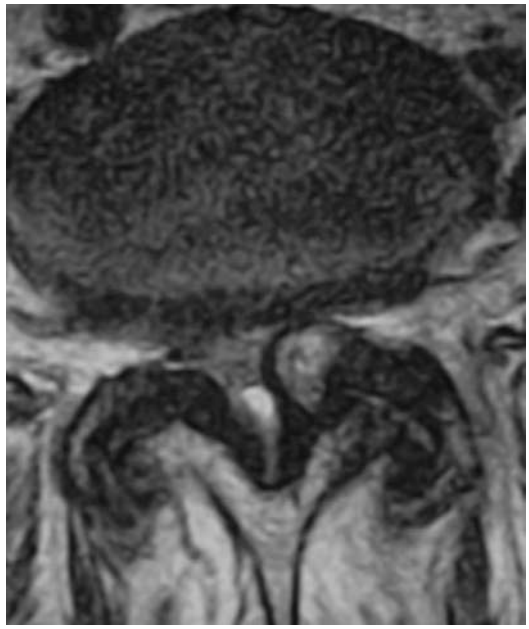

Fig. 2.39 Arthro-synovial cyst on axial T2-weighted slice

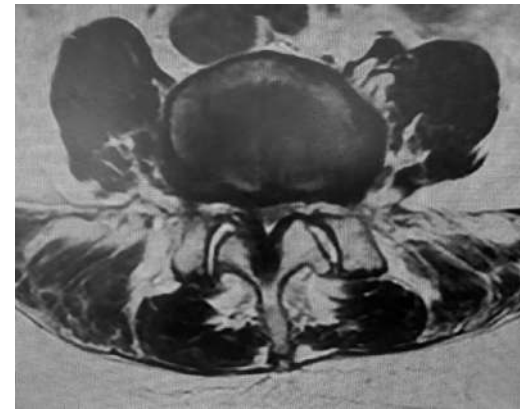

Fig. 2.40 Enlargement of interapophyseal fluid space on T2-weighted image

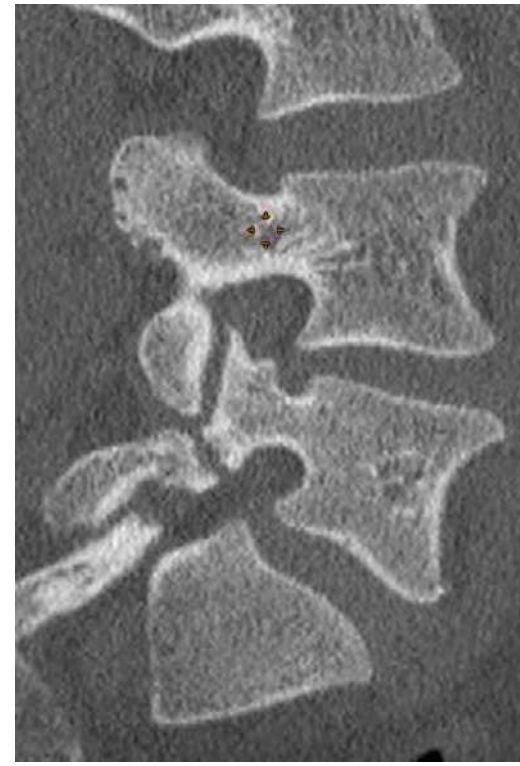

Fig. 2.41 Isthmic lysis on sagittal CT-scan reconstruction

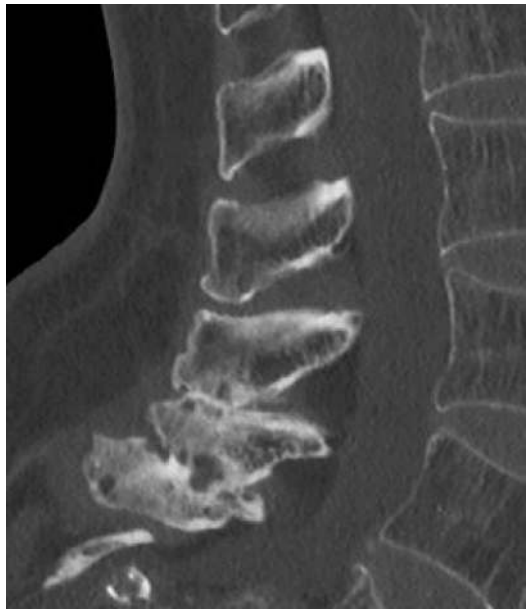

Fig. 2.42 Baastrup syndrome on sagittal CT-scan

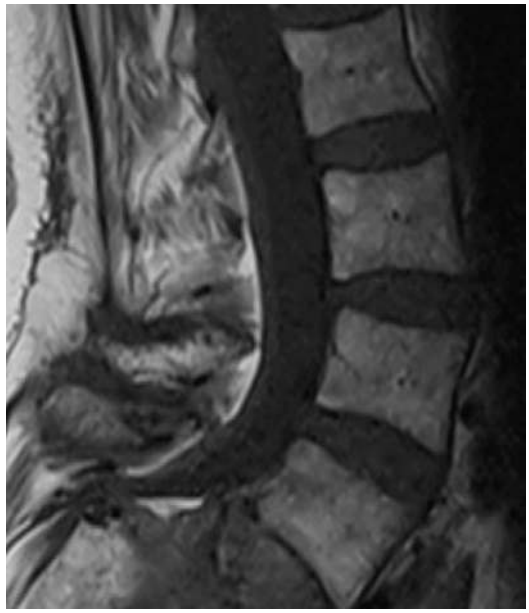

Fig. 2.43 Baastrup syndrome on T1-weighted sagittal T1-weighted image

tinguished in the case of calcifications which, if contiguous, become more or less extensive and fall within the nosological framework of Diffuse Idiopathic Spinal Hyperostosis (DISH), not to be confused with the consequences of inflammatory rheumatism such as Ankylosing Spondylitis. Ankylosis of the spine increases the risk of spinal fracture four-fold [29] but also increases the risk of mobile intervertebral segment degeneration between zones that have spontaneously fused (Fig. 2.44).

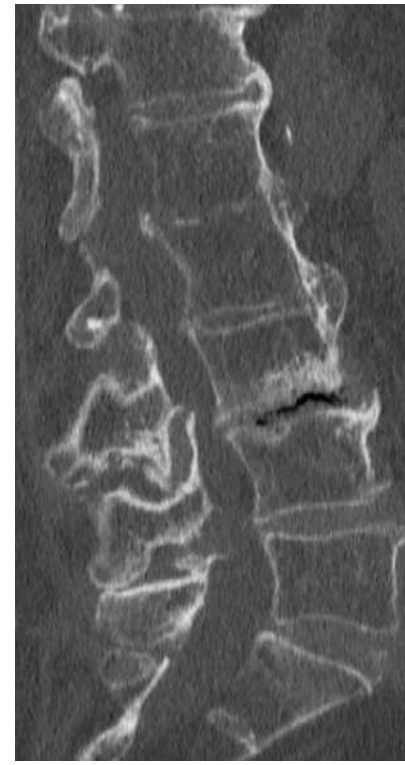

Fig. 2.44 Spinal segmental degenerative instability below Diffuse Idiopathic Spinal Hyperostosis

- Posterior Longitudinal Ligament is also barely visible, except behind the center of the vertebral body, from which it is detached by the anterior epidural venous plexuses. In protrusions or true discal herniation, the tension of the PLL can be seen moving away from the vertebral bodies (Fig. 2.45). It can also be detached from the disc if there is a tear within posterior annulus fibrosus (HIZ), which seems correlated with low back pain [30].

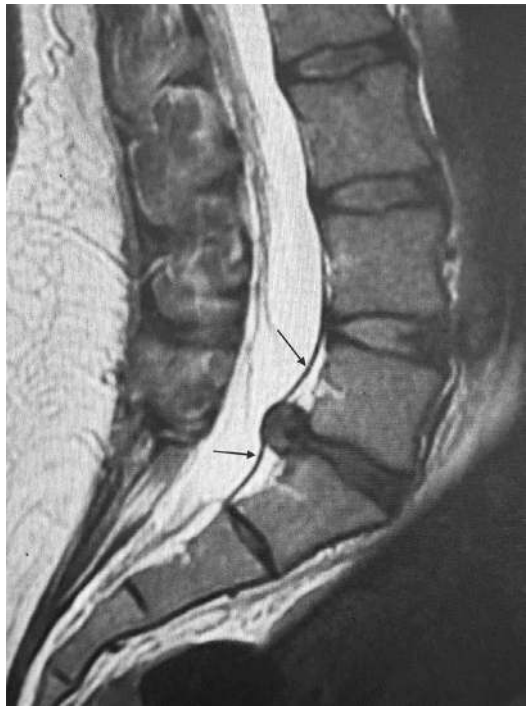

Fig. 2.45 Tension of the PLL (arrows) due to discal herniation on sagittal T2-weighted view

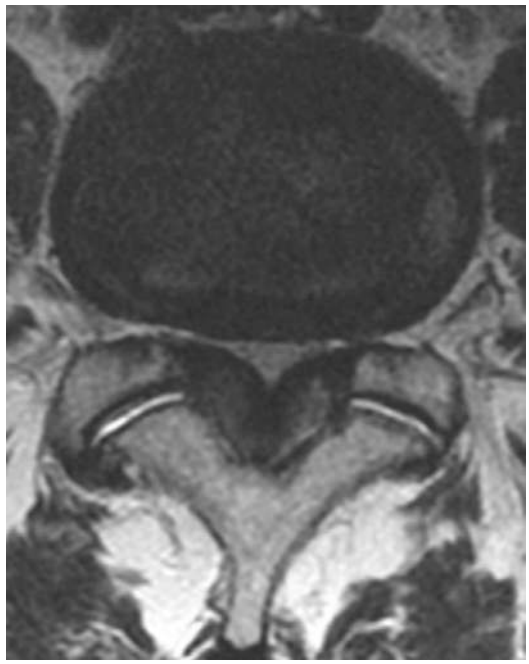

Fig. 2.46 Yellow ligaments hypertrophy on axial T2-weighted image

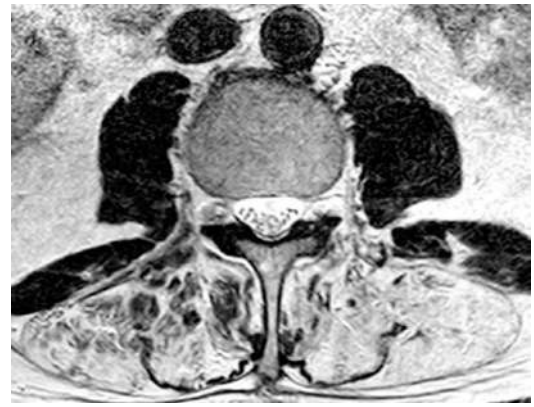

Fig. 2.47 Axial T2-weighted slice showing severe fatty degeneration of the paravertebral muscles, while the psoas and lumbar squares are intact

- Yellow ligament has two components: the superficial part, a true interlamar ligament, and the deep part, internal reinforcement of the interapophyseal joint capsule. Arthrosynovial cysts usually develop between these two layers (Fig. 2.39). The yellow ligament thickens with age, becomes hypertrophic with the degeneration of the elastin fibers and the proliferation of type II collagen [28]. It plays an important role in the compression of the arthrosic narrowing of lumbar central canal, as does joint hypertrophy (Fig. 2.46). It is well analyzed by CT, especially if calcifications are present, and even better by MRI.

(v) *Muscles*: while CT-scans provide an analysis of muscle mass in axial sections, MRI is the ideal examination. We note a very regular conservation of the muscle component for the psoas, in contrast with fatty degeneration in the sacro-lumbar mass, classically proceeding from bottom to top (from the lumbosacral junction to the upper lumbar spine) and from the multifidus (the deepest, paramedian muscle) to the more lateral muscles. This phenomenon increases with muscles degeneration (Fig. 2.47). Hadar [31] has described a classification of this muscle degeneration into three stages according to the percentage of the fatty component in relation to the muscular component (Fig. 2.48).

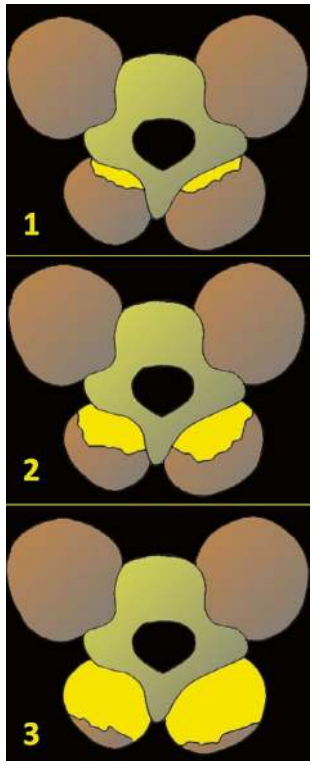

Fig. 2.48 Classification of fatty degeneration of paravertebral muscles according to Hadar

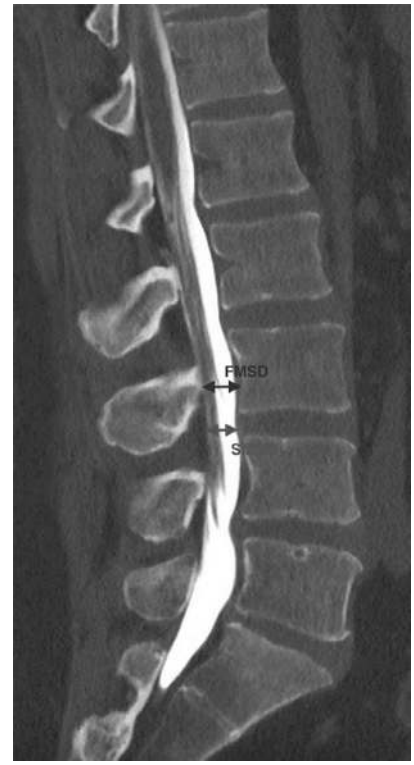

Fig. 2.49 FSMD and SMMD on sagittal sacco-scan

2.3 Exploration of the Contents

(i) *Spinal canals* [32]:

- For the central canal, on CT-scan sagittal sections, we can measure the Fixed Median Sagittal (or bony) Diameter (FMSD) (Fig. 2.49), which is considered narrow if it is less than 12 mm. We can also measure the frontal inter-pedicular diameter, which is normally greater than 15 mm, and the surface area of the spinal canal, which is normally between 150 and 200 mm^2. The FMSD is reduced in congenital (or constitutional) narrow lumbar spinal canal, whereas it is the Sagittal Medial Movable Diameter (SMMD) (Fig. 2.49), at the level of the disc that is reduced in the much more frequent arthrosic narrowing of lumbar spinal canal, associated with hypertrophy of the articular joints and the yellow ligament (Figs. 2.50 and 2.51). Constitutional stenosis of the central canal is linked to short pedicles, too wide vertebral bodies in the anteroposterior direction and thick, elongated neural arches in the craniocaudal direction. This kind of stenosis is usually global over the entire spine, so we have to beware of associated myelopathy, especially in cases of atypical symptoms.
- The lateral part of the SMMD corresponds to the disco-articular space, which is bounded anteriorly by the posterolateral edge of the disc, posteriorly by the superior articular process, and in which the root separates from the dural sac and enters the recess (Fig. 2.52). The lateral part of the FMSD, lateral recesses, are delimited laterally by the pedicles and posteriorly by the articular processes and the isthmus. They are best explored by CT-scan (Fig. 2.53).

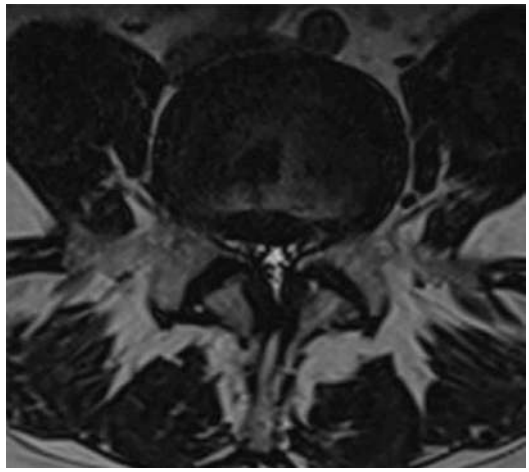

Fig. 2.50 Arthrosic narrowing of lumbar spinal canal on axial T2-weighted image

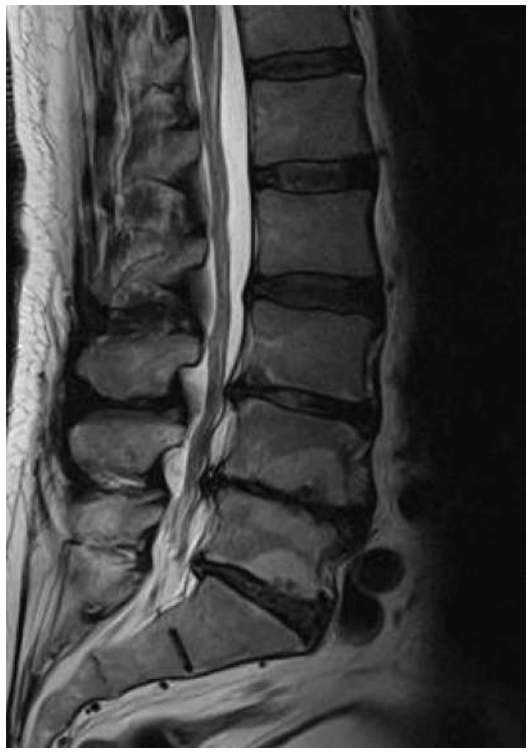

Fig. 2.51 Arthrosic narrowing of lumbar spinal canal on sagittal T2-weighted image

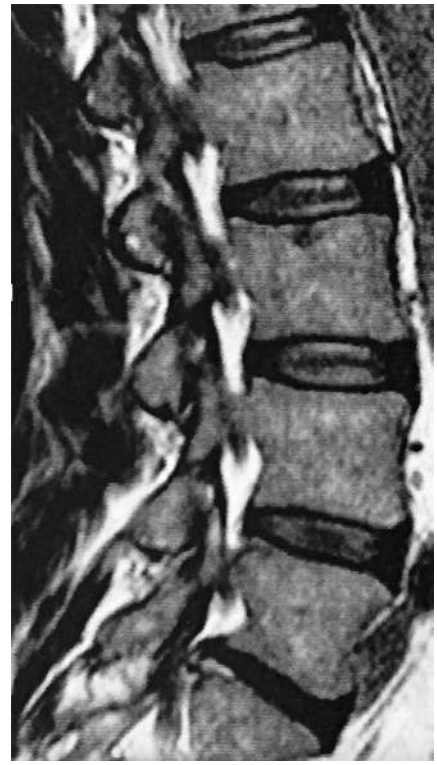

Fig. 2.52 Sagittal T2-weighted view of disco-articular spaces and lateral recesses

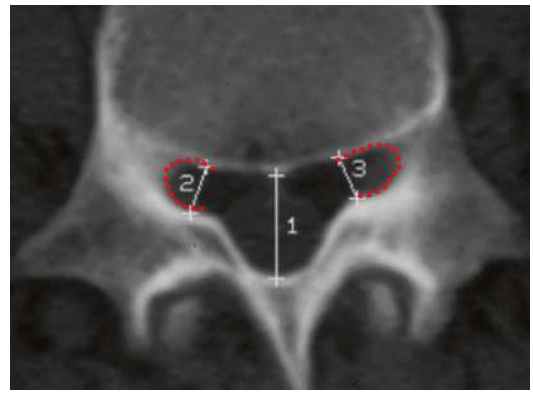

Fig. 2.53 Central lumbar canal (1) and lateral recesses (2–3) in axial CT-scan view

- Intervertebral foramen (IVF) is located between the pedicles of adjacent vertebrae. They have a fixed cranial subpedicular compartment and a mobile caudal portion, at the level of the disc and the articular process. This so-called "hidden" area of Mac Nab is perfectly explored by MRI, particularly in sagittal T1-weighted images (Fig. 2.54). The IVF may also be the site of a constitutional ste-

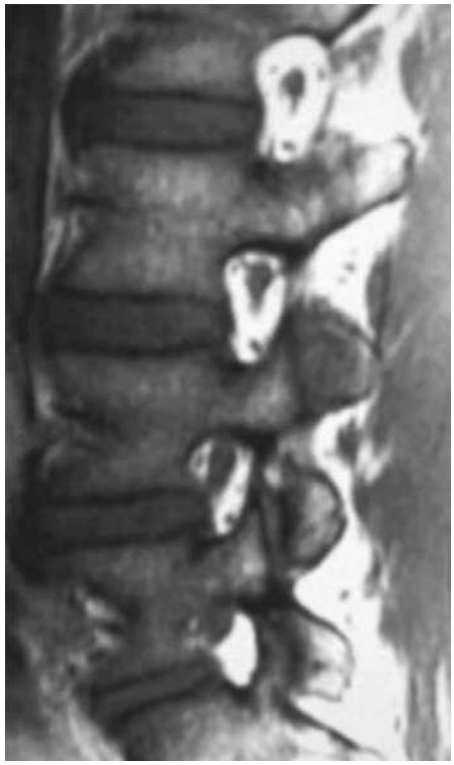

Fig. 2.54 Intervertebral foramina on sagittal paramedian T1-weighted slice

nosis associated with short pedicles. Here again, the L5–S1 level is marked by specific anatomical features, with a smaller, rounder and more elongated foramen due to the shape of the L5 pedicle.

(ii) *Neurological components*: These are best recognized on MRI in T2-weighted images, or possibly on saccoradiculography scanner.

- Within the central canal is the dura-mater, which surrounds the spinal cord and its conus up to L1 (in 80% of cases), then the cauda equina. Around the dura-mater there is the reserve volume (or safety space) occupied by epidural fat, which can become compressive in the case of lipomatosis, characterized by a deformation of the dural sac (Fig. 2.55), sometimes in a 3 branches star shape.

Degenerative canal narrowing may occur in constitutionally narrow canals. The latter are all

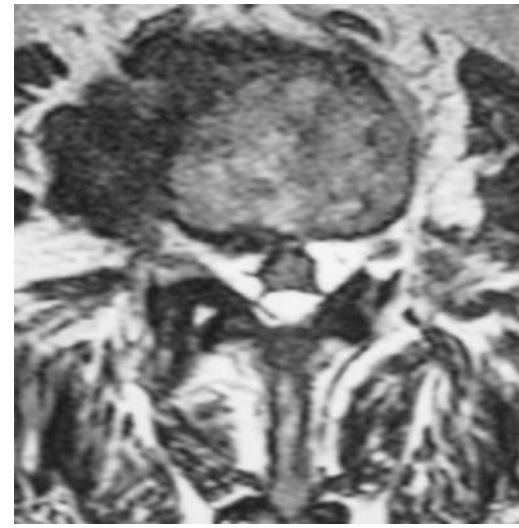

Fig. 2.55 Lipomatosis of spinal canal on axial T1-weighted slice

the more prone to decompensation as there is very little epidural fat (which acts as a shock absorber in a normally constituted canal). The factors responsible are bulging degenerative discs, hypertrophied or calcified yellow ligaments, cysts or, more often, degenerative facet joint hypertrophy, and anterior or posterior osteophytes. A distinction can be made between anterior stenosis related to disc disease, disc protrusion or osteophytic process (pain may predominate in the sitting position) and posterior stenosis secondary to arthritic hypertrophy of the zygapophysis and yellow ligament (the patient then has the classic symptoms of canal stenosis: pain in the standing position and painful intermittent claudication). Central stenosis is classically assessed by the Schizas classification [33], based on axial T2-weighted images, regarding the position of the cauda equina, which may or may not be sedimented, the accretion of this cauda equina and then the disappearance of epidural fat, to end up with a "black canal" (Fig. 2.56). This classification ignores lateralized stenoses of the disco-articular space. There is no correlation between the degree of narrowing and the importance of clinical signs.

- Within the IVF, the root, and more often than not its spinal ganglion, is located in

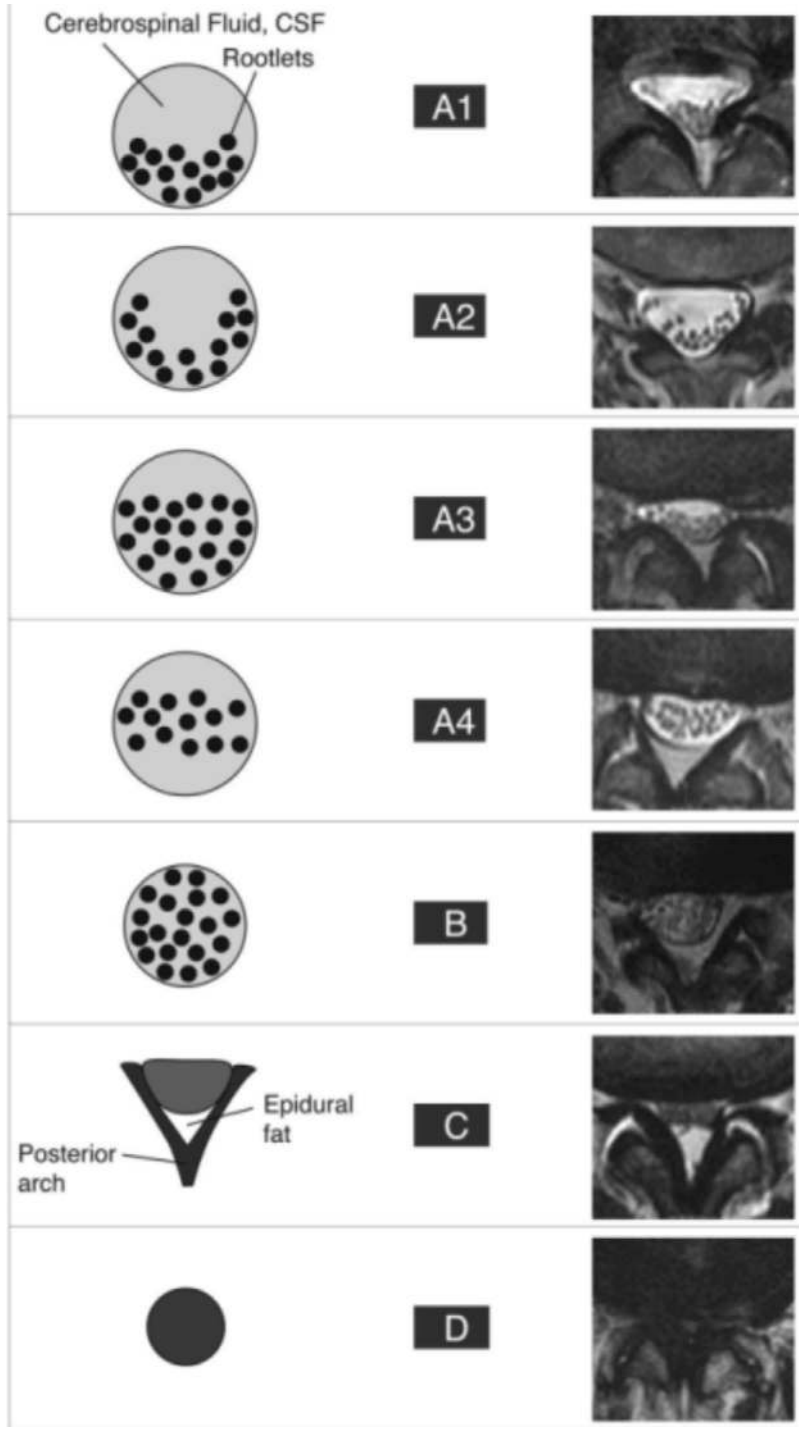

Fig. 2.56 Schizas classification of narrow lumbar canal in axial T2-weighted images

the upper part and may be compressed by a foraminal disc herniation originating from the inferior disc and necessarily migrating upwards (Fig. 2.57). Discal degeneration alone rarely leads to symptomatic foraminal narrowing, since the root is the fixed part of this space. It is especially if the disc impingement is

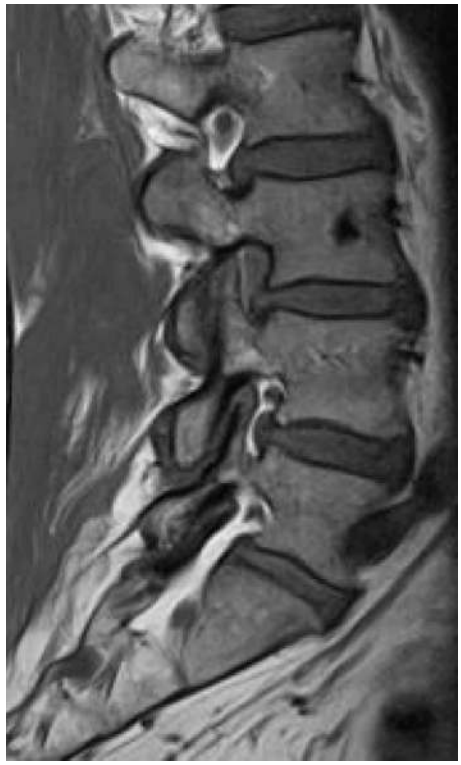

Fig. 2.57 Foraminal discal herniation on sagittal T1-weighted view

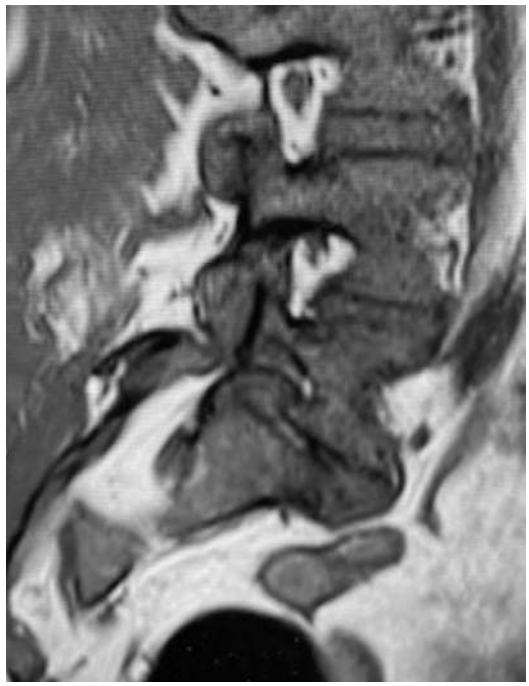

Fig. 2.58 L5–S1 foraminal stenosis due to isthmic spondylolisthesis (sagittal T1-weighted)

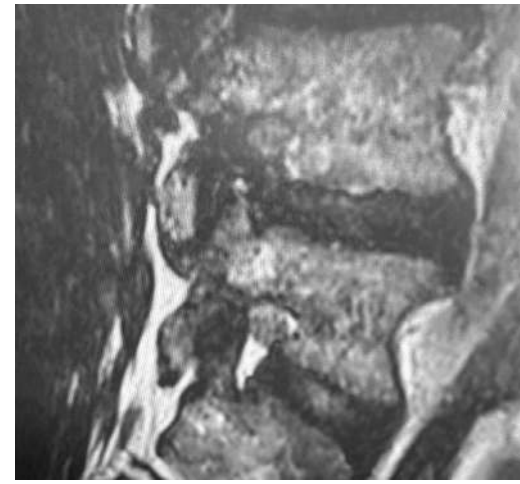

Fig. 2.59 Multifactorial stenosis with the disappearance of epidural fat around the spinal root (sagittal T1-weighted)

asymmetrical, or if there is a rotation that brings the upper part of superior articular process into the upper part of the foramina, or a spondylolisthesis with a "cigar-cutting" effect (Fig. 2.58), that there is real foraminal root compression, with the same mechanical symptomatology as central canal stenosis. Lumbar foraminal stenosis can be can be assessed with deformity of the epidural fat remaining around the existing nerve root (Fig. 2.59) [34].

2.4 Global Analysis of the Lumbar Spine: Relationships Between Each Segment

(i) Beyond each vertebral body, the relationship between the vertebral bodies and any misalignment must be analyzed. *The lateral view* is probably the most instructive. According to Aubry [35], lines can be drawn from front to back: the anterior wall, the posterior wall, the junction of the laminae, the posterior surface of the articular joints and the line of the spinous processes (Fig. 2.60), particularly to recognize short

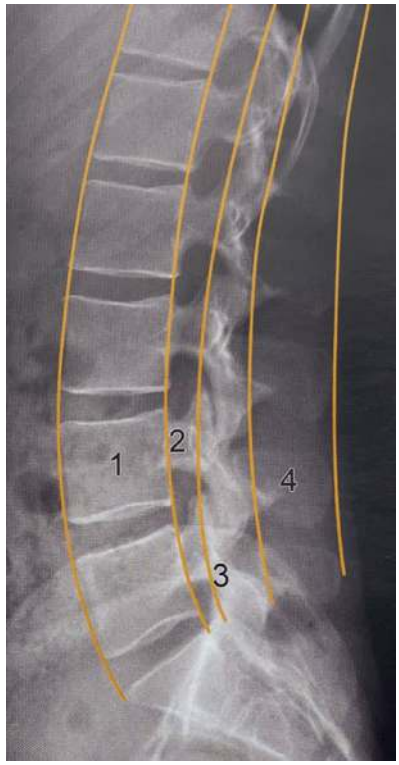

Fig. 2.60 Five lines of alignment analysis on lateral X-rays

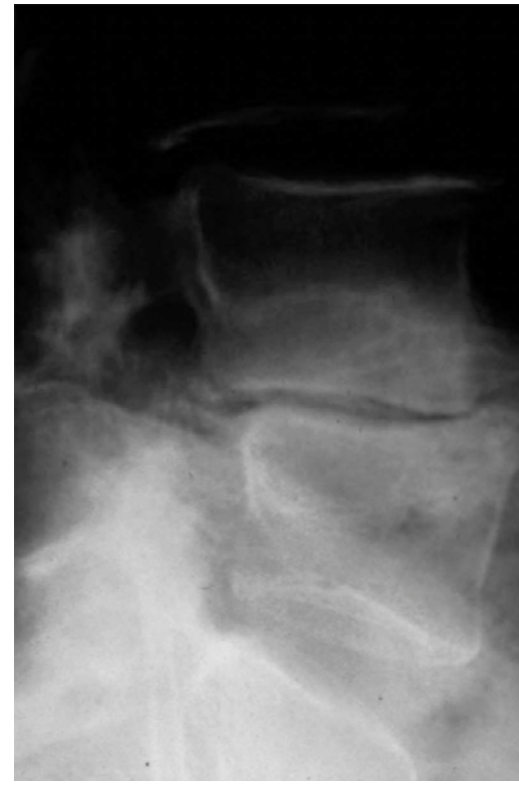

Fig. 2.61 Retrolisthesis on lateral X-ray

pedicles in the context of a narrow constitutional canal between the 2nd and 3rd lines.

On this lateral view, in standing position, the lumbar lordosis can be measured, not systematically between S1 and L1, but between the upper endplate of S1 at the bottom and the upper endplate of the most inclined lumbar vertebra, which is not always L1, at the top. Spondylolisthesis or retrolisthesis (Fig. 2.61) can be demonstrated, which may reduce the central spinal canal and, above all, the intervertebral foramina. In fact, in purely degenerative pathology, degenerative spondylolisthesis is sometimes associated with overlying retrolisthesis, especially on upright lateral views, which is there to restore balance as an upward compensation system (Fig. 2.62). It should be noted that the anterior displacement of degenerative spondylolisthesis may be more marked on the loaded lateral view than on the supine MRI (Fig. 2.63). Differentiation between normal and abnormal mobility remains challenging and diagnosis of intervertebral instability is based on those direct and indirect radiological findings.

Degenerative spondylolisthesis may be responsible for, or increase, canal narrowing. Spondylolisthesis due to isthmic lysis, on the other hand, tends to widen the canal by elongation of the isthmus, at least initially. Foraminal stenosis may also be due to spondylolisthesis, degenerative spondylolisthesis or, above all, by isthmic lysis. In both cases, there is a reduction in the height and anteroposterior diameter of the foramen. In the case of isthmic lysis, a Gill's nodule also contributes to foramen narrowing. In degenerative listhesis, posterior arthrosis and discarthrosis are added.

(ii) On an *AP view* of the entire lumbar spine, five lines can be described [35]: two aligned

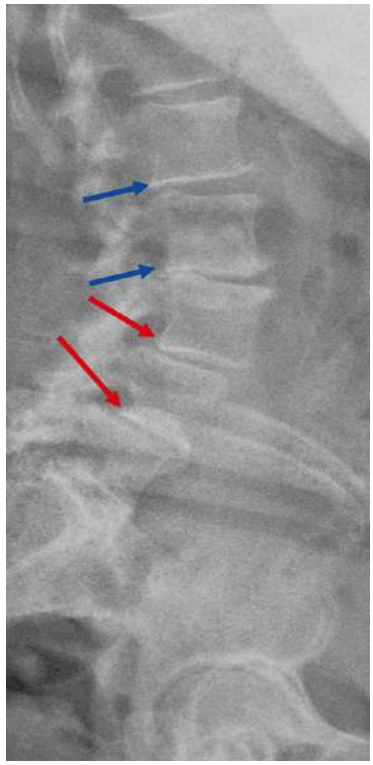

Fig. 2.62 Spondylolisthesis L3–L4 and L4–L5 (red arrows) and compensatory retrolisthesis L1–L2 (blue arrow) on lateral X-ray

with the lateral faces of the vertebral bodies, two others at the medial edge of the pedicles and the last vertical median line following the spinous processes (Fig. 2.64). In the case of a narrow lumbar canal, excessively visible joint spaces can be seen, corresponding to sagittalization of the interapophyseal joints.

The presence of a degenerative scoliosis is best assessed on this AP view, by measuring the Cobb angle on the most inclined vertebrae, and the degree of rotation on the vertebrae at the apex (Fig. 2.65). In the most advanced forms of degenerative scoliosis, dislocations may also be noted, corresponding to a lateral translation of the vertebral bodies and an offset of the lateral walls of the vertebrae (rupture of the lateral line described above). A distinction is made between:

- A closed dislocation below the lower limiting vertebra, with a pinched intervertebral disc on the convex side of the scoliotic curvature, with a high risk of root compression in the intervertebral foramen;
- A neutral dislocation with a horizontal disc and above this;
- An open dislocation with a disc open toward convexity.

(iii) Without many details about the angles exploring *sagittal balance*, we shall nevertheless mention [36]:

- Pelvic incidence (PI), angle that assesses the width of the pelvis and is strongly correlated with the angle of lumbar lordosis,
- Pelvic version (PV), an angle that studies the position of the pelvis, with an increase in retroversion and a decrease in anteversion,
- Sacral slope (SS), which evolves inversely with the pelvic version, since the sum of PV + SS is equal to PI, a fixed angle.

There are also two main axes in order to assess overall sagittal balance:

- C7 plumbline (Fig. 2.66), which measures the distance between the vertical lowered from the middle of the body of C7 and the anterior (or posterior) edge of the sacral endplate,
- More globally, the external auditory canal–femur head axis (Fig. 2.67), which incorporates the cervical spine (its position can be checked using a mirror).

On the lateral EOS image, we can see the compensation systems for severe anterior imbalances, i.e., retroversion of the pelvis, hyperextension of the thoracic spine and flexion of the knees (Fig. 2.68). A new classification of degenerative spondylolisthesis has been developed, which takes these compensation systems into account [37].

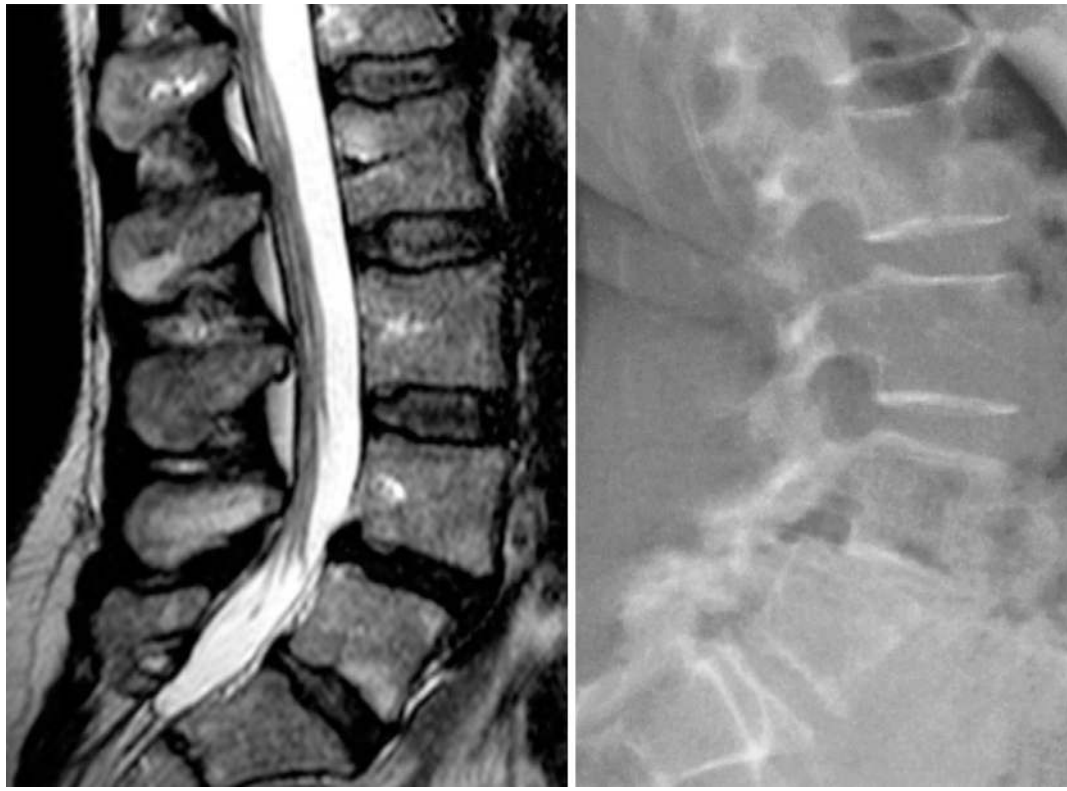

Fig. 2.63 Degenerative spondylolisthesis of L4 more marked on weight-bearing lateral X-ray than on supine MRI

2.5 Conclusion

Which examinations should be carried out according to the anatomical structures explored in lumbar degenerative pathology (in ascending order of interest, +, ++, +++)?

(i) *Vertebral bodies*

- Plain x-rays: osteophytes +
- CT-scan: osteophytes, sclerosis of vertebral endplates ++
- MRI: Modic changes of subchondral bone +++

(ii) *Intervertebral disc*

- Plain X-rays: Height loss, air, calcification +
- CT-Scan: Height loss air, calcification, discal herniation ++
- MRI: Height loss, HIZ, dehydration, discal herniation +++

(iii) *Neural arch*

- M.R.I. +
- Bone Scintigraphy/CT-scan ++
- CT-Scan +++

(iv) *Intervertebral ligaments*

- M.R.I. +++

(v) *Muscles*

- Scanner +
- M.R.I. ++

(vi) *Central spinal canal*

- CT-Scan +

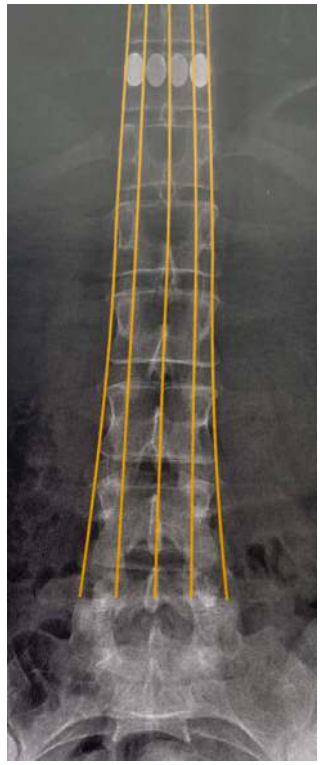

Fig. 2.64 Five lines of alignment analysis in the AP X-rays

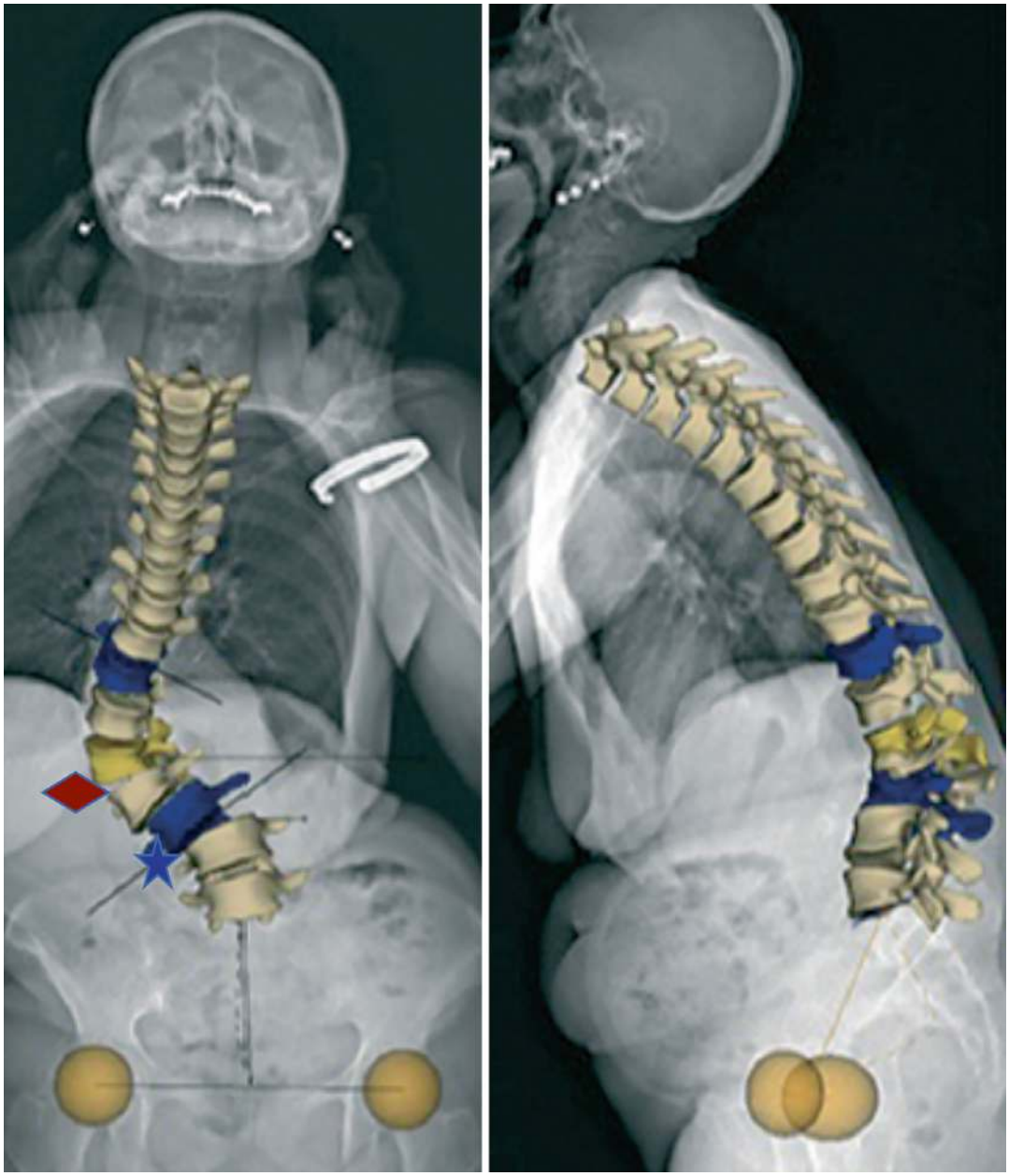

Fig. 2.65 Severe kyphoscoliosis with open and closed dislocations

Fig. 2.66 C7 plumbline

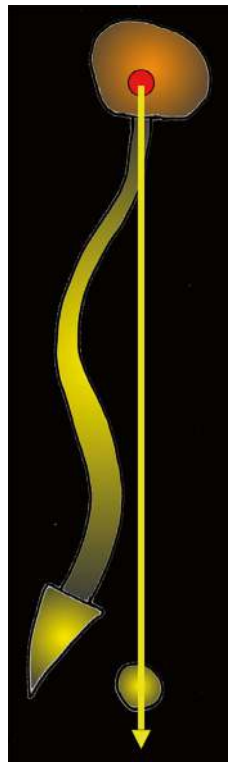

Fig. 2.67 Axis between external auditory canals and femoral heads

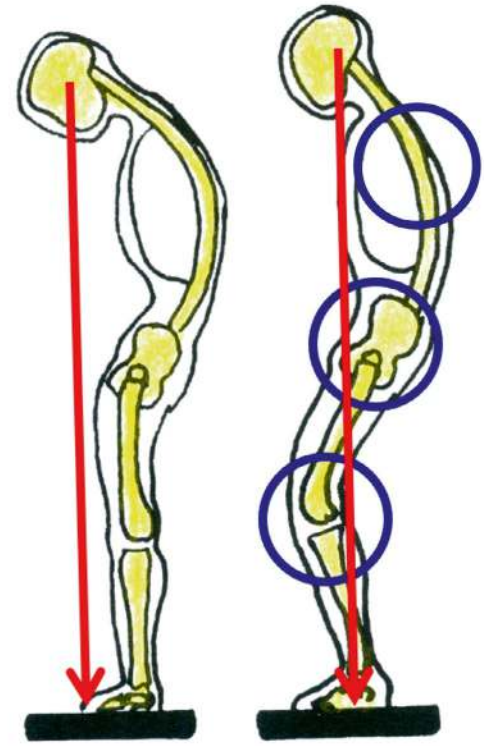

Fig. 2.68 Compensatory mechanisms in an anterior severe imbalance

- Saccoradiculography/CT-Scan r ++
- M.R.I. +++

(vii) *InterVertebral Foramen*

- CT-Scan +
- M.R.I. (Sag T1)++

(viii) *Conus medullaris and Cauda equina*

- Saccoradiculography/CT-scan +
- M.R.I. +++

(ix) *Alignment and elements of stability*

- Dynamic M.R.I. +
- Static and Dynamic views in standing position +++

(x) *Overall balance*

- Teleradiography ++
- E.O.S. +++

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3 Assessment and Management of Chronic Low Back Pain

Jean Guyot and Stéphane Litrico

3.1 Introduction

Low back pain, as defined by the World Health Organization (WHO) and the French *Haute Autorité de Santé* (HAS), is a pain localized in the lumbar region, between the lower ribs and the lower buttocks [1] [2]. 63% of the cases may be accompanied by radiculalgia, which has a poorer prognosis due to increased pain intensity and its socio-professional impact [3].

Low back pain can be defined by its etiology and duration.

- The HAS makes a difference between specific low back pain (as a "symptom" of another etiology: infection, tumor, etc.) and non-specific low back pain. The term "common low back pain" is about to be abandoned.
- According to literature, acute low back pain lasts less than 4 weeks, sub-acute back pain lasts between 4 weeks and 3 months, and chronic back pain lasts more than 3 months [1, 4].

This article will focus on chronic non-specific low back pain.

Chronic low back pain has a major impact on patients' social and professional lives. This matter becomes a heavy socio-economic burden on public health. That's why clinicians need to be aware of how to detect it early, understand its mechanisms and be familiar with the various treatment options available.

3.2 Epidemiology

Low back pain is a growing public health problem, both in France and internationally [5]. The most recent epidemiological review, published in The Lancet, found that 619 million people suffered from low back pain in 2020, representing approximately 10% of the global population [4]. The WHO predicts that this prevalence will increase to 843 million by 2050 [4]. Prevalence is highest among women [6], with a more marked gender difference among older subjects (>75 years) [7]. Prevalence increases with age, peaking at 85 years [4].

In parallel with this increase in prevalence, the socio-economic impact is reflected in the increase in Years Lived with Disability (YLDs) due to low back pain: from 43 million in 1990 to 64 million in 2017 and up to 69 million in 2020 [4, 8]. Low back pain thus accounts for 7.7% of all YLDs, making it the most significant cause of YLDs [4].

Forty percent of these YLDs are due to three risk-taking behaviors: the most significant is poor ergonomics at work (22%), followed by smoking (12.5%) and high BMI (11.5%) [4]. Other main

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factors are depressive and anxious disorders [9], comorbidities [9], and alcohol intoxication [10]. People with postures requiring prolonged sitting [11] or standing [12], repeated bending or heavy lifting are the most exposed. Moreover, it appears that chronic low back pain is linked to low skill levels [13]. This may be due, firstly, to jobs that are more physical than those requiring higher professional qualifications and, secondly, to a lifestyle that includes risk factors for low back pain (smoking, high BMI).

At the national level, no recent survey on the total prevalence/incidence of chronic low back pain has been identified, despite the fact that it's a recognized public health problem. Data about low back pain population, consultation rates, surgical incidences are underestimated because they are outdated. The majority of articles written in recent years are based on two surveys published more than 20 years ago: the 2003 Decennial Health Survey (DHS) [14] and the 1999 Survey on Disabilities, Incapacities, and Dependency (DID) [15].

In France, according to the results of the 2003 DHS, the total prevalence of low back pain was 54% among men and 57% among women [14]. More recently, the *Santé Publique France* journal revealed a prevalence in the 18–64 age group of 40% among men and 47% among women [16]. Among those in active employment, this prevalence reaches 42% among men, compared with 48% for women [16].

In 2003, the DHS ranked low back pain as the second most frequent reason for consultation with general practitioner, with 6 million consultations [14]. More recently, the French social security system has classified acute low back pain as the second most common reason for medical consultations, and chronic low back pain as the eighth [17]. It also accounts for one-third of all physiotherapy treatments and 5 to 10% of radiology acts [14].

Extrapolating all associated costs (medical and paramedical consultation expenses, drug treatments, hospitalization costs, diagnosis context), the DID survey found an annual estimate of €1.4 billion in healthcare expenditure attributable to low back pain [18]. This total represents approximately 1.5% of annual healthcare expenditure in France. When indirect costs (daily allowances, disability pensions, loss of production) are included, the HAS estimates the total cost to be 5 to 10 times higher [18]. It should be noted that 70 to 80% of these costs are associated with 5 to 10% of chronic resistant low back pain patients [18].

In socio-professional terms, chronic low back pain is the leading cause of medical incapacity in employees aged under 45 [19]. According to Eurofound, in 2015, 44% of European workers had suffered from low back pain in the previous 12 months [20].

Low back pain (acute and chronic) accounts for 20% of work-related accidents and 7% of work-related diseases ranking as the leading cause of workplace accidents resulting in sick leave [22]. These accidents and occupational illnesses are logically most prevalent among exposed professions: farmers, craftsmen, manual workers, etc. The INRS estimates the average duration of sick leave related to these work-related accidents at two months, with this duration having tripled over the past 40 years [21]. The average duration of occupational illnesses is one year. All these periods of unavailability (considering only those recognized as work-related) represent more than one billion euros in expenses per year for the social security system [21].

Low back pain (acute or chronic, work-related or not) is the third leading cause of sick leaves in France, after seasonal illnesses and mental health issues. The average duration of sick leave is 44 days, representing an annual loss of 3.6 million working days. Lower back pain is now the second leading cause of prolonged sick leave, behind psychosocial disorders [23].

The prognosis for sick leave due to low back pain is poor, with only 40–50% of employees returning to work after 6 months of sick leave, 15–25% after one year, and virtually none after two years [24].

There is no French register recording the number of surgeries for chronic low back pain. The recent studies are based on lumbar disc herniation surgery, which accounts for between 20,000 and 30,000 surgical cases per year, i.e., an

incidence rate of approximately 30 per 100,000 [25]. This indirectly estimates the impact of low back pain on the French healthcare system.

3.3 Degenerative Lumbar Physiopathology

Chronic low back pain has a complex origin, involving inflammatory, peripheral and central neuropathic mechanisms [26]. The anatomical structures located in the lumbar region (intervertebral disc, posterior joints, muscles, ligamentous structures, etc.) are rich in pain receptors. Damage to any of these structures can lead to low back pain with, often, a combination of factors involved.

3.3.1 Intervertebral Disc (IVD) Degeneration

This is the most common cause of chronic low back pain, accounting for approximately 40% of reported causes [27]. Beyond genetic heredity [28], this IVD degeneration is the result of natural disc aging aggravated by microtrauma and repeated mechanical stress during bending, leading to disc destruction that may be associated with disc herniation [29].

The intervertebral disc (IVD) is composed of a nucleus pulposus (NP), formed by a gelatinous matrix rich in proteoglycan, surrounded by an annulus fibrosus (AF) and then two cartilaginous plates (CP), attaching the disc to the vertebral bodies [30]. A healthy IVD is innervated only in its outer third, relaying its innervation via the dorsal root ganglion (DRG) and the sympathetic and parasympathetic ganglia [31].

Disc degeneration is a chronic, irreversible process consisting of a loss of proteoglycans from the NP matrix with dehydration and dedifferentiation of the NP and AF, leading to structural destruction and loss of disc height [32, 33].

This degeneration mechanism leads to:

- Stimulation of inflammatory infiltration with an increase in inflammatory markers (IL-1ß, IL-1æ, TNF-æ, catabolic factors, etc.) and vascular and nerve growth factors. In fact, since the NP matrix via proteoglycans prevents the growth of blood vessels and nerve fibers under physiological conditions, the destruction of this matrix leads to the development of these elements [26, 32].
- Deeper integration within the IVD of peripheral nerve endings, which are usually stopped at the outer third via structural destruction and nerve growth factors [34], leading to increased peripheral sensitization and thus facilitating pain sensation. This phenomenon of increased innervation spreads to the vertebral endplates and vertebral body [35]. More recent studies suggest that this nerve regrowth is even more significant in the vertebral endplates (75%) than in the IVD (35%) [36].

This degeneration of the IVD also spreads to the vertebral cartilage, probably through chemotaxis of discogenic algogenic factors [36]. Damage to these disc cartilages creates an inflammatory loop, both in the vertebral endplates and in the IVD, increasing catabolic enzymes, pro-inflammatory cytokines and pro-apoptotic proteins [37]. This inflammatory cascade in the adjacent vertebral body ultimately leads to a change in the bone marrow, visible on MRI and described in the Modic classification [38, 39] (Fig. 3.1).

Various studies have shown that the nociceptors of the vertebral bodies relay signals in the basivertebral nerve, a nerve that is part of the sino-vertebral nerves, located on the posterior surface of the vertebral body and richly innervating the vertebral endplates [40]. A densification of these nerves, linked to nerve growth factors and associated with inflammatory markers, has been demonstrated in patients with Modic I or II [31, 36, 41]. Percutaneous intradiscal thermocoagulation, or intradiscal electrothermal therapy (IDET), has been studied with the aim of destroying these painful nerve fibers, but there is currently insufficient evidence to fully support its use [42]. More recently, a randomized controlled trial was published in 2020, studying radiofrequency ablation of the vertebral nerve, with encouraging results [43].

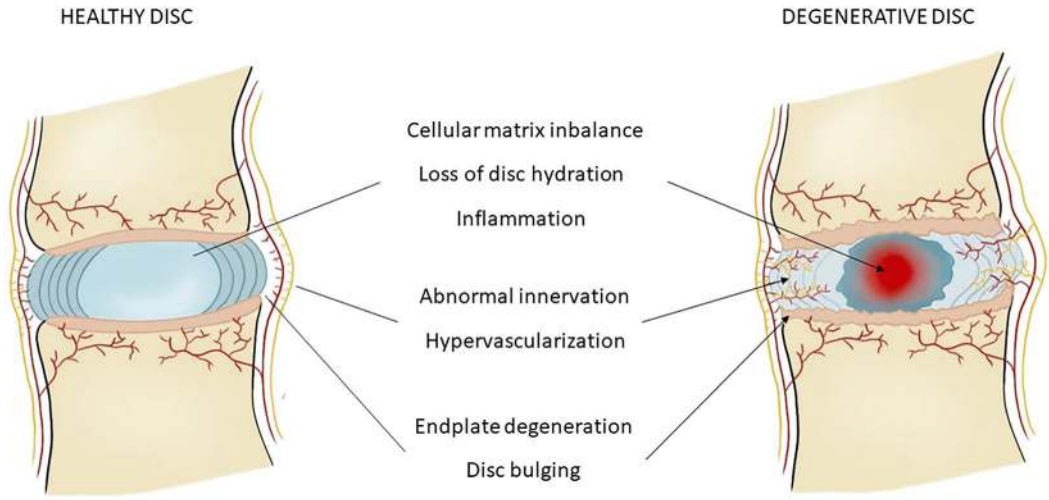

Fig. 3.1 Degenerative mechanism leading to structural modification of the disc

At the same time, sympathetic fibers are located around the annulus, the vertebral endplates and the adjacent body, as well as at the level of the anterior spinal artery. A significant proportion of nociceptive fibers thus pass through the sympathetic system [35]. As degeneration of the IVD allows for increased regeneration of nociceptive and sympathetic fibers, the transmission of pain stimuli is ultimately increased [35].

3.3.2 Joints Degeneration

The facet joints are highly innervated structures, comprising subchondral bone, articular cartilage, a synovial membrane and a fibrous capsule [44]. This innervation occurs through two medial branches of the dorsal lumbar ramus, one originating from the ramus at the corresponding level and the other from the ramus at the level above, whose path passes through the joint capsule [45, 46]. Various studies have also shown the presence of numerous nociceptors in the facet joints [47] and adjacent muscles [48]. These nociceptors respond to mechanical and chemical stimuli.

At the same time, joint hypertrophy easily encounters the root passing through the lateral recess, contributing to lumbosciatica. The degeneration of these facet joints through mechanisms of osteoarthritis, destruction by microtrauma or sagittal alignment abnormalities of the facets [49] mechanically stimulates the nociceptors [50]. Beyond the compressive and mechanical mechanism, the destruction of joint tissue also triggers an inflammatory cascade, responsible for painful impulses through stimulation of chemoreceptors.

Thus, the patient may experience mechanical pain, similar to osteoarthritis pain, as well as inflammatory pain caused by synovitis.

The pain caused by all of these mechanisms is grouped under the term Facet Joint Syndrome [51]. It is estimated that this joint degeneration is involved in 16 to 40% of chronic low back pain cases [52].

3.3.3 Adjacent Muscle Degeneration

The proper functioning of the paravertebral muscles, particularly the multifidus and erector spinae muscles, is essential for spinal stability. In patients with chronic low back pain, structural alterations of these muscles are frequently observed [53]. These changes include fatty infiltration, muscle

atrophy and changes in muscle fiber type, particularly a reduction in type I fibers (oxidative, aerobic) in favor of type II fibers (glycolytic, anaerobic), which are less resistant to fatigue [54].

The origin of these structural alterations is multifactorial and part of a vicious circle, with inactivity caused by low back pain and misconceptions leading to muscle wasting, which in turn perpetuates low back pain.

These changes are illustrated by the phenomenon of arthrogenic muscle inhibition, a reflex mechanism described in peripheral orthopedics and triggered by joint pain, reducing the nervous activation of the spinal stabilizing muscles [55]. This alteration of the nerve fibers of the multifidus and erector spinae muscles in patients with low back pain has been documented by electromyographic studies [56, 57]. This decrease in neuromuscular control compromises trunk stability and impairs proprioception, leading to defects in postural control by the motor cortex, perpetuating poor posture and low back pain [58].

Beyond muscle degeneration, fatty infiltration of the paravertebral muscles is a determining factor. In some patients, paravertebral muscle fatty infiltration has been shown to be more closely correlated with pain than disc degeneration or changes in the vertebral endplates [59]. While this muscle degeneration results in overrecruitment of type II fibers, it should be noted that high levels of type I fibers have been reported in the paravertebral muscles in some patients, illustrating the mechanical overload imposed on the muscles of patients with chronic low back pain [60]. In parallel with this mechanical overload, the combination of fatty infiltration and recruited anaerobic fibers leads to reduced muscle quality and efficacy [61], perpetuating the mechanism.

Finally, animal studies suggest that inflammation of the muscle fascia may also play a role in lumbar nociception, particularly through the activation of myofascial trigger points [62]. These areas, subjected to prolonged nociceptive stimulation, show an increase in inflammatory mediators, such as substance P, CGRP, TNF, and IL-1, contributing to local hyperalgesia [63].

3.3.4 Central Dysregulation

In addition to peripheral hyperexcitability, the literature suggests that patients with chronic low back pain have a lower pain threshold than healthy people [64].

At the spinal level, prolonged pain impulses cause structural changes in the dorsal root ganglion and the neurons that originate from it, resulting in greater excitability and a lower pain threshold than in the healthy population [65].

At the cerebral level, the increased excitability of the neurons in the dorsal horn leads to a phenomenon known as "wind-up." This phenomenon corresponds to a cascade of chemoreceptors increasing neuronal excitability and leading to cerebral hypersensitivity and therefore a reduction in the cerebral pain threshold [66]. It is this cascade that leads to secondary hyperalgesia.

Functional imaging studies have highlighted structural changes in pain modulation and sensory systems, as well as in the default mode network [67]. These changes result in reduced activity in areas of the central nervous system responsible for negatively modulating pain.

During the transition to chronic pain, structural changes in the functional connectivity areas of the pain regulatory centers and the emotional dimension of pain (prefrontal medial cortex, limbic system) have been highlighted [68]. The areas involved in emotional circuits become increasingly activated as pain becomes chronic, to the detriment of a purely nociceptive aspect [69, 70]. Some studies suggest that once the condition has become chronic and the emotional areas are involved, this system remains unchanged for years. Time to achieve this change is estimated at one year, illustrating the importance of avoiding the transition to chronicity [26].

3.4 Clinical Examination and Socio-Professional Impact

The assessment of a patient with chronic low back pain involves several elements of questioning and clinical examination. The most important

part of the consultation will be the interview, assessing the impact of this low back pain on the patient's socio-professional life. The clinical examination, which is relatively limited, will look for elements of differential diagnosis, as well as potential emergency criteria.

3.4.1 Medical History

Pain is the most frequent reason for consultation. It is classically described as a "lumbar band-like pain," most of the time medial but, sometimes, lateralized. Its intensity is assessed, potentially using the lumbar and radicular Visual Analog Scale (VAS). An associated radicular pain is searched for, pointing to a disc or canal etiology. Pain aggravated in extension (suggesting a posterior joint cause) is distinguished from pain aggravated in flexion (suggesting a disc cause). The circumstances of onset are specified if they exist (in particular, by looking for an occupational cause, and eliminating trauma, infections, tumors, etc.)

The rhythm of the pain tends to be mechanical in the chronic phase, and inflammatory in the acute and sub-acute phases. Chronic low back pain most often evolves in cycles or crises, medication and paramedical treatments will help to get through some of these cycles. When the underlying pain becomes intolerable and crises are too frequent, the surgery begins to be discussed (Fig. 3.2).

Risk factors for chronicity and prolonged disability, as identified by the HAS, are investigated: associated emotional problems (depression, anxiety, withdrawal from social activities), inappropriate representations and false beliefs, painful avoidance or activity reduction behaviors, professional or financial problems (professional dissatisfaction or search for a secondary financial benefit).

3.4.2 Clinical Examination

The clinical examination is often disturbing in its poverty. The examiner will look for spinal static disorders suggestive of chronic scoliosis (flexible with gibbosity in anteflexion), a scoliotic posture (flexible, disappearing in anteflexion) or an antalgic posture (stiff, fixed in flexion), as well as focal and localized points of pain on spinal palpation. Spinal mobility may be examined, allowing differentiation between the stiff and painful lumbago and the chronic low back pain with subnormal, progressively decreasing mobility.

The radicular pain, if there is one, is specified. A sensory-motor deficit and a cauda equina syndrome are searched and rated with a potential emergency criterion.

A sacroiliac, hip or gluteal origin is investigated as a potential differential diagnosis. A paraclinical investigation of these anatomical regions is carried out if there is any doubt.

Before concluding that the patient has true non-specific chronic low back pain, the HAS recommends ruling out a number of red flags [1]:

- Atypical inflammatory pain.
- Neurological deficit syndrome, perineal paresthesia.
- Significant trauma, associated back pain, significant structural deformity.
- Alteration of general condition, history of cancer, febrile syndrome.
- Intravenous drug use or prolonged use of corticosteroids for another condition.

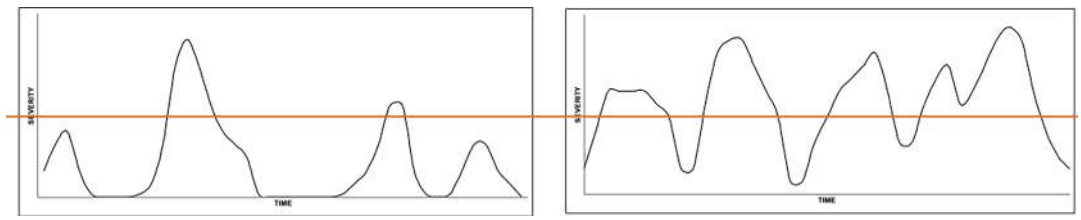

Fig. 3.2 Pain progression over one year: the curve represents pain intensity, the horizontal orange bar the tolerance threshold. The more attacks there are, the more often the tolerance threshold is exceeded

In this way, any traumatic, tumor, infectious, or inflammatory causes can be detected and ruled out, allowing the diagnosis of degenerative low back pain.

3.4.3 Physical Impact Questionnaires

Numerous clinical scores exist to assess patients with low back pain. Due to their time-consuming nature, they are more used for research than in everyday practice. A distinction is made between non-specific and specific scores.

For non-specific scores, the classic Visual Analog Score (VAS) and Numerous Rating (NR) scales, although relatively unreliable, allow a rapid and patient-specific assessment of pain intensity [71]. Despite their subjectivity, they are particularly useful for early pre- and post-operative assessment [72].

Among the non-specific scores, the guidelines of the American academic society emphasize the use of the SF-36 [73], specifically in its functional section. This score is validated in French [74]. It includes the assessment of pain, the impact on the patient's social and professional life, and the patient's psychological state. However, these same recommendations stress the lack of specificity of this score for chronic low back pain, as well as visual analog and numerical scales, and do not recommend them as a first-line evaluation [75]. Still, a version specific to low back pain, incorporating 10 items from the SF-36 and 4 from the ODI, is validated and widely used in the literature [76].

There are more scores specific to chronic low back pain, but they are rarely used in everyday practice. In 2010, a review by Longo counted 28 different scores for chronic low back pain, the most widely used being the Roland-Morris Disability Questionnaire (RDQ), the Oswestry Disability Index (ODI), the Quebec Back Pain Disability Scale (QBDS), the Waddell Disability Index (WDI), the Million Visual Analog Scale (MVAS), the Low Back Outcome Score (LBOS), the Low Back Pain Rating Scale (LBPRS), and the Clinical Back Pain Questionnaire (CBPQ) [77].

The Roland-Morris Disability Questionnaire (RDQ), validated in French [78] is available in several versions depending on the number of questions it contains. It provides a simple assessment of basic daily living functions and the impact of chronic low back pain on them. Based on a total of 24 points, the minimum significant change is recognized as 5 points or 30% of the baseline score [79]. It is one of the most widely used in studies, but does not include the psychological or socio-professional impact of pain.

The Oswestry Disability Index (ODI), validated in French [80], is a functional score that incorporates the patient's social and sexual issues, and is one of the most widely used in studies. Based on a total of 100, the minimum significant change is recognized as 10 points or 30% of the baseline score. The ODI and RDQ are highly correlated [81, 82]. In recent reviews, the ODI is recommended for patients with severe disability, while the RDQ is effective for mild to moderate disability [81, 83].

These two scores are therefore recommended by the American Society (grade A).

Other specific scores include:

The QBPDS, validated in French [84], studies simple activities of daily living, without including social and sexual life or pain intensity. Useful for post-therapeutic follow-up, it is as reliable and at least as sensitive to pre- and post-therapy changes as the RDQ and ODI [75].

The other scores mentioned, which have not been validated in French, incorporate questionnaires on pain intensity and physical or professional impact to varying degrees, without resulting in a unique, comprehensive and validated score.

3.4.4 Psychological Impact Questionnaires

Focusing on physical symptoms (painful or impacting daily life through physical activities), the questionnaires mentioned above do not (or only minimally) address the mental impact of chronic low back pain. However, it is essential to

look for signs of depression, catastrophism or psychosocial stress related with low back pain.

Various studies show that clinical impressions alone are not sensitive enough to detect depression, so the American Society recommends using two specific questions from the Primary Care Evaluation of Mental Disorders (PCEMD), which is commonly used for screening mental disorders [75]. These two questions are as follows:

During the past month, have you often been bothered by feeling down, depressed, or hopeless?
During the past month, have you often been bothered by little interest or pleasure in doing things?

A positive response to either of these two questions should prompt a more detailed investigation for a true characterized depressive episode. The American Society recommends the systematic use of these simple questions whenever the emotional component of pain appears to be at the forefront. It should be noted that the HAS, in its good practice recommendations, recommends the use of Hopital Anxiety and Depression (HAD) score, which has 14 items and is therefore necessarily longer to complete [1].

Among the various risk factors for chronicity and prolonged disability mentioned above, some can be assessed using specific scores, which have been validated for chronic low back pain and are recommended by the American Society.

False beliefs related to pain can be assessed using the Fear Avoidance Belief Questionnaire (FABQ) score. This score comprises two scales, one related to physical activity (FABQ-PA) and one related to work (FABQ-W). This score, which has been validated and reproduced several times, is recommended in current practice [69, 75].

Pain catastrophizing during episodes of low back pain, which is predictive of disability at 6 months, is measured by the Pain Catstrophising Scale PCS, a 13-item score [75].

Psychosocial distress can be assessed using two scores, the Orebro Musculoskeletal Pain Questionnaire (OMPQ) and the StarT Back screening tool, specifically developed for low back pain [75, 85].

The HAS mentions the FABQs, OMPQ, and StarT scores in its recommendations [1].

3.5 Diagnosing and Understanding "True" Degenerative Low Back Pain

Once the clinical assessment and the socio-professional impact of the pain are considered, the clinician can diagnose chronic low back pain. After confirming the non-specific degenerative cause, it is possible to proceed with the etiological investigation.

Although degenerative low back pain is not caused by tumors, infections or trauma, it can have multiple origins: discogenic, articular, static… Imaging tests, combined with the previously conducted interview, sharpen the diagnosis.

In France, the HAS recommendations have recently changed, in line with international recommendations. In cases of acute low back pain without any alarming factors, no radiological examination is necessary [86]. In cases of chronic low back pain, the first-line examination is now Magnetic Resonance Imaging (MRI) rather than X-rays. Therefore, most patients come with an MRI scan at their initial surgical consultation. It is often necessary to add static and dynamic X-rays, or even an EOS assessment, as well as thin-section scans as part of the initial assessment. Scintigraphy is useful for confirming inflammatory disc or joints, or for assessing pseudarthrosis.

By combining the clinical examination with the imaging work-up, the clinician is able to determine the anatomical origin of the low back pain [87].

– *Discogenic.*

Age, repeated trauma and high-risk professions are the main risk factors for discogenic low back pain. Type I and II backs according to Roussouly are more prone to disc degeneration due to greater axial mechanical stress [88].

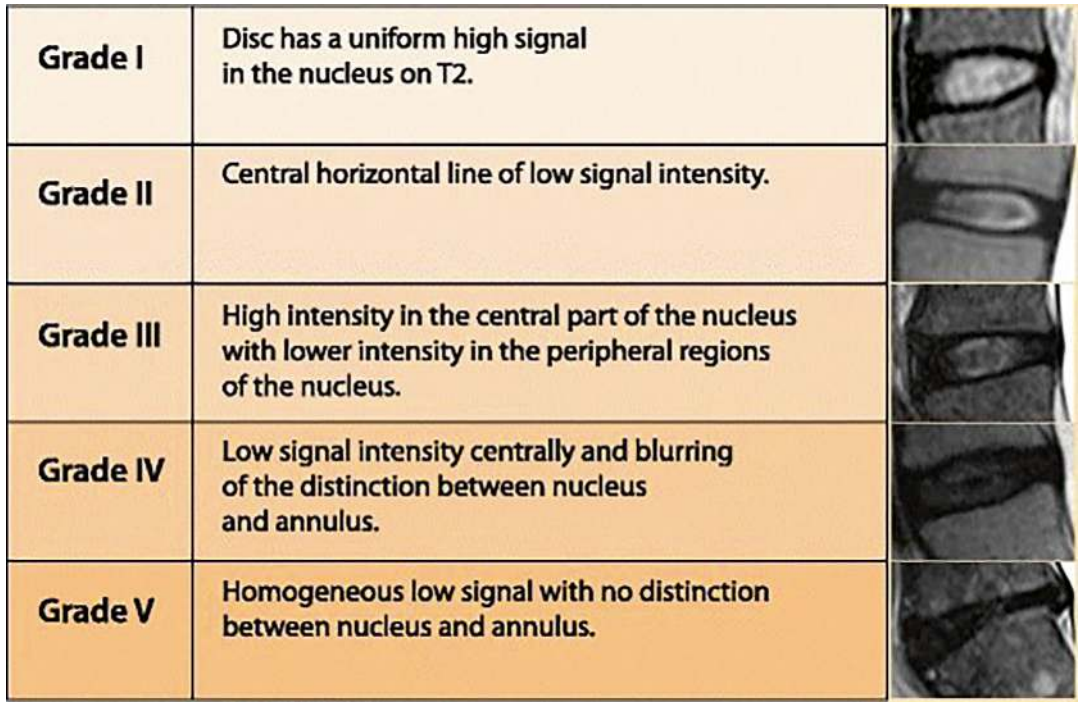

Fig. 3.3 Pfirmann Disc Degeneration's Classification based on T2-weighted MRI study

The clinical examination will typically look for band-like lower back pain with permanent, fixed, localized or more diffuse pain, tightness, heaviness, or spinal stiffness. Recurrent lumbago, impulsiveness when coughing or defecating and painful spasms are sought. Mobility is limited by apprehension, particularly in anteflexion.

Imaging confirms disc degeneration. It can be graded using the Pfirrmann classification [89] (Fig. 3.3). Only MRI is the most efficient to diagnose discogenic origins by finding focal disc degeneration [90]. The number of affected discs is determined as well as any associated damage to the vertebral bodies [38].

Asymptomatic disc degeneration, however, is present in 37% of people in their twenties and up to 96% of people aged 80. Similarly, asymptomatic disc protrusion is present in 29% of people in their twenties and 43% of people aged 80 and over [91]. Anatomical-clinical correlation and prior use of non-surgical therapies are therefore essential before indicating surgical treatment, although there is no pathognomonic link between clinical examination, imaging, and anatomical lesions.

– *Posterior joints.*

Facet joint damage is the second leading cause of chronic low back pain, which also develops slowly over time. Osteoarthritis and spondylolisthesis are the main risk factors. Type 3 and 4 backs are more prone to joint osteoarthritis. Facet pain presents as axial low back pain, with possible pseudo-radicular radiation to the buttocks, hips and thighs. The pain worsens with trunk rotation and lumbar extension movements. There are no pathognomonic signs [92, 93].

Imaging tests will most often reveal facet joint osteoarthritis, which can be identified on both CT and MRI scans [94]. CT scan is more sensitive [95], but MRI provides greater precision in detecting foraminal stenosis and potential radiculopathy [96]. To grade this osteoarthritis, the Weishaupt classification is most often mentioned in the literature [97]. Scintigraphy can detect joint inflammation [98].

It is indeed the only imaging modality that can predict the effectiveness of a medial branch nerve block (MBB), considered the gold standard for confirming the joint etiology of low back pain [99], and to a lesser extent of the intra-articular infiltration [100].

Thus, there is no clinical or radiological reference for confirming the joint origin of chronic low back pain, but various studies have identified more than 50% improvement in pain after MBB as the diagnostic and prognostic threshold for chronic low back pain of joint origin [101]. Once this threshold is reached, the literature suggests the use of radiofrequency joint denervation as an effective non-surgical alternative for joint-related pain [102, 103].

3.6 Initiating Treatment

Once the diagnosis of chronic low back pain is correctly made and its anatomical etiology identified, a therapeutic strategy is proposed. Except in urgent cases, the treatment process almost always follows the same sequence: therapeutic education, non-pharmacological treatments (physical activity and physiotherapy) and pharmacological treatments including injections, then potentially followed by surgery if none of these measures are successful.

The 2019 HAS recommendations, supported by those of the WHO published in 2023, recommend a "bio-psycho-social" management as the first line of treatment [1, 2].

This patient-centered multidisciplinary approach involves physiotherapists, ergotherapists, psychologists, rheumatologists, specialists in Physical Medicine and Rehabilitation (PM&R), occupational physicians and, if necessary, spinal surgeons or pain specialists.

This multitude of practitioners who can be consulted for low back pain presents a risk of diagnostic and therapeutic wandering, accentuated by consultations with non-specialists. To fight against this wandering and centralize care, genuine "back schools," multidisciplinary health centers bringing together most of these specialists, are developed. They are the gold standard in care, but there are still too few of them and thus are difficult for patients to access.

3.6.1 Initial Care

The first line of treatment is therefore therapeutic education. As strict rest is no longer recommended (and should be discouraged, as it is one of the most widespread misconceptions), the practitioner encourages pain self-management and a return to social and professional activities, provided that the professional activity does not risk perpetuating the pain. A return to appropriate physical activity and weight loss are also suggested. For chronic patients, the introduction of physiotherapy sessions is recommended from the outset.

Education on the neurophysiology of pain, which is more complex and less accessible, is recommended as a second step, again with the aim of combating false beliefs. This education is ideally carried out in pain management centers, bringing together psychologists, neurologists, and algologists. Similarly, psychological interventions such as cognitive-behavioral therapy (CBT), carried out by trained professionals, can be used as a second line of treatment.

3.6.2 Physiotherapy

The addition of physiotherapy to therapeutic education has proven effective as a first-line treatment [104].

In recent years, physiotherapists have developed an "evidence-based practice" (EBP), similar to evidence-based medicine, with the aim of harmonizing and optimizing practices [105, 106]. Recommendations for low back pain are published by the American Physical Therapy Association, based on this EBP, and largely agreed by the HAS and WHO [1, 2, 104].

It is recommended that exercises appropriate to the clinical situation be performed and, above all, that patients be taught these exercises so that they can perform them at home. These exercises

involve the patient as much as possible and are not limited to isolated passive therapies (not effective in the progression of low back pain [1, 104]). Aerobic exercises, balneotherapy and lumbar muscle strengthening have proven to be effective [107]. Stretching, yoga, Pilates, and muscle strengthening at home are also grade A [2]. Massages are of limited use. It should be noted that lumbar traction, ultrasound and TENS are not recommended. According to the HAS, wearing a lumbar belt or corset for a short period of time is possible to promote the resumption of social and professional activities and combat kinesiophobia, but it has not been proven to be effective and is therefore not recommended by the WHO [1, 2].

3.6.3 Medication

The first-line treatment is based on NSAIDs, in accordance with the recommendations of the HAS and the WHO, respecting contraindications, for a short period of time and at the lowest effective dose. The use of paracetamol is recommended according to the HAS (Grade A) but without recommendation or counter-recommendation due to lack of evidence for the WHO [1, 2].

As a second-line treatment, the use of opioids and opioid derivatives is recommended as grade B, with the same precautions as for NSAIDs. The risk of misuse must be considered, particularly in high-risk patients, who can be identified using the Opioid Risk Tool score for initial prescriptions and the Prescription Opioid Misuse Index (POMI) score for renewals. There are no studies available to determine the benefits of treatment with nefopam or corticosteroids.

In cases of pain with a neuropathic component, the introduction of antidepressants (tricyclics or SNRI) or gabapentinoids is recommended. If this fails and surgery is not an option, the use of spinal cord stimulation may be considered.

Muscle relaxants, vitamin D, lidocaine patches and antibiotics are not recommended.

3.6.4 Percutaneous Techniques

3.6.4.1 Epidural Infiltrations

The role of corticosteroid spinal infiltrations in low back pain is studied since the 1950s. Injections currently include a mixture of long-acting corticosteroids combined with a local anesthetic [108]. Initially empirical and rapidly widely used, it is the subject of recent systematic reviews to clarify its indications [109]. There are four potential approaches: interlaminar, caudal, transforaminal, and intra-articular [110, 111]. The choice of approach depends essentially on the suspected location of the cause of the pain, as well as the surgeon's habits and the availability of equipment [112]. Recent guidelines do not indicate a preferred approach, but agree on the need for imaging guidance (radiology, CT-scanner, MRI) for all these approaches [112].

Epidural infiltration may be useful mainly for low back pain with radicular irradiation, radiculitis and spondylolisthesis with axial pain [109]. However, studies on the subject differ [113] and suggest above all a short-term effect, in cases of predominant radiculalgia [114, 115].

3.6.4.2 Joint Etiologies

As previously described, low back pain of joint origin is partly due to injury of the medial branch from the dorsal branch of the spinal nerve. In addition to infiltration, this branch can be destroyed by heat (radiofrequency ablation) or cold (cryoablation) [116]. These techniques, which have limited efficacy over time, are currently dedicated to fragile patients, and have the advantage of being able to be performed under local anesthetic and multiple times. The average reduction in pain is 1 to 2 years, with a success rate varying from 55 to 85% [117]. The various studies show similar results between infiltration and denervation, with essentially short-term results—and a slight superiority for denervation [118].

High-intensity focused ultrasound (HIFU) is a less commonly used denervation alternative, due to its duration, lack of availability and cost. This technique is aimed directly at the articular surface where the articular nerve terminates, but

remains anecdotal in current practice for all the limitations mentioned [119].

3.6.4.3 Discogenic Etiologies

In addition to infiltrations, recent years have seen a development of percutaneous decompression techniques, under the lead of interventional radiologists. There are three mechanisms of action. The most commonly used is mechanical decompression, in which the equipment used is placed within the disc to reduce disc volume and potentially reduce nerve irritation, or even to remove the hernia directly [120]. This is followed by thermal decompression, similar to intradiscal radiofrequency, and chemical decompression, by intradiscal chemical destruction of the nucleus pulposus [121, 122]. Because of the mechanism of action of this intradiscal decompression (reduction of disc volume to reduce the associated herniation volume), the ideal patients are those suffering from non-deficient discogenic low back pain with contained disc herniation. In some studies with well-selected patients, these techniques appear to have been more effective than conventional infiltrations [123, 124]. There are few studies documenting the results of these techniques in relation to each other and even fewer comparing them to conventional surgical techniques. The trend appears to be equivalent in terms of short-term efficacy on pain, with a higher rate of recurrence requiring secondary surgery in the percutaneous group [125, 126].

3.6.5 Surgery

Quoting the latest HAS recommendations, "no study has evaluated the optimal period of medical treatment prior to surgery for chronic degenerative low back pain." Recourse to an operation becomes logical as soon as chronic low back pain, well managed by the various techniques mentioned above, becomes long-lasting and disabling in socio-professional terms.

Clear and fair information on the specific risks of surgery and the expected results is essential, as low back pain surgery remains functional surgery and is one of the leading causes of legal complaints every year.

The choice of surgical technique depends on the etiological, clinical and imaging findings. There are many surgical techniques available for the treatment of chronic low back pain. They are all detailed later in this book.

Each technique responds more specifically to certain etiologies or clinical situations. The surgeon must be able to offer each patient the most adapted technique. However, there is no consensus on any of these techniques, so each surgeon establishes his own selection criteria based not only on the patient's characteristics, but also on his experience and surgical culture.

We propose an algorithm to decide which technique to use based on the factors studied above (Fig. 3.4).

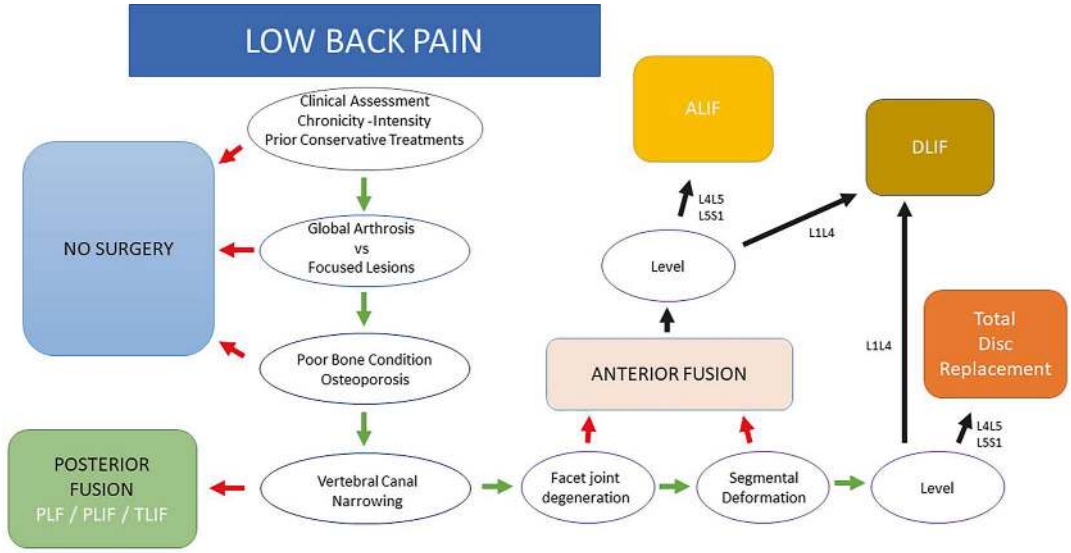

Fig. 3.4 Example of a technical strategy to treat Chronic Low Back Pain based on the clinical and imaging elements of analysis

3.7 Conclusion

Chronic low back pain is a major socio-economic problem of growing importance. Our understanding of its pathophysiology and mechanisms remains incomplete. As a result, current treatment options, although increasingly sophisticated, are often only partially or temporarily effective.

Given the complex and multifactorial nature of chronic low back pain, treatment must necessarily be multidisciplinary and progressive. It is crucial to consider the patient's psychosocial context and to inform them of the origin of their pain, its possible progression, and the lack of certainty regarding their response to the therapies proposed.

By better assessing the precise etiology of the pain, through clinical examination, imaging and potential percutaneous techniques, the clinician will be able to propose the "right" treatment (surgical…or not) for the "right" patient.

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Lumbar Disc Herniation: Diagnosis and Treatment

4

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4.1 Introduction

A lumbar herniated disc (LDH) is defined as the localized displacement of disc material beyond the normal margins of the intervertebral disc space, producing posterior or lateral nerve compression that leads to radicular pain, motor weakness, or sensory disturbances in a dermatomal distribution [1]. More rarely, it can cause cauda equina syndrome (CES). LDH is best understood as a container–content discordance: structural failure of the annulus allows nucleus material to escape into the spinal canal or foramen, where it occupies space and irritates neural elements. Massive central herniation can compress multiple rootlets and the distal cauda, resulting in CES with urinary retention, saddle anesthesia, and bilateral deficits. As with lumbar stenosis, imaging findings are common in asymptomatic adults, and clinico radiologic correlation is essential to avoid overtreatment [9].

4.2 Epidemiology

Sciatica affects around 1–5% of the population annually, with lifetime prevalence approaching 40% in some series [3]. LDH is uncommon before the age of 20, peaks between 30 and 50, and gradually declines thereafter [11]. The L5–S1 and L4–L5 levels account for most cases; with advancing age, relatively more herniations appear at higher levels (L3–L4 or L2–L3), paralleling age-related changes in disc composition and sagittal alignment [10]. Risk is modified by both intrinsic and extrinsic factors. Evidence from twin studies confirms a genetic predisposition to LDH [13]. Additional risk is conferred by a positive family history, elevated body mass index, smoking [15], cardiovascular comorbidities, occupations involving heavy manual labor [12, 17], repetitive forward flexion, and exposure to whole-body vibration such as long-haul driving [18]. Recreational activity patterns show heterogeneous associations; patients often report that brisk walking exacerbates symptoms in the acute phase, whereas graded exercise later becomes a pillar of rehabilitation [16]. The practical implication is to individualize prevention and counseling: coach smoking cessation, core conditioning, and workplace ergonomics while acknowledging a meaningful genetic substrate [14].

4.3 Anatomy and Pathophysiology

The intervertebral disc comprises a proteoglycan-rich nucleus pulposus (NP), a collagenous annulus fibrosus (AF), and thin cartilaginous endplates

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anchoring the disc to adjacent vertebrae. NP aggrecan–hyaluronan aggregates hold water and generate hydrostatic pressure; the AF's concentric lamellae resist tension and shear [4, 5]. With aging and degeneration, proteoglycans decline, water is lost, the disc flattens, and annular fissures appear—especially posterolaterally, where the posterior longitudinal ligament is thinner [6].

Repetitive loading drives NP through a radial annular defect. If the posterior longitudinal ligament contains the fragment, the herniation is subligamentous; if not, extruded material reaches the epidural space (Fig. 4.1).

Neurologic effect depends on location: central/paracentral fragments typically compress the traversing root (e.g., L5 root at L4–5), while foraminal/extraforaminal fragments impinge the exiting root (e.g., L4 root at L4–5) [4, 6].

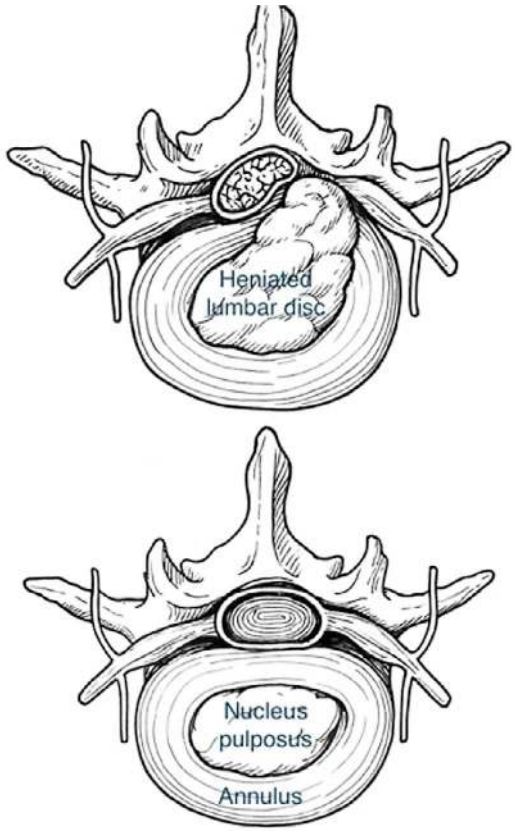

Fig. 4.1 Image of the nucleus pulposus through an annular defect created a lumbar disc herniation

Pain is not purely mechanical. Extruded NP is immunogenic; cytokines (TNF-α, IL-1β, IL-6) and matrix metalloproteinases sensitize dorsal root ganglion neurons and amplify ectopic firing [7]. This explains the severe, lancinating quality of sciatica and the occasional mismatch between herniation size and symptom intensity. The natural tendency of the immune system to resorb extruded fragments underpins the success of watchful, structured conservative care [25].

4.4 Clinical Presentation

Patients typically recall a precipitating event—lifting, twisting, or even a sneeze—followed by low back pain that migrates into the leg over hours to days. Radicular pain tracks a dermatome (commonly L5 or S1) and worsens with cough, sneeze, or Valsalva. Sitting intolerance is common; standing or gentle walking may partially relieve symptoms. Sensory disturbance like sensory change (paresthesia, hypoesthesia) is reported; patients frequently report paresthesias, hypoesthesia, or anesthesia in the affected dermatome. Motor disturbances as a focal weakness in muscles of the involved myotome, and diminished reflexes complete the classic picture [19–21]. Muscle strength should be graded using the Medical Research Council (MRC) scale [2] Tables 4.1 and 4.2.

The physical examination reveals that the reflexes are diminished or absent; reflexes may indicate root involvement. L4 radiculopathy typi-

Table 4.1 MRC (0–5) muscle-strength grading scale (Aids to the Examination of the Peripheral Nervous System LONDON: HER MAJESTY'S STATIONERY OFFICE, 1976)

Grade	Description
0	No muscle contraction detected
1	Flicker or trace of contraction, but no movement
2	Active movement with gravity eliminated
3	Active movement against gravity only
4	Active movement against some resistance
5	Normal muscle strength

Table 4.2 Primary motor functions by lumbosacral spinal root [21]

Spinal root	Primary motor function
L1	*Hip*: Flexion, adduction, medial rotation
L2	*Hip*: Flexion, adduction, medial rotation
L3	*Hip*: Flexion, adduction, medial rotation *Knee*: Extension
L4	*Knee*: Extension *Ankle*: Dorsiflexion *Foot*: Inversion
L5	*Hip*: Abduction, extension, lateral rotation *Knee*: Flexion *Ankle*: Dorsiflexion *Foot*: Eversion *Great-toe*: Extension
S1	*Hip*: Abduction, extension, lateral rotation *Knee*: Flexion *Ankle*: Plantar flexion *Foot*: Eversion
S2	*Knee*: Flexion *Ankle*: Plantar flexion *Intrinsic foot muscles*
S3	*Intrinsic foot muscles*

cally reduces the patellar reflex, while S1 radiculopathy abolishes the Achilles reflex [21].

A straight-leg raise reproduces ipsilateral leg pain; a crossed straight-leg raise, though less sensitive, is strongly specific [19].

Cauda Equina Syndrome (CES) must be investigated and ruled out. Red flags include new urinary retention (or overflow incontinence), fecal incontinence, saddle anesthesia, and bilateral or multi-root weakness. Only a minority of suspected cases are confirmed on MRI, but any suspicion mandates urgent imaging and prompt decompression [22, 23]. Even with timely surgery, some patients retain residual bladder dysfunction [24], another reason to minimize delays from symptom onset to treatment.

4.5 Paraclinical Investigations

The evaluation of lumbar disc herniation (LDH) is essential for confirming the diagnosis, defining the extent of pathology, and guiding surgical planning. Although clinical history and neurological examination remain the cornerstone of diagnosis, they are often supplemented by imaging and neurophysiological studies to establish an accurate correlation between symptoms and structural abnormalities.

Magnetic resonance imaging (MRI) is the gold standard in the diagnostic work-up of LDH. Its superior contrast resolution and multiplanar capability allow excellent visualization of disc morphology, nerve root impingement, and secondary changes such as endplate edema or epidural inflammation [2, 8]. T2-weighted sagittal and axial sequences are particularly valuable, as they not only demonstrate the extent of herniation but also delineate the affected nerve root within the dural sac. In suspected cauda equina syndrome (CES), MRI is indispensable and should be performed without delay, since urgent decompression within 24 to 48 h is strongly associated with improved bladder and rectal function [35, 36]. Nonetheless, MRI is not infallible; disc protrusions are frequently observed in asymptomatic individuals, underscoring the need for cautious interpretation in the clinical context [9]. Contraindications such as pacemakers or severe claustrophobia may also limit its use (Fig. 4.2).

Computed tomography (CT), although less sensitive for soft tissue, retains significant diagnostic value, particularly in detecting disc calcification and characterizing osseous anatomy [37]. For patients in whom MRI is contraindicated, CT provides a rapid and widely available alternative. It is also helpful in preoperative planning, particularly in revision procedures or when concomitant bony stenosis is suspected. CT myelography, once the standard of care, now plays a subsidiary but not obsolete role. It remains useful in cases of multilevel disc disease where the symptomatic level is unclear on MRI, in postoperative patients with metallic instrumentation obscuring MRI interpretation, or when MRI is not feasible [38]. Although invasive and associated with risks such as post-dural puncture headache or contrast reactions, CT myelography can yield critical information on nerve root sleeve compression and cerebrospinal fluid dynamics (Fig. 4.3).

Electrodiagnostic studies add a complementary dimension to imaging. Electromyography (EMG) and nerve conduction studies (NCS) are particularly useful when the clinical radiologic correlation is ambiguous or when multilevel degenerative changes complicate localization. EMG detects denervation potentials in myotomal muscles, thereby confirming radiculopathy and

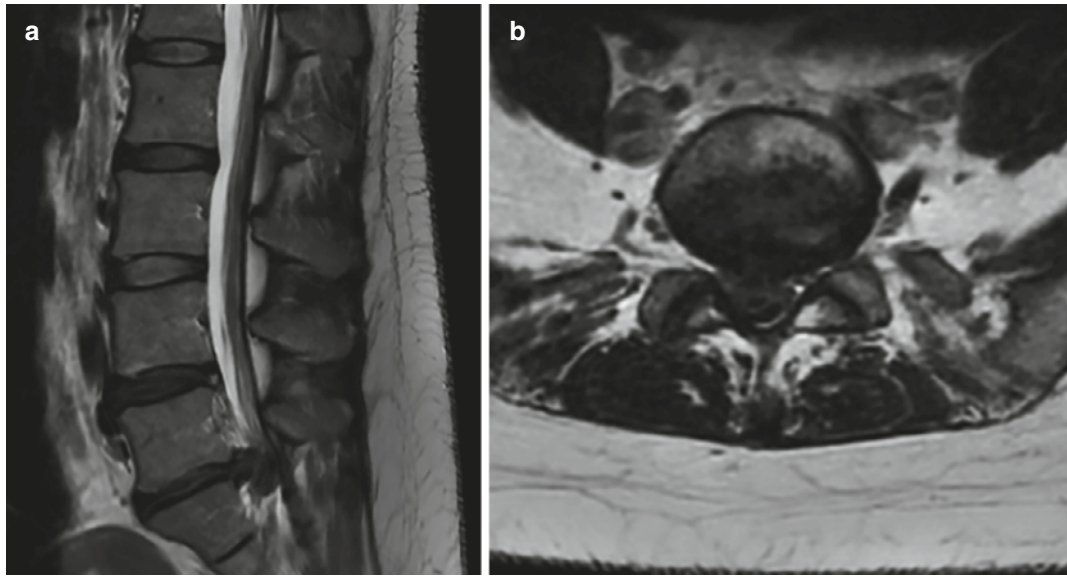

Fig. 4.2 Sagittal (**a**) and axial (**b**) T2-weighted MRI images in a patient presenting with acute cauda equina syndrome demonstrate a large, central L5–S1 disc herniation causing marked compression of the distal cauda equina nerve roots

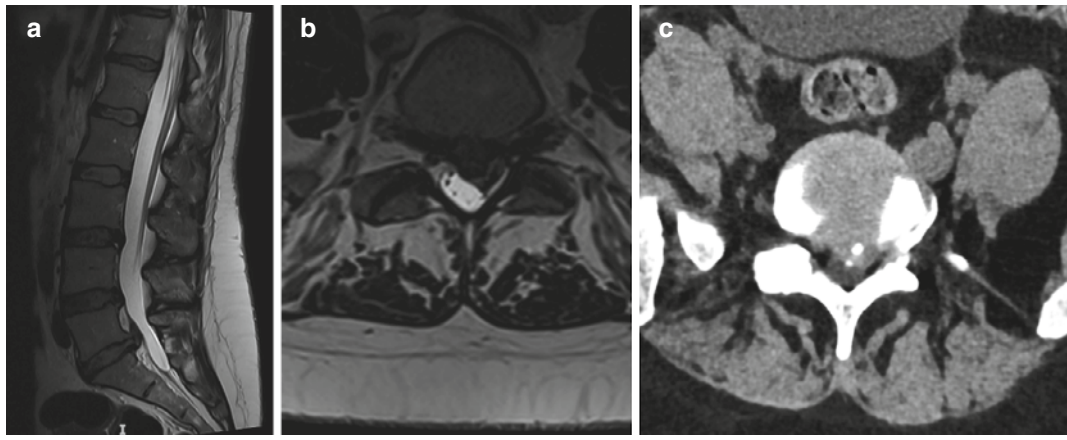

Fig. 4.3 Sagittal (**a**) and axial (**b**) T2-weighted MRI images in a patient with an L5–S1 disc herniation refractory to conservative management demonstrate a left centrolateral extrusion compressing S1. Corresponding CT scan (**c**) shows focal calcifications in the LDH

identifying the specific root involved. NCS are valuable in excluding conditions that mimic radiculopathy, such as diabetic polyneuropathy or entrapment neuropathies [39]. Importantly, EMG has temporal limitations: abnormal findings are most reliably detected at least three weeks after symptom onset, once Wallerian degeneration has occurred [40]. Despite their utility, electrodiagnostic tests are operator-dependent, uncomfortable for patients, and less sensitive in cases of purely sensory radiculopathy.

Taken together, these ancillary investigations form a hierarchical diagnostic algorithm. MRI is the primary modality and should be urgently performed in cases of CES or progressive paresis. CT and CT myelography provide valuable alternatives in selected situations, particularly when

MRI is contraindicated. Electrodiagnostic studies contribute functional information that imaging cannot, particularly in distinguishing clinically relevant root compression from incidental findings. International guidelines converge on these principles, recommending MRI as the first-line modality, reserving CT and myelography for specific scenarios, and employing EMG when clinical and imaging findings do not align [2, 34]. Thus, while the clinical examination sets the stage, the thoughtful integration of ancillary investigations ensures accurate diagnosis and optimally tailored treatment strategies in patients with LDH.

4.6 Natural History and Prognosis

Sciatica due to LDH is often self-limiting. Approximately 75% of patients improve substantially within one month, although nearly 30% still report intermittent symptoms after one year without surgery [25].

4.6.1 Conservative Treatment

First-line management includes analgesia (according to the WHO pain ladder), short-term activity modification, and physiotherapy. Guidelines recommend sustained analgesic therapy during both the acute and chronic phases, with structured exercise therapy introduced in the subacute phase. Orthoses may be considered in selected cases. By contrast, traction, ultrasound, electrotherapy, and massage are not recommended in the acute setting [32].

4.6.2 Surgery and Timing

Symptom duration is a major predictor of surgical outcome. Multiple studies, including the SPORT trial, identify six months as a critical threshold: patients undergoing surgery earlier achieve superior functional outcomes and report less residual pain compared with those treated after longer delays [26, 30]. Surgery within 6–8 months consistently correlates with improved results relative to later intervention [27–29].

A landmark randomized trial by Peul et al. compared early surgery (6–12 weeks after onset) with prolonged conservative management. Early surgery produced faster relief and functional recovery, though long-term outcomes converged due to high crossover rates [31].

4.6.3 Guidelines

German and Danish societies recommend 6–12 weeks of conservative treatment unless progressive neurological deficits or intractable pain necessitate earlier surgery [32, 33]. The North American Spine Society advises early surgery for severe motor deficits, whereas in other cases, surgery within 6–12 months remains appropriate [34].

The time factor therefore matters: prolonged preoperative symptom duration correlates with slower and less complete recovery of both pain and strength. This observation does not mandate early surgery for all patients, but it guides shared decision-making. If disabling sciatica persists beyond 6–8 weeks despite structured care, the probability of rapid, durable relief with discectomy increases, while the likelihood of full neurological recovery gradually diminishes with further delay.

4.7 Nonoperative Treatment

4.7.1 Education and Activity

Patients should be reassured that movement is safe and beneficial. Short, frequent walks are encouraged, while prolonged bed rest should be avoided. Clinicians should explain the rationale for graded exposure to flexion and extension based on symptom response, thereby fostering patient confidence and adherence to rehabilitation programs [1, 32].

4.7.2 Analgesia

Nonsteroidal anti-inflammatory drugs (NSAIDs), with gastroprotection when indicated, remain the first-line pharmacological option. Short courses of weak opioids may be considered for acute, refractory pain but should be avoided for long-term use. Neuropathic agents may be prescribed in selected patients with prominent dysesthesia, provided realistic expectations for onset of benefit and potential adverse effects are discussed [1].

4.7.3 Physiotherapy

Initial physiotherapy should emphasize pain-controlling postures and neural mobilization. As symptoms abate, programs should progress to core stabilization, hip-hinge mechanics, and graded loading. The McKenzie method can be useful for extension-responsive patterns, while flexion-biased protocols may benefit patients with concomitant stenosis [32, 34].

4.7.4 Adjuncts

Epidural corticosteroid injections—delivered transforaminally or interlaminarly—may provide temporary pain relief lasting 6–12 weeks and can reduce reliance on systemic analgesics [41]. Evidence for traction and other electrotherapies remains mixed; if used, they should supplement rather than replace the core triad of education, medication, and exercise [32].

4.7.5 Defining Adequate Conservative Care

A genuine trial of conservative management includes appropriate analgesia, structured physiotherapy with measurable functional goals, and sustained activity modification for at least 6–8 weeks, with reassessment every 2–3 weeks. Treatment failure should not be defined simply as persistent pain, but rather as pain that prevents a patient's return to essential life roles despite comprehensive nonoperative care [1, 32].

4.7.6 Indications for Surgery and Timing

- *Emergency*: CES or rapidly progressive major motor deficit—immediate MRI and decompression once diagnosis is confirmed. Earlier intervention (preferably within 48 h of symptom onset for CES) is associated with better bladder and sensory outcomes.
- *Semi-urgent*: progressive or severe monoradicular weakness (e.g., foot drop) even without CES.
- *Elective*: persistent, disabling radicular pain after ≥6–8 weeks of optimized nonoperative care, especially when the clinico radiologic map is concordant and symptom duration is <6 months.

4.8 Surgical Techniques

4.8.1 Standard Open Microdiscectomy

Under general anesthesia in prone position, a short midline incision is done. A unilateral para vertebral muscle dissection from the spinous process and the lamina exposes the interlaminar window using an autostatic retractor. A limited laminotomy and flavectomy open the canal, revealing the dural sac and traversing root. Gentle root mobilization with patties protection exposes the herniation; the fragment is removed under direct vision. A limited intradiscal curettage retrieves loose fragments without destabilizing the motion segment. Hemostasis is meticulous; the wound is closed in layers.

4.8.2 Minimal Invasive Spine Procedure Using the Tubular Technique

Instead of traditional paravertebral muscle dissection from the spinous process and lamina, the tubular technique employs sequential muscle dilation using small tubular retractors. Magnification achieved through an operating microscope or high-quality binocular loupes is essential for adequate visualization.

The tubular system maintains muscle and soft tissue retraction, creating a working corridor that allows the surgeon to access the spinal pathology without the need for a large open incision. This approach minimizes the extensive muscle disruption that typically occurs during open procedures. At the conclusion of surgery, the tubes are withdrawn, permitting the retracted muscles to approximate and reducing postoperative tissue trauma.

4.8.3 Uniportal Endoscopic Interlaminar Discectomy

Planning begins with fluoroscopic confirmation of the operative level and an approach trajectory that aligns the working cannula through a ~7-mm skin incision. A uniportal endoscope is then introduced via the cannula. A micro-hemilaminotomy performed with a high-speed drill facilitates entry into the interlaminar window. The ligamentum flavum is opened, and epidural fat, small veins, and adhesions are cleared using bipolar cautery and blunt dissection. Continuous endoscopic visualization permits targeted fragment retrieval while minimizing neural retraction. At the conclusion, the traversing nerve root is inspected to confirm adequate decompression before closure.

4.8.4 Endoscopic Transforaminal Discectomy

Through a lateral skin entry point 8–12 cm off the midline, the working cannula is advanced to dock on the superior articular process. The operative trajectory, typically angled 20–30°, provides access to the foraminal annular window; the selected levels are up to L4L5. Following annular release, herniated fragments are removed with graspers, while bipolar cautery assists with hemostasis and dissection. Caudally migrated fragments may require partial pediculotomy, whereas rostrally migrated fragments may necessitate a steeper angulation. The endpoint of the procedure is a freely mobile traversing root with no residual impingement.

4.8.5 Biportal Endoscopic (UBE) Decompression/Discectomy

In the biportal approach, two ipsilateral portals are created to form an isosceles triangle directed toward the docking point. Under continuous saline irrigation, a partial ipsilateral hemilaminotomy and flavectomy are performed to gain access. Contralateral decompression can be achieved via an "over-the-top" technique when necessary. In cases of herniation, discectomy is performed with the nerve root protected by the bevel of the cannula or a blunt dissector. Hemostasis is verified by temporarily pausing irrigation. Drains are generally unnecessary when meticulous hemostasis is achieved.

4.9 Conclusion

Lumbar disc herniation (LDH) is one of the most frequent and treatable causes of radiculopathy. Its natural history is often favorable, with many patients improving under structured conservative care. The clinician's responsibility is to distinguish those who will recover with time and rehabilitation from those who require timely surgical intervention to prevent irreversible neurological compromise or prolonged disability.

Modern minimally invasive techniques—including tubular, uniportal, and biportal endoscopic discectomy—achieve the goals of traditional microdiscectomy while minimizing collateral tissue damage and expediting recovery.

Optimal management of LDH requires careful clinico radiologic correlation, shared

decision-making, and tailoring the least invasive effective treatment to each patient. When this strategy is applied consistently, most patients achieve excellent relief of radicular pain and restoration of function.

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Lumbar Spine Stenosis: Diagnosis and Treatment

5

Nicolas Ross and Guillaume Lonjon

5.1 Introduction

Lumbar spine stenosis (LSS) is a pathological condition characterized by a narrowing of the spinal canal, resulting in compression of the neural elements.

Conceptually, it can be understood as a discordance between the capacity of the spinal canal (the container) and the volume of the neural and vascular contents (the contained). This mismatch becomes increasingly relevant with age-related degenerative changes that affect the size of the lumbar canal.

LSS is a frequent pathology and currently the number one spine surgery in people over 60. Given the demographic shift toward an aging population worldwide, its prevalence and burden on healthcare systems are expected to rise [1].

Patients with LSS present with a wide variety of symptoms, including neurogenic claudication, radicular leg pain, sensory disturbances, and weakness. Low back pain is also a frequent complaint in LSS, which contributes to disability in this group of patients [2].

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Radiological evidence of stenosis is frequently observed in asymptomatic individuals [3–5], which can make proper diagnostics challenging for clinicians. Furthermore, current literature shows that clinical symptoms and degree of stenosis are not entirely related; therefore, a high level of suspicion is warranted when encountering patients with complaints of neurological claudication or radiculopathy.

While conservative treatment (physiotherapy, drugs, lifestyle modification, and multidisciplinary rehabilitation) remains the first line of treatment for LSS before surgical intervention, only moderate quality evidence is available regarding the best choice for nonoperative care [6].

The primary surgical goal in LSS is decompression of neural elements, which can be achieved through various techniques.

Conventional open laminectomy has classically been considered the standard of care. Recent systematic reviews and meta-analyses have provided compelling evidence that MIS approaches (tubular and endoscopic) not only achieve comparable, if not superior, clinical outcomes relative to conventional open laminectomy but also offer additional benefits, including reduced postoperative pain, complications, and shorter hospital stays [7].

Another issue to consider in the management of lumbar spinal stenosis is the risk of destabilization and reoperation. A systematic review and

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meta-analysis by Schöller et al. [8] demonstrated that patients undergoing minimally invasive decompression had significantly lower rates of subsequent fusion or revision surgeries compared to those who received open decompression. This reduction in reoperation rates is likely attributable to the tissue-sparing nature of MIS techniques, which minimize disruption to stabilizing structures. These findings suggest that beyond offering comparable short-term clinical outcomes, MIS may confer a durable advantage by decreasing the likelihood of further surgical intervention and should be considered the current gold standard of care.

In this chapter, we considered LSS without spondylolisthesis, which will be addressed in a separate chapter.

5.2 Epidemiology

LSS predominantly affects older adults, with the average age at presentation being around 65 years. It is slightly more common in males, with a male-to-female ratio of approximately 1.5:1. Anatomically, the L4–L5 level is the most affected, followed by the L3–4 level. Several risk factors have been identified: heavy and physical workload, increased body mass index (BMI), diabetes mellitus, and congenital spinal anomalies [9–11].

A systematic review and meta-analysis by Jensen et al. [12] reported considerable variability in LSS prevalence, depending on the population and diagnostic criteria. Clinically defined LSS had a prevalence of 11% in the general population, rising to 25–39% in primary and secondary care settings. Radiologically defined LSS showed similar variability: 11% in asymptomatic individuals, 15–32% in clinical settings, and up to 38% in the general population. The prevalence was higher in older populations, reflecting the age-dependent nature of this pathology.

5.3 Anatomy and Physiopathology

To properly understand and treat LSS, it is essential to have knowledge of the anatomy of the lumbar canal in its different levels. The LSS is often divided into three zones: the central canal, the lateral recess, and the foramen. For each zone, the nerve roots are called differently: the nerve rootlets in the central part of the sac, the so-called "traversing" root, which is the emergence of the root at the level of the recess, and the "exiting" root when it enters the foramen.

5.3.1 The Central Spinal Canal [13]

It surrounds and protects the spinal cord and cauda equina. The spinal canal extends from the foramen magnum to the sacrococcyx. It is bounded anteriorly by the posterior aspect of the vertebral bodies, intervertebral disks, and the posterior longitudinal ligament. Posteriorly, it is limited by the laminae, facets, and ligamentum flavum, which form a tile-like structure in the thoracic region but leave gaps in the cervical and lumbar areas for needle access. Laterally, the canal is bordered by the pedicles, with intervertebral foramina between them.

The shape of the lumbar spinal canal varies from L1 to L5 (Fig. 5.1). In the upper lumbar region, it is mainly ovoid, like the rest of the cervical and thoracic spine. As the articular processes become more coronally oriented, they create a bony ridge that leads to the formation of the lateral recess within the canal [14].

The anatomical definition of stenosis can refer to the narrowing of a container. Verbiest [15] defined absolute stenosis when the spinal canal measures less than 10 mm during surgery. A measurement between 10 and 12 mm, therefore, indicates relative stenosis and is considered wide if the anteroposterior distance (AP) exceeds 14 mm.

Fig. 5.1 Shape variation of the central spine canal

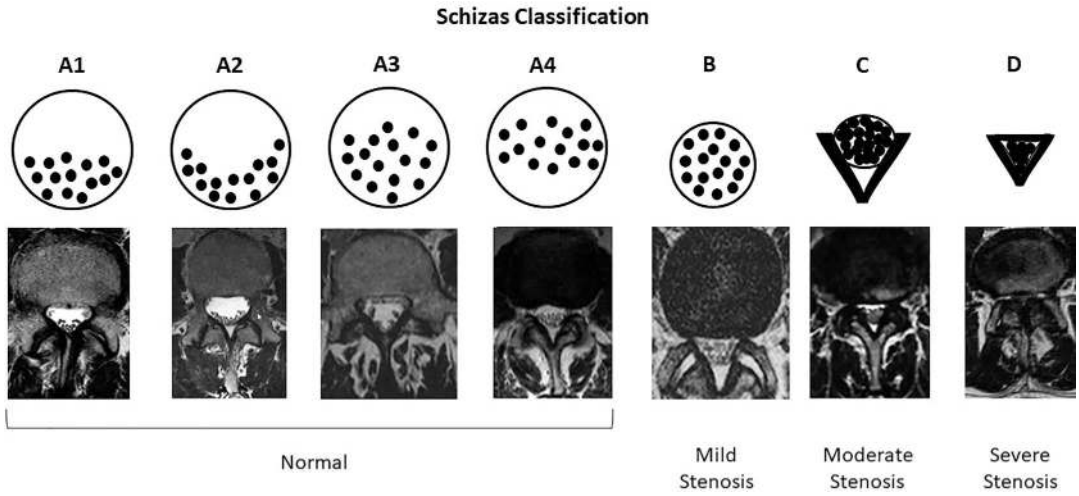

Fig. 5.2 LSS classification by Schizas et al.

The condition of the contents within the canal can also be assessed for stenosis. Schizas et al. [16] defined various degrees of stenosis based on the morphological characteristics of the dural sac and the rootlets (Fig. 5.2).

5.3.2 The Lateral Recess

Described by various authors [17–19], the lateral recess of the lumbar spine is bounded laterally by the pedicle, anteriorly by the disk and vertebral body, and posteriorly by the articular mass covered by the capsule. In a three-dimensional context, the lateral recess remains open toward the central spinal canal.

After exiting the dural sac, the lumbar nerve root passes posterior to the intervertebral disk, courses through the lateral recess, and ultimately exits via the foramen [20].

This space is especially susceptible in degenerative spines, leading to radicular compression

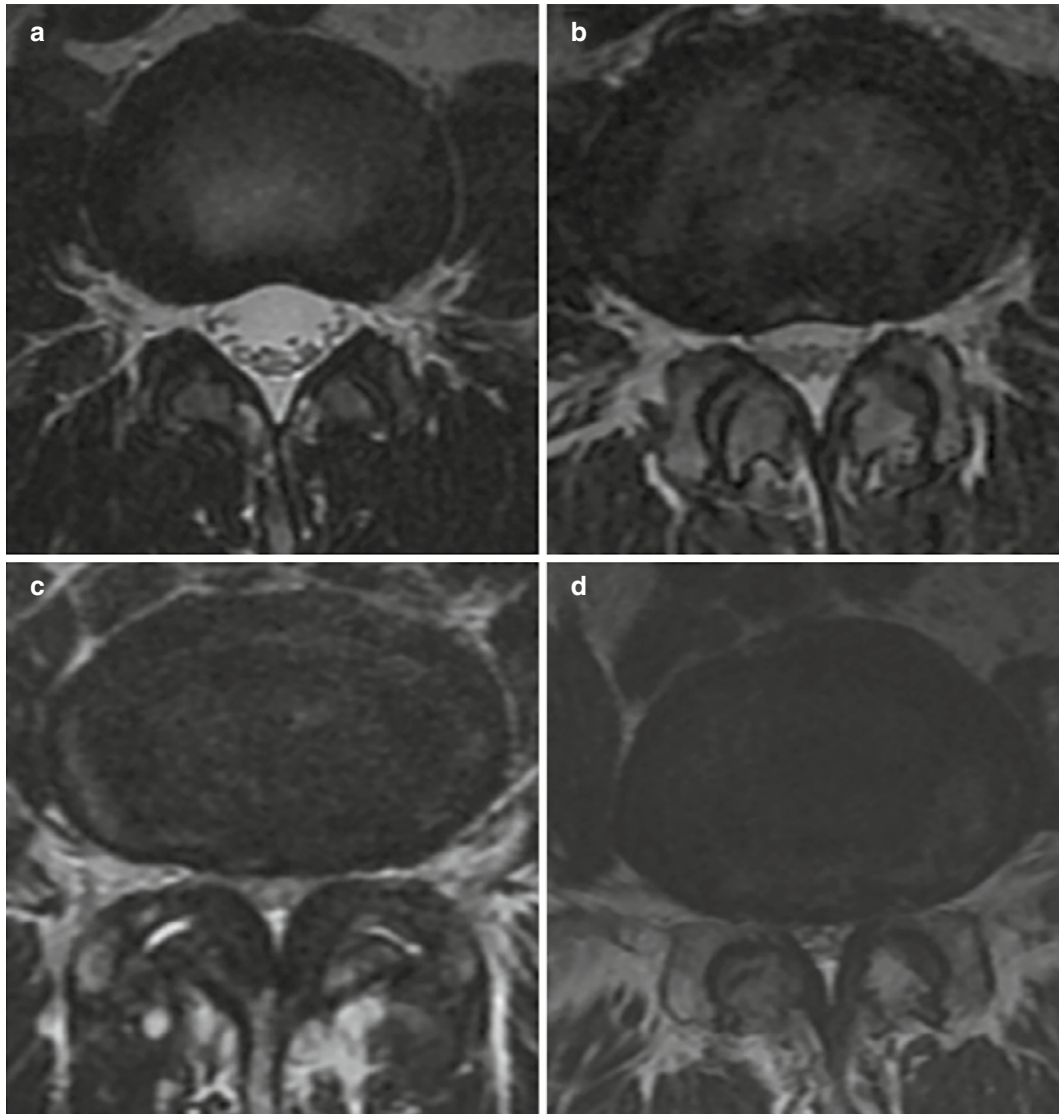

Fig. 5.3 Recess stenosis classification by Splettstößer et al.

of the transversing nerve root, primarily due to the hypertrophy of both the superior articular process and the insertion of the deep layer of ligamentum flavum in this area.

MRI can objectify lateral recess stenosis. Classification is based on the analysis of the freedom of the traversing root and the space between the disk and the joint on axial MRI slices [21] (Fig. 5.3).

5.3.3 The Foramen

The lumbar intervertebral foramen allows spinal nerves and associated structures to exit the spinal canal. It is bordered superiorly by the superior pedicle and inferiorly by the inferior pedicle. Anteriorly, the superior vertebral body and the intervertebral disk define it. In contrast,

posteriorly, the isthmus and lamina of the superior articular process of the lower vertebra contribute to its limits.

Several structures traverse the foramen, including the anterior and posterior roots, the radicular artery and vein, the sinuvertebral nerve, and the foraminal venous plexus. The closed nature of the foramen makes it especially susceptible to compression from various degenerative pathologies such as disk bulging, ligamentum flavum buckling, and osteophyte formation (Fig. 5.4).

Several scoring systems exist for classifying foraminal stenosis, with reasonable evidence of reliability and feasibility in clinical settings, which rely on epidural fat obliteration, stenosis, or root deformity resulting from compression [22].

A recent article by Sartoretti et al. [23] proposes a novel grading system for foraminal stenosis based on previous classifications in 6 grades (Fig. 5.5).

Grade A: Absence of foraminal stenosis.
Grade B: Very mild foraminal stenosis with perineural fat obliteration surrounding the nerve root in only one direction.
Grade C: Mild foraminal stenosis with perineural fat obliteration surrounding the nerve root in two directions. It involves contact with two positions of the nerve root.
Grade D: Moderate foraminal stenosis with perineural fat obliteration surrounding the nerve root in three directions. It involves contact with three positions of the nerve root.

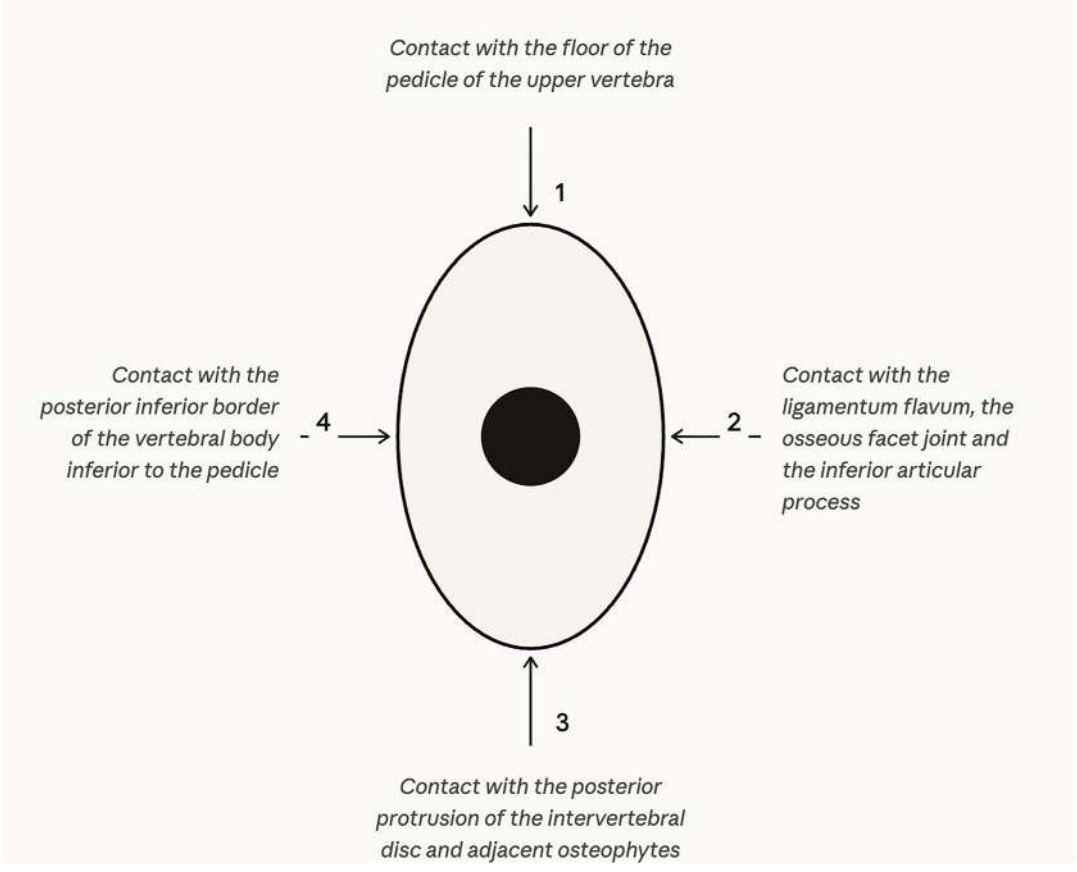

Fig. 5.4 Zones of compression in the foramen

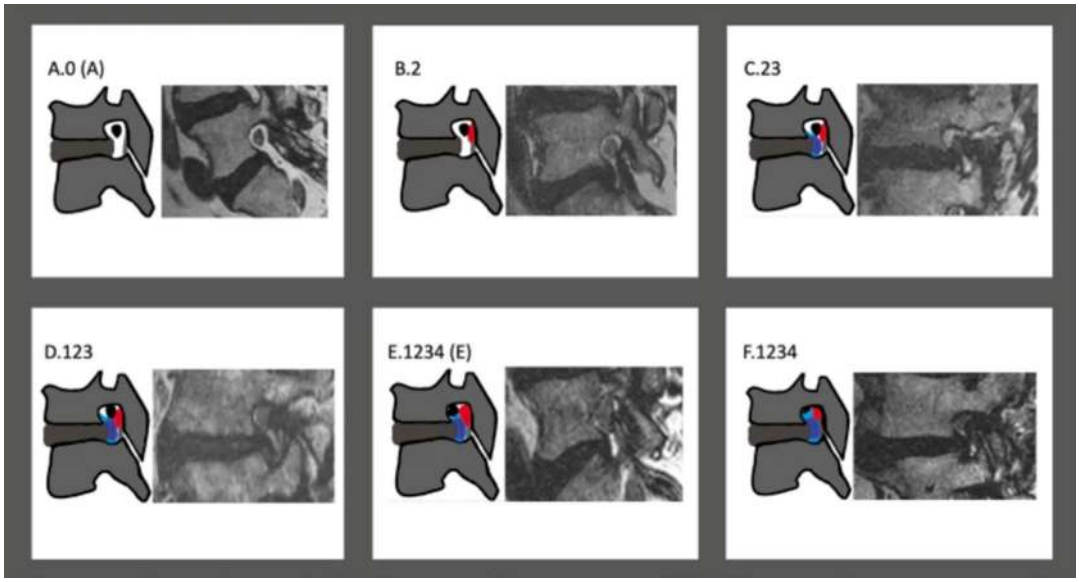

Fig. 5.5 Foraminal stenosis by Sartoretti et al.

Grade E: Severe foraminal stenosis with perineural fat obliteration surrounding the nerve root in four directions. It involves contact with four positions of the nerve root.

Grade F: Very severe foraminal stenosis with nerve root collapse or morphological change.

5.4 Etiopathology of LSS

LSS can be roughly divided into congenital and degenerative. Congenital stenosis can be attributed to an abnormal development of the spinal canal and surrounding anatomy. These patients present clinical signs of stenosis at a much earlier age and are more prone to suffer from multilevel disease [24].

Given that congenital LSS is relatively rare, the focus of this chapter shall concentrate on degenerative LSS [25].

Degenerative LSS is theorized to be a consequence of disk degeneration, facet modification, and ligament and capsule hypertrophy.

The disk degeneration results in a reduced disk height and posterior bulging. The loss of disk height also causes narrowing of the foramen and compression of the nerve roots.

This alteration of spinal loads causes hypercontact between the posterior joints, promoting osteoarthritis and potentially leading to the development of vertebral slippage, known as degenerative spondylolisthesis. Hypertrophy of articular joints leads to diminished space in the canal and the lateral recess, giving compression to the transversing nerve root in the lateral recess [26].

Other factors may contribute to the contents of the spinal canal, such as articular cysts, epidural lipomatosis, or certain tumors originating from the central nervous system or meninges.

Understanding the dynamic component of LSS is also crucial for understanding the frequent discrepancy between clinical findings and imagery. CT scans and MRIs are almost always performed in the supine position, which may underestimate the degree of degenerative changes and the extent of disk bulging. Weight-bearing MRI effectively demonstrates this fact and reveals larger compression, especially in the lateral recess and foramina [27].

Patients' complaints, particularly neurogenic claudication, may not be solely due to mechanical compression, but also result from a mix of vascular compromise: venous stasis and ischemic hypoxia. The venous stasis theory

suggests that compression of the epidural venous plexus impairs drainage, leading to elevated intraneural pressure and edema. This venous congestion disrupts axonal transport and sensitizes nerve roots, resulting in pain and neurological symptoms. The hypoxia theory posits that reduced arterial perfusion, caused by compression, leads to localized ischemia of the cauda equina. Since the nervous system is susceptible to ischemia, even mild deprivation during activity can provoke symptoms. These proposed mechanisms may act in synergy, providing an explanation for activity-dependent symptoms and the often weak correlation between imaging and clinical findings [28].

5.5 Clinical Findings

5.5.1 Claudication

The most specific sign of LSS is neurogenic claudication, which consists of progressive pain, numbness, or tingling in the lower back, buttocks, and/or thighs when walking or performing prolonged lumbar extension, and is relieved by sitting or flexing the spine [29]. Differentiating between neurogenic claudication and vascular claudication is crucial, as both present with leg pain during walking. Neurogenic claudication is typically posture-dependent, improving with just sitting or leaning forward, while vascular claudication improves with rest while standing. A recent study [30] identified that symptoms triggered by standing, relieved by sitting, located above the knees, and a positive shopping cart sign strongly indicate neurogenic claudication (likelihood ratio of 13). In contrast, relief with standing and symptoms below the knees suggests a vascular origin (likelihood ratio of 20). During physical examination, all patients should be questioned about a history of smoking, hypertension, and diabetes mellitus, and distal pulses should be examined. Whenever in doubt about the vascular condition, a CT Angiography (CTA) should be performed to asses perfusion in lower limbs.

5.5.2 Back Pain

Pain is often the primary symptom prompting care-seeking. Although patients with LSS nearly always have some degree of low back pain, if not accompanied by leg symptoms or claudication, back pain alone does not justify a surgical treatment of LSS even in the presence of severe anatomic stenosis. In case of LLS and significantly low back pain, special care must be taken to propose fusion surgery in addition to the decompression. No evidence of benefits exists in the absence of mechanical instability.

5.5.3 Radiculopathy and Other Neurological Findings

Patients may experience not only back pain and claudication, but also other symptoms. Foraminal and lateral recess stenosis often results in radiculopathy. Extreme care should be taken when interpreting imaging results. Determining the exact source of compression can prove challenging. For the same nerve root, impingement may come from central compression, lateral recess stenosis, foraminal stenosis, or a combination of those.

Other less frequent neurological findings that may accompany LSS include loss of balance, sensory loss, and weakness in the lower limbs [31]. If the numbness or sensory loss is associated with anxiety for the patient, only the weakness is a surgical emergency.

5.6 Natural History of Disease

Understanding the natural history of lumbar spinal stenosis (LSS) is critical for clinicians, particularly when advising patients who either decline or are unfit for surgery.

Although LSS is increasingly diagnosed in aging populations, high-quality data on its untreated course remains limited. Available

evidence suggests that LSS does not invariably progress, and many patients managed conservatively experience stable or even improved symptoms over time [32]. No predictive factors can reliably predict deterioration in this patient group.

Multiple non-randomized studies [33–35] highlight that many patients, particularly those without severe symptoms, do not require surgery. A partially randomized trial by Amundsen et al. [36] found that patients with mild to moderate symptoms who received conservative treatment experienced sustained improvement in approximately two-thirds of cases over 10 years.

Outcomes of delayed surgery after failed conservative therapy are also comparable to those of early surgery, suggesting that immediate surgical intervention is not necessary and that conservative measures remain the first line of treatment.

While surgery offers more rapid and substantial improvement, conservative treatment can yield favorable long-term results in a large subset of patients, especially those who may not be candidates for surgery. Physicians must be able to reassure such patients that non-surgical management is a valid and often successful approach, particularly when symptoms are not severely disabling.

5.7 Imaging

5.7.1 Radiography

Standard X-rays are fundamental in the initial evaluation of any spinal pathology. They are quick to perform, widely accessible, cheap, and have low levels of ionizing radiation. While they do not visualize soft tissues, X-rays, which are done in a standing position, still provide valuable information about the spine under load.

In patients with LSS, X-rays enable the assessment of basic coronal and sagittal alignment, which may warrant further studies if a deformity is detected. They also help detect associated abnormalities such as pars defects (lysis), vertebral fractures, spondylolisthesis, disk collapse, and transitional anomalies like lumbarization or sacralization. These findings can directly influence management decisions and must be considered.

Dynamic radiography is essential for assessing segmental instability, which can significantly modify the surgical planning, shifting from a simple decompression to a decompression and fusion. Based on imaging findings of abnormal vertebral motion, flexion-extension radiography is the most widely used method currently. Multiple parameters are utilized to define segmental instability, and the cut-off values are debated by various authors, such as translation exceeding 4 mm or greater than 8% of the vertebral body width, and sagittal angulation exceeding 10° [37]. However, the lack of standardization for obtaining these images, the difficulty of reproducibility, and variation in the range of displacement render its real utility controversial. A prospective study by Liu et al. [38] compared standard flexion-extension radiographs to supine MRI and standing x-rays and found mobility to be greater in the latter, indicating that new standards of intervertebral instability are warranted.

Although beyond the scope of this chapter, it is essential to note that in patients being considered for decompression and fusion surgery in LSS, full-length standing spine X-rays are also crucial. These images are essential for preoperative planning, not only to correct existing deformities, but more importantly, to prevent the creation of new ones. Failure to recognize and preserve global spinal alignment leads to poor functional outcomes, adjacent segment disease, and revision surgery [39, 40].

5.7.2 MRI

Magnetic Resonance Imaging (MRI) is the current gold standard for diagnosing lumbar spinal stenosis due to its ability to visualize neural structures, intervertebral disks, and ligaments. It allows for detailed imaging of the spinal canal and foramina without the use of ionizing radiation.

As previously noted, the degree of radiological stenosis often does not correlate directly with

clinical symptoms. Many individuals, especially older patients, can have significant narrowing while asymptomatic, and others with mild stenosis may present with severe neurogenic claudication or radicular symptoms.

The Schizas classification [16] is a widely used MRI-based grading system that categorizes lumbar spinal stenosis based on the morphology of the dural sac and nerve root visibility on axial T2-W images, ranging from grade A (mild) to grade D (severe) [41].

Quantitative measurements can be performed, such as an anteroposterior diameter of the spinal canal <10 mm or a cross-sectional area of the dural sac <75 mm^2, both of which are generally indicative of significant central canal stenosis, although clinicians seldom perform these measures during consultation.

Recess and foraminal stenosis should also be routinely assessed. For foraminal stenosis, it's essential to examine sagittal views for perineural fat obliteration, flavum or joint capsule hypertrophy within the foramen, and morphologic changes in the nerve root.

MRI can also provide indirect signs of instability that might be missed on standard radiographs [42]. Facet joint effusion, positive vacuum sign, facet angle over 45°, and a greater disk height are associated with the presence of instability in degenerative LSS.

5.7.3 Computed Tomography

Computed tomography (CT) and CT myelography can also provide valuable information [43], particularly in cases where MRI is contraindicated or unavailable. CT also offers superior visualization of bony anatomy, and CT myelography enhances contrast around the spinal cord and nerve roots by injecting contrast dye into the subarachnoid space. CT is also beneficial when planning for revision surgery, where previous hardware has been placed, or to assess whether the spinal canal is open, thereby minimizing the risk of dural breach.

However, CT scans expose the patient to ionizing radiation and have a poorer definition, which limits their use as first-line imaging tools. However, some studies suggest that their sensitivity for detecting stenosis may not be inferior to MRI [44].

5.8 Treatment

5.8.1 Non-surgical

Excluding cases involving severe neurological deficits or bowel/bladder dysfunction, which necessitate urgent surgical intervention, the initial approach to managing lumbar spinal stenosis (LSS) is typically conservative. This non-operative strategy often involves a combination of oral medications, physical therapy, and epidural corticosteroid injections. While various treatment combinations have been suggested, a systematic review by Ammendolia et al. [45] examined the available evidence on conservative care for LSS. The review found moderate evidence that manual therapy and exercise are effective treatments. Interestingly, it also concluded that epidural steroid injections do not appear to be effective in treating LSS associated with neurogenic claudication. Other conservative treatment options remain under investigation, with varying levels of supporting evidence.

5.8.2 Surgical Treatment

Current evidence suggests that decompression for LSS is effective and superior to non-operative treatment when conservative measures have failed [46]. The classical gold standard approach for LSS is open laminectomy. While effective and safe, the risk of dural tears, infection, and iatrogenic instability is still present. For this reason, less invasive techniques have been proposed, such as unilateral laminotomy for bilateral decompression (ULBD) [47], which can be accomplished via tubular or endoscopic approaches. These minimally invasive techniques have proven to be superior to conventional open surgery in terms of clinical effectiveness, complication rates, and patient satisfaction [7, 8, 48].

5.8.3 Effect of Decompression on Back Pain

While it is classically thought only to mitigate neurological symptoms, decompression surgery has been shown to decrease LBP even in some patients whose main complaint is axial back pain [49–51].

However, attention should be paid to patients whose chief complaint is back pain, as it has been associated with significantly worse outcomes after decompression [52]. Clinicians should be aware of this for informed decision-making and effective patient management.

5.8.4 The Role of Arthrodesis

The role of fusion in decompression surgery is a subject of controversy. Generally recommended for patients with concomitant LSS and degenerative spondylolisthesis or instability [53], fusion has failed to demonstrate better outcomes than decompression alone for patients without severe deformity or gross instability, only adding additional operative time and costs [54]. Results of high-evidence randomized trials, including the NORDSTEM trial [55], show that patients with LSS and degenerative spondylolisthesis fare equally well in the short and long term without undergoing fusion.

However, decision-making on fusion should be made on a patient-to-patient basis, especially for those with degenerative spondylolisthesis associated with LSS. A prospective study by Blumenthal et al. [56] searched for predictors of instability following decompression for this type of patient and found that patients with motion of over 1.25 mm, a disk height greater than 6.5 mm, and sagittally oriented facets (over 50°) had an increased risk of reoperation compared to those without these characteristics.

In a retrospective study of 445 patients with LSS, Dimitriou et al. [57] sought to identify risk factors for reoperation and develop a score for decision-making. They found that low back pain, bilateral facet effusion on MRI, and disk degeneration (Pffirman 3 or worse) were associated with an increased risk for treatment failure following decompression.

It should be stressed that fusion surgery is not intended to relieve back pain but to treat instability, which can manifest as low back pain. There is no evidence to support that patients with LSS whose chief complaint is back pain without signs of instability or deformity will benefit from fusion surgery.

5.9 Surgical Techniques

5.9.1 Open Conventional Laminotomy

A midline incision is carried over the spinous processes from pedicle to pedicle as referenced from preoperative marking. The lumbar fascia is encountered and cut in line with the skin incision. Paraspinal muscles are detached from their insertions in the spinous process and lamina in a subperiosteal fashion to avoid bleeding. Dissection should be carried up to the medial edge of the articular facets. Care must be taken not to damage the articular capsule. Radiological check is carried out.

At this stage, the interspinous and supraspinous ligaments are removed, and the interlaminar window is exposed, allowing visualization of the ligamentum flavum and the edge of the lamina.

With the use of a drill or Kerrison rongeur, a laminotomy is performed, starting from caudal to rostral and from central to lateral. Bone resection is carried out until we encounter the insertion of the ligamentum flavum in the lamina. Care should be taken to leave enough pars interarticularis/isthmus to avoid fracture and potential instability.

Lateral bony resection is done with a partial facetectomy. Again, as iatrogenic instability is a concern, this arthrectomy should be as minimal as possible and carried out obliquely from central to lateral. Indeed, the compression of the transversing nerve root in the lateral recess is mainly caused by the superior articular facet of the inferior vertebra, its capsule, and the lateral insertion of flavum.

Once exposed and partially detached, the ligamentum flavum can be removed from central to lateral with the aid of Kerrison rongeurs. The partial arthrectomy and osteotomy of the superior articular process allows for decompression of the nerve root in the lateral recess and along its foraminal trajectory.

After the lateral recess is identified and decompressed, the quality of the decompression can be assessed by various means: free mobilization of the nerve root, introduction of a spatula following the nerve into the foramen, or radiographic imaging showing decompression from pedicle to pedicle.

5.9.2 Minimally Invasive Decompression

Regardless of the specific technique used, the core principle of minimally invasive spine surgery (MIS) for lumbar decompression relies on unilateral laminotomy for bilateral decompression (ULBD), which enables effective bilateral neural decompression through a unilateral approach. Among MIS techniques, the tubular technique with a microscope is the most commonly used one. The tubular retractor system relies on specialized equipment. However, it may provide efficient access, but its effectiveness and time requirements can vary depending on the surgeon's experience. Despite these differences, all techniques share the same minimally invasive goal: maximizing decompression while minimizing tissue disruption.

For the endoscopic techniques, the monoportal endoscopic approach has a steeper learning curve, longer operative time, and higher costs; however, it benefits from reduced irrigation use and a lower incidence of hematomas and dural tears. The biportal endoscopic technique, in contrast, offers easier adoption, shorter operative times, lower costs, and often more effective decompression. However, it is associated with a higher rate of hematomas and dural tears compared to the monoportal technique.

Whatever the techniques, the procedure is quite similar. Initially, the spinal levels of interest are identified using biplanar fluoroscopy and marked on the skin. The target area for docking to start decompression is at the spino-laminar junction. Serial dilators are used to split the paraspinal muscles and create a working and visual channel.

After hemostasis and identification of the lamina, interlaminar window and edge of the articular facet, drilling of the ipsilateral lamina is carried with a burr, starting from its lower border until the insertion of ligamentum flavum and epidural fat are exposed. Subsequently, burring of the medial facet joint is carried out with care to remove as little bone as possible to avoid pain and instability. Next, drilling the base of the spinous process will provide access to the contralateral lamina. Once differentiated, separation of the ligamentum flavum from the undersurface of the contralateral lamina can be initiated using either the radiofrequency probe or a dissector. Drilling of the contralateral lamina is carried out until encountering the contralateral articular facet to ensure access for lateral recess decompression and the rostral insertion of the contralateral ligamentum flavum. Using Kerrison and pituitary rongeurs, the superficial ligamentum flavum is removed to maximize the working space and profit from the deep layer as a protector agent.

The final use of power tools involves drilling the upper margin of the inferior lamina, which helps detach the ligamentum from its caudal insertion. Finally, the lateral insertions of the ligamentum can be detached from the articular joints, exposing the dura and the transversing nerve roots.

5.9.3 Interspinous Process Devices

Conceived as a middle ground between surgical decompression and conservative treatment, interspinous process devices (IPDs) were introduced into the field over fifty years ago [58]. Its rationale is that neurological symptoms of LSS are relieved in flexion; therefore, IPDs limit the extension of the spine to mitigate pain and claudication.

Recent systematic reviews of spinous process spacers [59, 60] show that they do not outperform traditional decompression surgery for LSS. While

they offer a lower rate of short-term surgical complications, they are associated with significantly higher long-term reoperation rates (23.7% vs. 8.5%) and greater overall costs. Clinical outcomes also do not show a significant advantage for IPDs, whether used alone or with decompression. Additionally, complications specific to IPDs, including spinous process fractures and heterotopic bone formation, raise concerns, particularly in elderly or osteoporotic patients. Therefore, decompression appears to be a more effective and durable treatment option.

5.10 Conclusion

Lumbar spine stenosis is a prevalent and increasingly common condition, particularly in aging populations. Given its rising incidence, clinical evaluation remains the cornerstone of diagnosis, as radiologic findings often fail to correlate directly with patient symptoms. Fortunately, many individuals with lumbar stenosis respond well to non-operative treatment, with the majority experiencing symptom stabilization rather than progression. When surgical intervention is warranted, careful patient selection and treatment are crucial. In the absence of segmental instability or spinal deformity, current evidence supports decompression alone as the preferred surgical approach. Fusion, although previously common, has not demonstrated superior clinical outcomes in these cases and carries a greater risk of reoperation and increased resource utilization.

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6 Degenerative Spondylolisthesis: Physiopathology, Natural History and Surgical Strategy

Cédric Y. Barrey

6.1 General Considerations

6.1.1 Definition

Spondylolisthesis is defined as a slippage of a vertebra in relation to the vertebra below (Fig. 6.1). The slippage may be forward, i.e. antelisthesis, backward, i.e. retrolisthesis, lateral, laterolisthesis or rotatory, i.e. rotatory subluxation. Degenerative spondylolisthesis (DS) is most often associated with arthritic changes in the facet joints at the level of the listhesis. It differs from isthmic spondylolisthesis characterized by the absence of a pars interarticularis defect. DS was first described as early as 1930 by Junghanns who introduced the term 'pseudospondylolisthesis' [1]. In 1950, MacNab [2] describe spondylolisthesis 'with the neural arch intact' as opposed to the spondylolisthesis of children and adolescents by isthmic lysis and finally Newman in 1963 [3] proposed the term 'degenerative spondylolisthesis' observing that DS was quasi-systematically associated with facet arthritis. In the lumbar spine, it usually occurs in patients over 50 years of age, with female predominance and ligament hyperlaxity as a predisposing factors. DS corresponds to type III according to Wiltse spondylolisthesis classification [4] modified by the Scoliosis Research Society [5].

6.1.2 Epidemiology and Prevalence

The degenerative spondylolisthesis is most commonly found at the L4–L5 level (80 to 85% of cases) or above (L3–L4 or L2–L3) in contrast to the isthmic spondylolisthesis which occurs most commonly at the L5–S1 level [6]. In fact, DS is rarely observed at L5–S1 for purely anatomical reasons: first, the frontal orientation of S1 upper facets which represent a solid obstacle to anteroposterior slippage, and secondly, the abundance of ligamentar structures around L5–S1 complex with the presence of the strong ilio-lumbar ligaments. Prevalence is variable according to the age and sex, augmented by a factor of 4 in female's population and is estimated to around 10% after 60 years-old for females (up to 43% referring to population-based studies) [7–9].

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6.1.3 Imaging Findings

Positive diagnosis of DS is established on standards X-rays in standing posture (Fig. 6.1). The diagnosis is retained when the slippage is ≥3 mm or when the slippage is measured to more than 10% according to Meyerding classification considering that 1 or 2 mm only slippage can be tolerated. One must pay attention to the fact that around 20% of DS are undetected on MRI due to the lying position and elimination of gravity action [10]. Usually, MRI underestimates the slippage up to 50% in the case of high disc (Fig. 6.2). Therefore, standing radiographs are mandatory and must absolutely be performed for the management of lumbar DS in addition to lying imaging explorations (CT-scan and/or MRI) (Fig. 6.2).

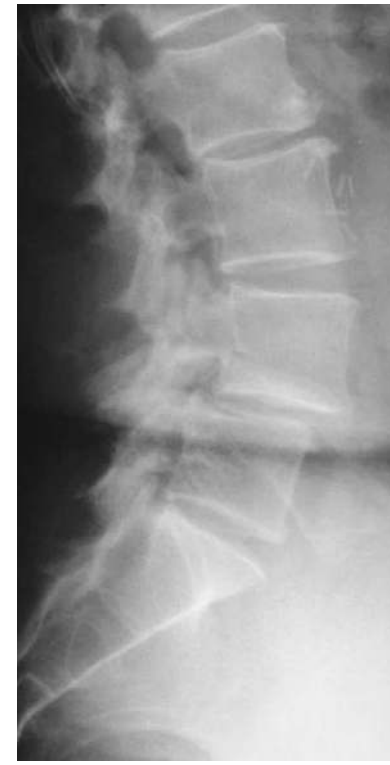


Fig. 6.1 Standing X-Rays demonstrating L4–L5 degenerative antelisthesis, grade I, with a slippage less than 25%, and hyperextension of the disc above (L3L4)

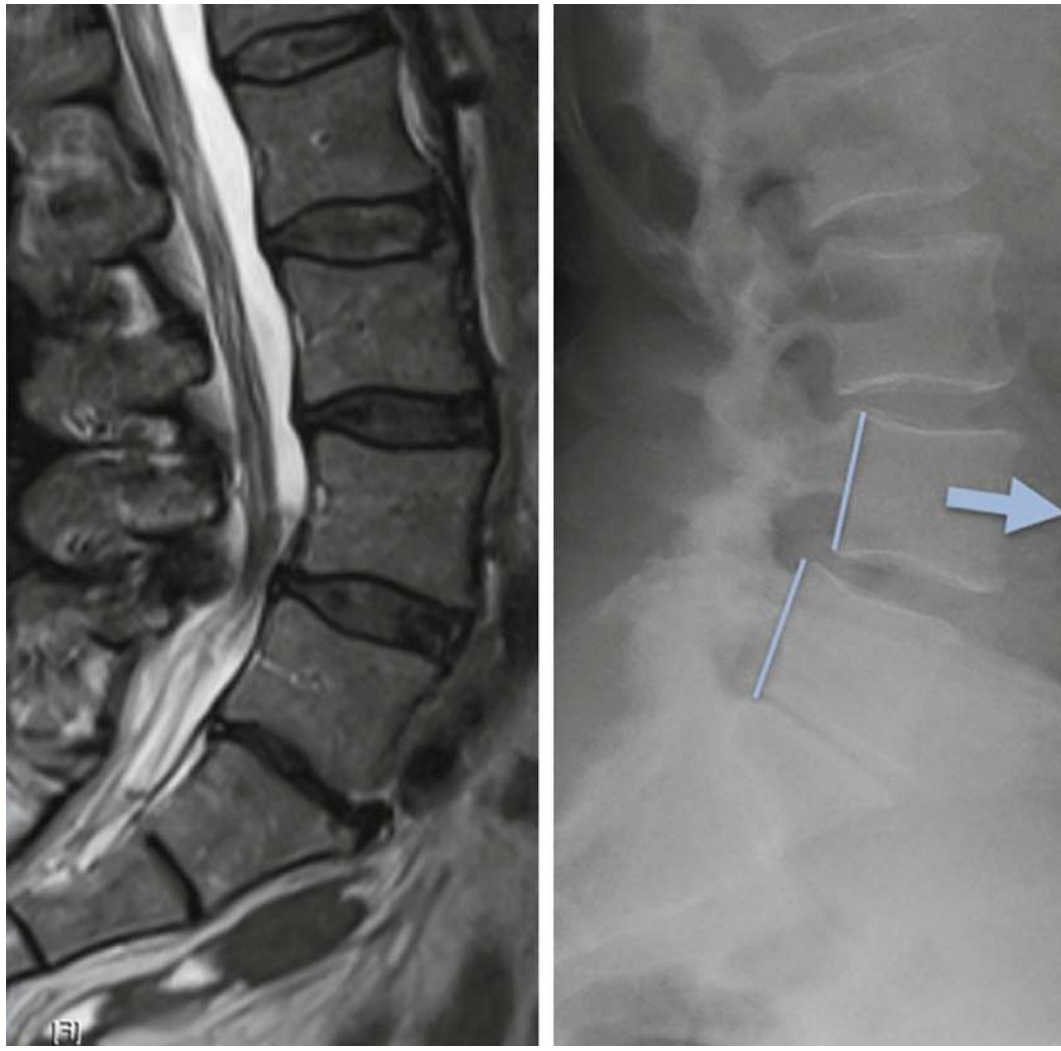


Fig. 6.2 Appearance of L4-L5 listhesis on standing X-rays which was not clearly visible on MRI. In 20% of cases, listhesis is undetected on lying imaging modalities (MRI and/or CT-scan)

6.2 Physiopathology

Factors influencing the occurrence and/or progression of DS can be divided into 3 categories: general, regional (including the sagittal balance) and local factors (Fig. 6.3).

6.2.1 General Factors

6.2.1.1 Genetic

The role of genetical factor to develop DS in certain populations and families remains unclear. It has been reported that DS was more frequent in elderly Caucasian Americans, estimated up to around 31% after 74 years old for Denard et al. [11]. On the contrary, prevalence of DS among women ranged from only 8% in Denmark, 8.9% in Japan and 12% in Thailand [12–14].

6.2.1.2 Obesity

Obesity seems to be a key factor for DS permanently reported in the literature generating increases stresses on facet joints and disc in the lower lumbar spine. Schuller et al. [15] found a greater BMI in DS group, equal to 28, vs. 24 only

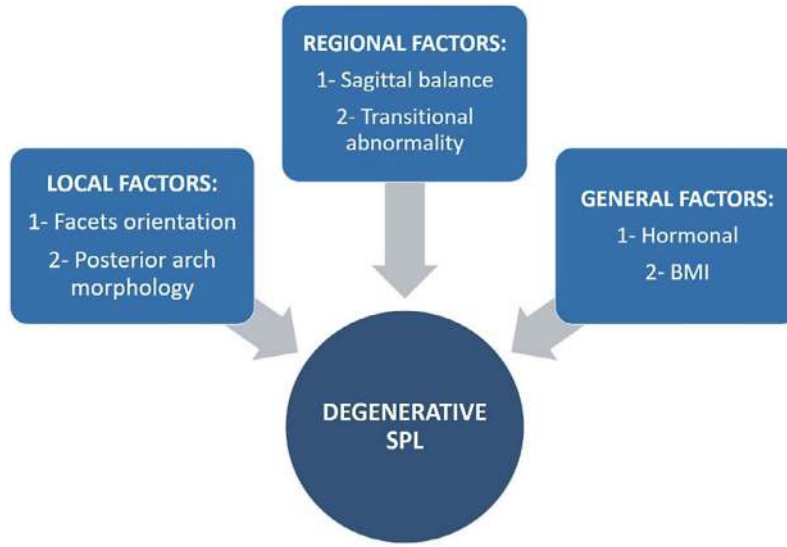


Fig. 6.3 Factors influencing the development of DS can be divided into 3 categories: general, regional (including the sagittal balance) and local factors

in the control group (without DS) and up to 70% of patients with DS presented with a BMI ≥ 25. The excessive loads due to overweight certainly accelerates disc and zygapophyseal degeneration and may therefore favour the development of DS.

6.2.1.3 Hormonal Factors

DS is constantly reported to be more frequently observed in women than men before 50 years old (risk augmented by a factor of 3 to 4). For instance, Jacobsen [16] found a prevalence of DS in women 8.3% vs. 2.7% only for men. Otherwise, Enyo et al. [6] reported a risk of female slip progression 3.5 times greater than in men due to joint hyperlaxity and instability. There is also a high proportion of patients with ligament hyperlaxity in DS patients, up to 65 per cent of patients according to Postacchini et al., 1991. Otherwise, Cholewicki et al. [17] found a risk multiparity and hysterectomies for developing DS.

Also, Sanderson et al. [18] found an association between nulliparous and parous women and DS (28% vs. 16%) and the incidence of DS increased in parallel to the number of pregnancies. Several physiological changes during pregnancy including relaxation of the pelvic and increase of the flexion moment on the lower back seem to play an essential role for the progression of the listhesis.

6.2.1.4 Hyperlaxity

In presence of hyperlaxity, Matsunaga [19] reported that the prevalence of DS was augmented by a factor of 8. It makes sense that reduction of ligaments stiffness and less resistance to motion may favour occurrence and/or progression of vertebral slippage.

6.2.1.5 Age

The advanced age represents one of the main factors impacting the natural history of degenerative spondylolisthesis, with a clear progressive increase in incidence after the age of 50 y-old, which is nevertheless greater in women than in men [20].

6.2.2 Regional Factors

6.2.2.1 Spinopelvic Alignment

We previously reported, in 2004 [21–24], that patients with DS presented with a greater pelvic incidence compared to normal population. Roussouly's types 3 and 4 (high PI) are found in more than 85% of DS patients vs. 60% only into the control group. Also, in our study mean PI was measured to 60° vs. 52° only for the control group (normal population).

Pelvic incidence and high lumbar lordosis represent therefore important risk factors to

develop degenerative spondylolisthesis due to the report of stresses on the posterior elements and to the inclination of L5 upper endplate. Since our original work in 2004, many studies have confirmed the association between high pelvic incidence and DS patients [21, 22, 25–27] with a mean PI around 58–60° in DS patients.

In fact, we assume that a high pelvic incidence favours the occurrence and progression of DS by 3 main actions:

1. First, high PI is associated with a greater sacral slope and greater inclination of sacral plate and L5 endplates (inferior and superior L5 endplates). Due to gravity action, greater is the slope, higher is the risk of sliding.
2. Secondly, high PI is associated with hyperlordosis and report of stresses on the posterior structures of the lumbar spine, especially on posterior facets, which may favour degenerative changes of L4–L5 facets making them less resistant to slippage. We have seen that facets arthritis was one of the predisposing conditions for DS.
3. Finally, high PI and hyperlordosis influence the geometry of the lumbar spine reducing the space available for the posterior elements (posterior arches/spinous processes) and making them more compact. By limiting the cranio-caudal development of posterior arches, hyperlordosis reduce their ability to resist to antero-posterior shear forces and to limit antero-posterior translation of the vertebra.

Further considerations about spino-pelvic alignment and DS will be discussed into part 3 of the chapter.

6.2.2.2 Sacralization of L5

Lumbosacral transition vertebra (LSTV) is the most frequently observed congenital anomaly of the lumbosacral spine found in 8.1% in general population [28]. In DS patients, this condition is observed in high rates up to 70% according to Kong et al. [29]. Sacralization of L5 results into greater concentration of stresses on the L4–L5 segment with higher risk of hypermobility.

6.2.2.3 Degenerative Ankylosis of L5–S1

For the same reasons than above, degenerative evolution of L5–S1 segment with reduction of motion at this level will lead to hypermobility of the upper adjacent segment with the risk to develop DS, Rosenberg et al. [7].

6.2.3 Local Factors

Local factors are represented by some specific predisposing anatomical variations of the involved vertebra (most often L4 and L5) at the index level.

6.2.3.1 Sagittal Orientation of the Facets

The joint facets play an essential role in segment balancing and stability. The orientation of the facets may limit the amount of axial rotation and increase torsion resistance. Many authors [30–34] assume that an exaggerated sagittal orientation of the facets at the index level is associated with a reduction of resistance to shear forces in antero-posterior direction thus favouring development of anterolisthesis. Liu et al. (2017) [30] in a literature review found a significant association between sagitalization of facets and the appearance of degenerative spondylolisthesis. The transverse facet angle of more than 50° represents a significative factor of listhesis (Fig. 6.4a, b). This angle was found to be around 60° in DS population vs. 40° only in the normal population.

6.2.3.2 Horizontalization of the Posterior Arch

Another anatomical variation which may favour the slippage is represented by a horizontal orientation of the posterior arch of the index vertebra. Once again, a horizontal of the posterior elements (lamina, facets) offer less resistance to AP shear forces with the risk to favour AP translation of the vertebra, Matsunaga, Naggosa [19, 35].

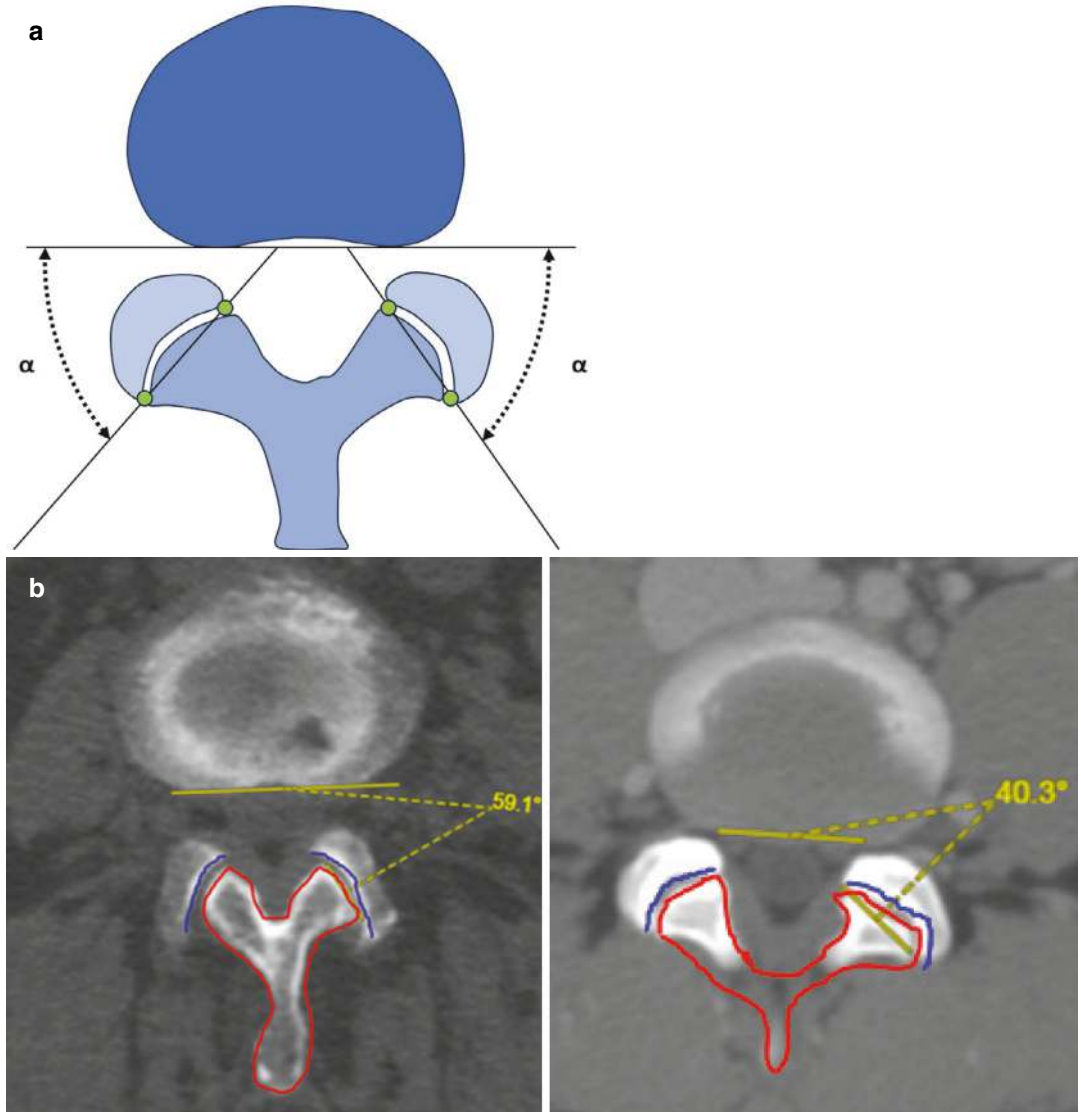


Fig. 6.4 (**a**) Sagittal orientation of the facet. α angle $\geq 50°$ is associated with the risk to develop degenerative spondylolisthesis. (**b**) Illustration showing posterior facets sagittally oriented (α equal to 59°) on the left vs. posterior facets normally oriented (α equal to 40°) on the right. Sagittal orientation of posterior facets ($\alpha > 50°$) represent a risk factor to develop degenerative spondylolisthesis

6.2.3.3 Controversy

In fact, there are some controversy regarding the role played by the local anatomy in the development of DS and some authors [36] consider that these anatomical variations result in fact mainly from the degenerative changes. They are mostly to be the consequence of the DS and not the primary cause.

6.3 Spinopelvic Alignment

Roussouly [37] (Fig. 6.5) described a classification into 4 morphotypes of back depending on pelvic incidence and sacral slope. Type 1 is characterized by a sacral slope less than 35°, low pelvic incidence and short lumbar lordosis which consequently predisposes to early arthritis of

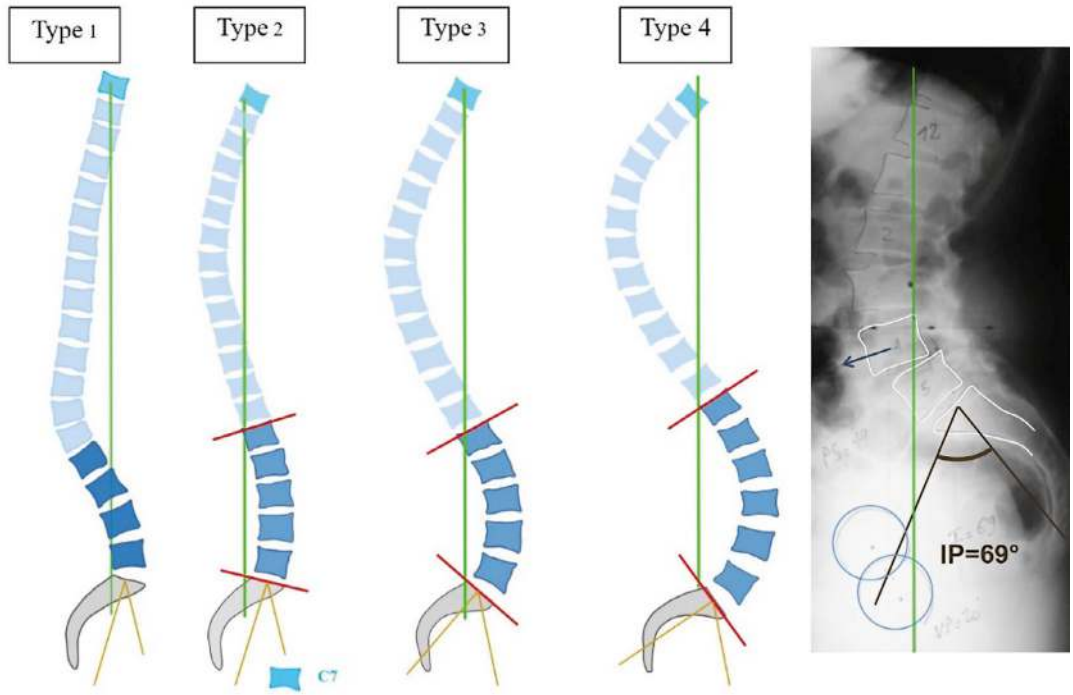


Fig. 6.5 Roussouly's Classification into 4 morphotypes (on the left). Type 1 is characterized by a short lumbar lordosis and a long thoraco-lumbar kyphosis above and types 2, 3 and 4 represent harmonious types with a progressive increase of pelvic incidence, sacral slope and spinal curvatures, from type 2 to type 4. Types 3 and 4 with PI around 60–70° (on the right) represents the typical predisposing morphotype for DS

posterior elements (facets, spinous processes) in the lower lumbar spine. Type 2, 'flat' backs, is characterized by low sacral slope (<35°), low pelvic incidence and low lumbar lordosis and predisposes to premature disc degeneration. The type 3 back is the most common in the general population and is characterized by harmonious curves. The sacral slope is between 35° and 45° and PI around 50–52°. Type 4 is characterized by a high pelvic Incidence with great sacral slope >45° and important inclination of vertebral endplates at L4–L5–S1 that may cause spondylolisthesis or lumbar stenosis.

In DS population, 85% of patients present with a morphotype 3 or 4 and mean PI was around 60° [original work by Barrey 2004], which a distribution significantly different from the normal population. Also, it has been reported that the lordosis was slightly reduced with a mean lack of lordosis around 10°. In fact, the global L1–S1 lordosis was not so reduced but the distribution of the lordosis between L1 and S1 was changed. Indeed, the lordosis was significantly reduced at the L4-S1 segment with compensation in the upper lumbar spine, i.e. augmentation of the lordosis between L1 and L4 [15, 22] see Fig. 6.1. The disc degeneration associated with the anterior slippage at the index level (typically L4–L5) result into a local loss of lordosis necessitating for compensation into the upper lumbar spine (extension of L1–L4 segments). In most cases, the local loss of lordosis due to DS is limited and the compensation provided by slight extension of the adjacent spine above work very well.

The global balance is typically preserved even if some amount of pelvic compensation may be noted with increased PT and decreased SS. In fact, most of variations were regional except in the cases of multilevel DS with severe and global lumbar kyphosis (Fig. 6.6).

It is also important to analyse the sagittal orientation of the slippage (Fig. 6.6). First, this one

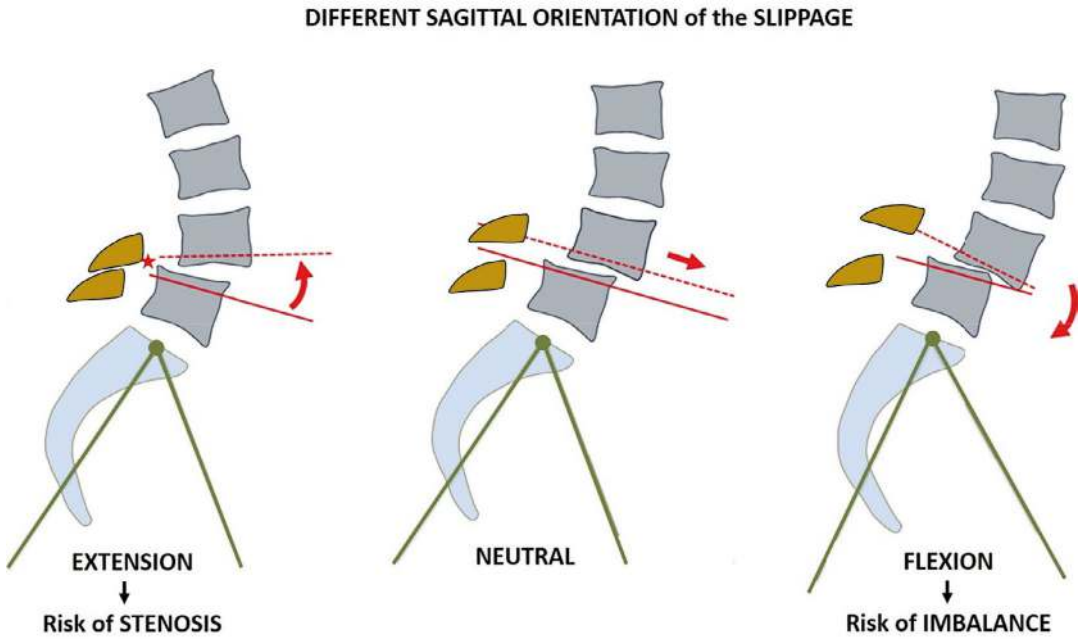


Fig. 6.6 Sagittal orientation of degenerative spondylolisthesis may be into neutral, extension or kyphosis with different consequences in terms of alignment and compromise of neurological structures. Local extension permits to rebalance the patient but exposes to the risk of nerve roots compression into the foramens. Local kyphosis increases the different parts of the canal but induces a severe situation regarding the balance

may develop into neutral direction with the slippage progressing parallel to the superior endplate of L5. Secondly, the slippage may be in extension permitting to compensate locally the lack of lordosis and thus limiting the consequences of the DS on the sagittal balance. The drawback of DS in extension is the risk to generate central canal and/or foraminal stenosis with the development of radicular symptoms. Last situation is represented by the slippage in flexion (kyphosis) which is the worst situation regarding the balance and generally associated with global sagittal imbalance. However, the slippage in flexion permit to open the canal, increase the foramen size and indirectly decompress the neurological structures. At the end there is not a perfect situation, both have consequences on the balance on one side and on the risk of canal stenosis on the other side. DS represent a degenerative disease of the spine exposing to the risk of kyphosis and stenosis.

Finally, we have to underline the situation of multilevel DS which induce an important lack of lordosis in the lumbar spine due to multilevel slippages and multilevel DDD in the lumbar spine (Fig. 6.7). This condition (multilevel DS) represent around 5 to 8% of DS patients [19]. In this situation, the surgical strategy must restore adequately the lumbar lordosis and sagittal alignment and generally requires extensive instrumentation of the lumbar spine.

Similarly, if DS is associated with multilevel DDD in the lumbar spine, there is an additive effect of the segmental loss of lordosis and at the end the deficit of lumbar lordosis is more severe but not only due to the DS. In case of DS associated with multilevel DDD, especially at the level below (L5–S1) and above (L3–L4), the disease consists more of an extended degenerative lumbar disease with global kyphosis and spinal deformity rather than into a simple '1-level disease' with DS.

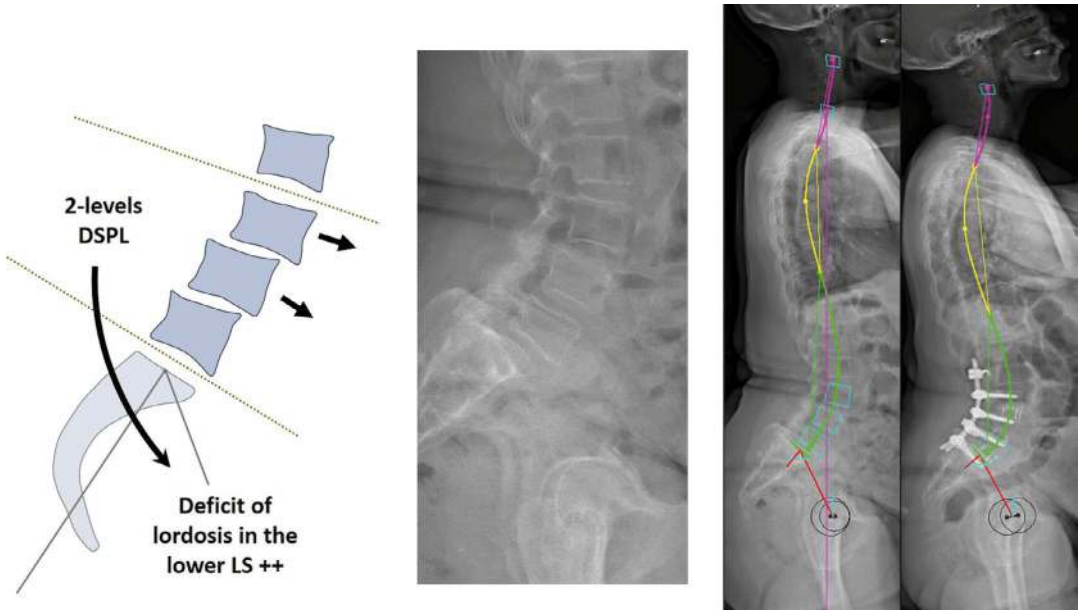


Fig. 6.7 Multilevel degenerative spondylolisthesis, observed around 5–8% of cases, result into a global imbalance with a kyphotic deformity of the lumbar spine. This situation generally requires an extensive instrumentation of the spine to rebalance the patient

6.4 Natural History of DS

In the majority of degenerative spondylolisthesis sliding rarely exceed 30% (grades I–II). In contrast to isthmic lysis, the posterior arch in DS stay intact and therefore limit the possibility for the vertebra to slip more than few millimetres. High grade DS are very rare and low grade sliding around 3 to 10 mm represent the rule for DS. Also, it has been hypothesized that the slippage progresses in parallel to the disc degeneration and reach its maximal grade when the disc was completely collapsed and ankylosed (similarly than what is observed for isthmic listhesis) (Fig. 6.8). Indeed, through a cohort of 145 non-surgically patients with a minimum of 10 years follow-up (10–18 years), Matsunaga et al. [19] reported that the progression of slippage was typically minimal in adults and more than 25% for 7% patients only (n = 10/145). In addition, these authors noted that the slippage progresses in almost all patients (96%, i.e. n = 49/51 patients) when the disc height was initially normal suggesting the fact that the slippage progresses in parallel to the disc degeneration.

Analysing the degenerative lesions associated with DS and their sequence, it is possible to establish the natural history of DS and this was published in Neurosurgery in 2007 [22] and is presented in Fig. 6.9. Initially, there is a predisposing morphotype and this was largely confirmed by several papers after our publication in 2004 [21–27]. This favouring morphotype corresponds to Roussouly's morphotype type 3 or 4 and is characterized by an increased PI with a mean value of around 60°. Also, the first anatomical lesion, prior to disc degeneration, is represented by the degenerative sub-luxation of posterior facets. DS with normal facets joints are not the rule and this was notably observed by Newman in the 60s. In addition, at the first stage, we know that the disc may be normal in contrast to the facets joints which are quasi-systematically affected. Consequently, we assume that the disease starts into the facet's joints on a predisposing morphotype.

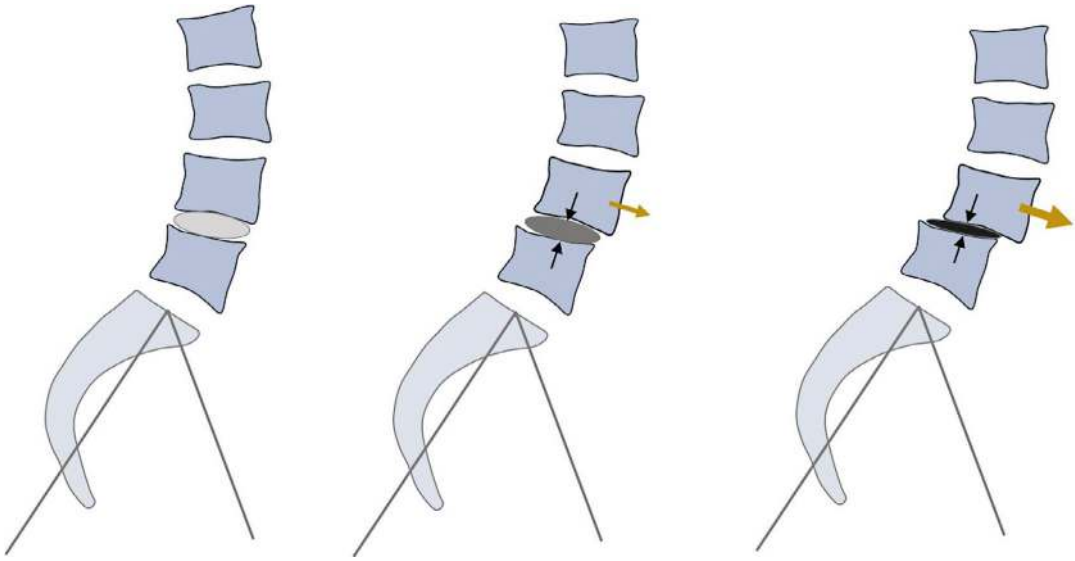


Fig. 6.8 Progression of the slippage parallel to the progression of disc degeneration at index level

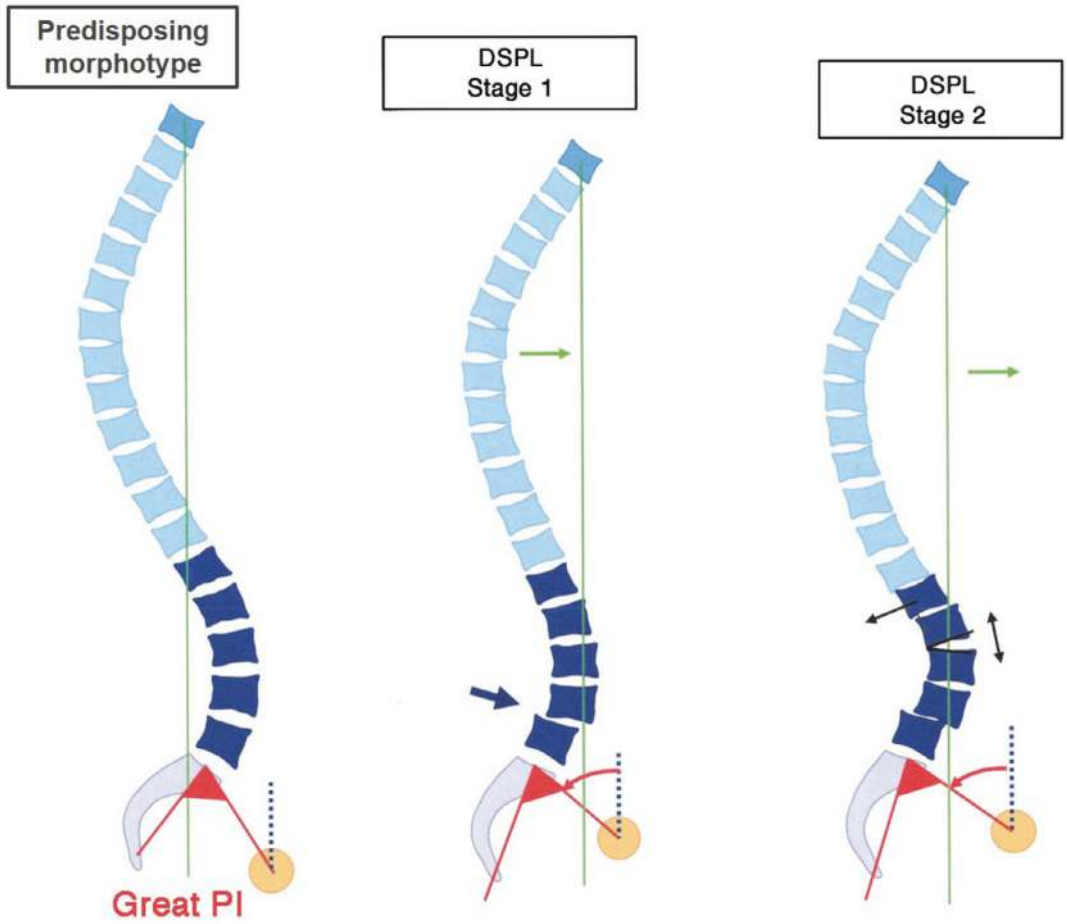


Fig. 6.9 Natural history of degenerative spondylolisthesis. Existence of predisposing morphotype with progressive development of local loss of lordosis due to both the slippage and disc degeneration. In most cases the global balance is preserved, and only regional compensation take place [22]

The slippage then progresses in parallel to the disc degeneration over the years and result gradually into segmental loss of lordosis. The combination of the anterior shift and the disc collapse induce a significant local kyphosis. This effect may be potentialized in the cases of adjacent DDD, especially at L5–S1. In most patients, the need for compensation is limited and slight pelvis back tilt (increased PT) with moderate extension of the upper lumbar spine is enough to keep the global balance of the spine (Fig. 6.9).

Hyperextension of the upper lumbar spine (L1–L4 segments) in DS patients was reported in the literature [15, 22] and, in some patients, may result into true instability and retrolisthesis at these levels. In general, compensation in the upper lumbar spine is observed when the loss of lordosis in the lower part (between L4 and sacrum) is significant and severe; and in fact, this is not specific for DS patients but for all patients with kyphotic disease between L4 and sacrum.

6.5 Degenerative Lesions Associated with Degenerative Spondylolisthesis

To describe the degenerative lesions associated with DS, we propose to refer to Kirkaldy-Willis stages (Clin Orthop 1997) which divide the degenerative natural history of spinal unit degeneration into 3 main stages (Fig. 6.10):

1. Dysfunction characterized by micro-lesions of the disc, capsules and cartilages but normal imagery.
2. Instability characterized by hyperlaxity, appearance of the slippage and the risk to develop synovial cyst. At this stage, the disc is still high, and the slippage is typically reduced between standing and lying position. Instability results into a 'dynamic' stenosis.
3. Restabilization characterized by the development of severe degenerative lesions of both the discs and facets with osteophytes and disc collapse. The slippage is typically fixed at this stage whatever the position of the patient. Restabilization results into a 'fixed' stenosis.

6.5.1 Instability Stage

The instability, which can be defined clinically by an excessive motion on dynamic X-rays, is not the rule and in fact is rarely observed for DS. It corresponds to the initial phase of the degenerative process. Most authors considered that more than 3 mm of translation and/or more than 15° of angular motion on dynamic X-rays as instability (Fig. 6.11).

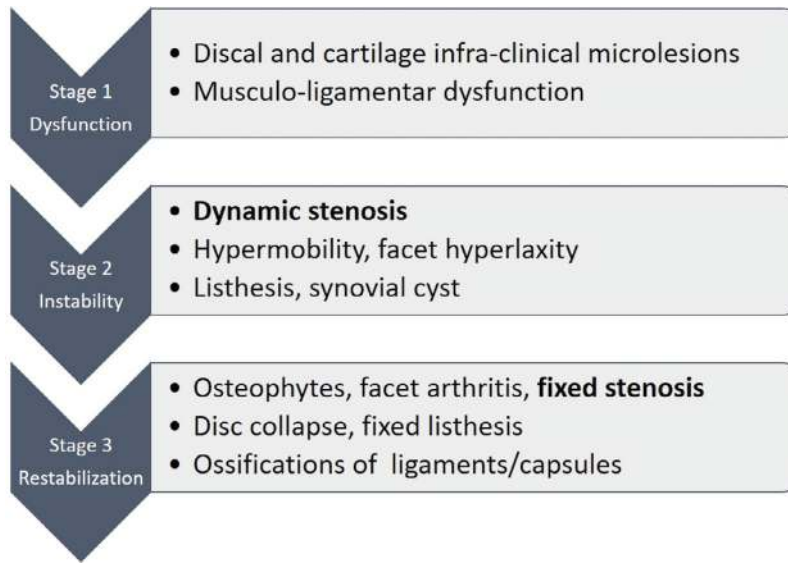


Fig. 6.10 Stages of Kirkadly-willis describing the successive degenerative lesions during the degenerative process of the spinal unit

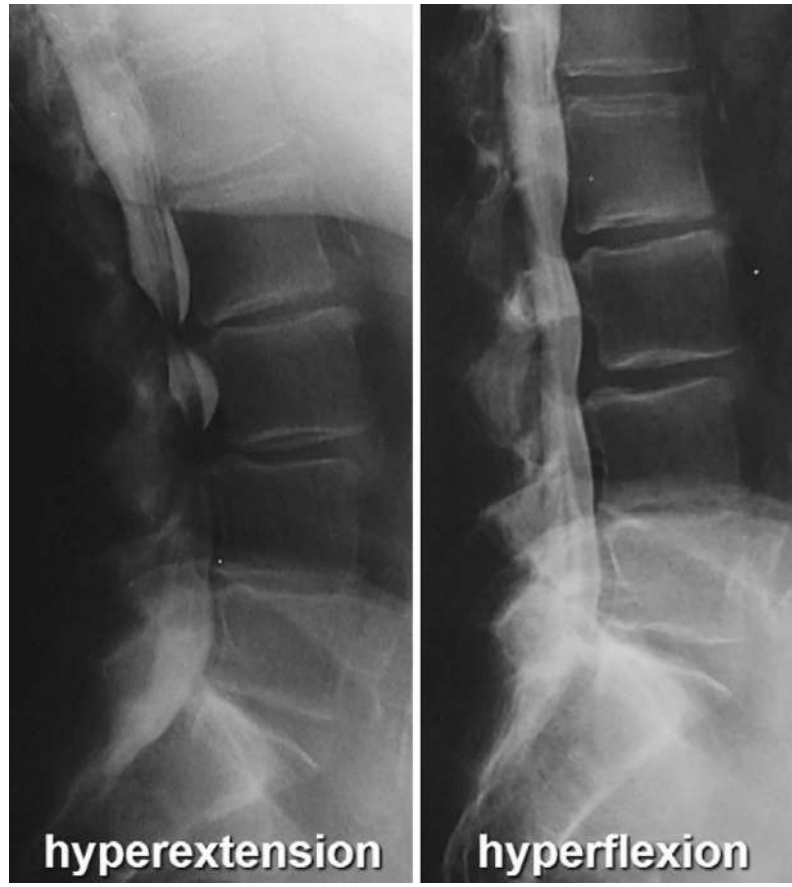


Fig. 6.11 Dynamic stenosis due to hypermobile degenerative listhesis at L3L4

For low-grade listhesis at initial phase, the slippage may completely reduce in lying position, especially on MRI and CT-scan imaging, and standing X-rays must always be performed. Chaput et al. found that around 20% of DS were not detected on lying MRI [Chaput Spine (2007) [10].

Synovial cyst develops during this early phase of DS and is synonymous on instability. It develops most frequently at L4–L5 and is associated with DS in 60% up to 90% of cases. Synovial cyst may contribute to nerve root compression when growing inside the canal resulting especially in compression of the nerve root in the lateral recess. Central canal stenosis may occur in the case of giant cyst. In 80% of patients with synovial cyst, intra-articular fluid collection is observed on lying MRI. Also, it has been reported that fluid collection in the facets superior to 1.5 mm was highly predictive of the presence of DS [10] (Fig. 6.12).

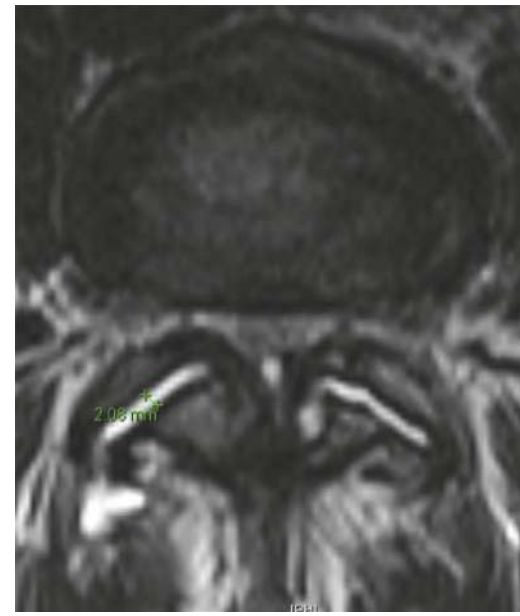


Fig. 6.12 Fluid collection on MRI more than 1.5 mm is predictive of the presence of a degenerative spondylolisthesis on standing X-rays. Fluid collection and synovial cysts are observed at the early stage of the degenerative process

6.5.2 Restabilization

After the initial phase of hypermobility and hyperlaxity, the spinal unit is characterized by the progressive development of arthritic lesions, osteophytes and ankylosis. At this stage, the DS is no more mobile, the disc is typically collapsed and there is no motion on dynamic X-rays between lying and standing imaging modalities (Fig. 6.13).

At this stage, hypertrophy and arthritic changes of the superior and inferior facets of the functional spinal unit result in the compression of the nerve root in the lateral part of the canal. In fact, the compression in the lateral recess may be consecutive to the anterior sub-luxation of the lower facet (of the upper vertebra) or, most often, by the hypertrophy of the superior facet (of the lower vertebra). For L4–L5 DS, the L5 nerve root is typically compressed into the L5 lateral recess due to degenerative changes of L4–L5 facets (Fig. 6.14).

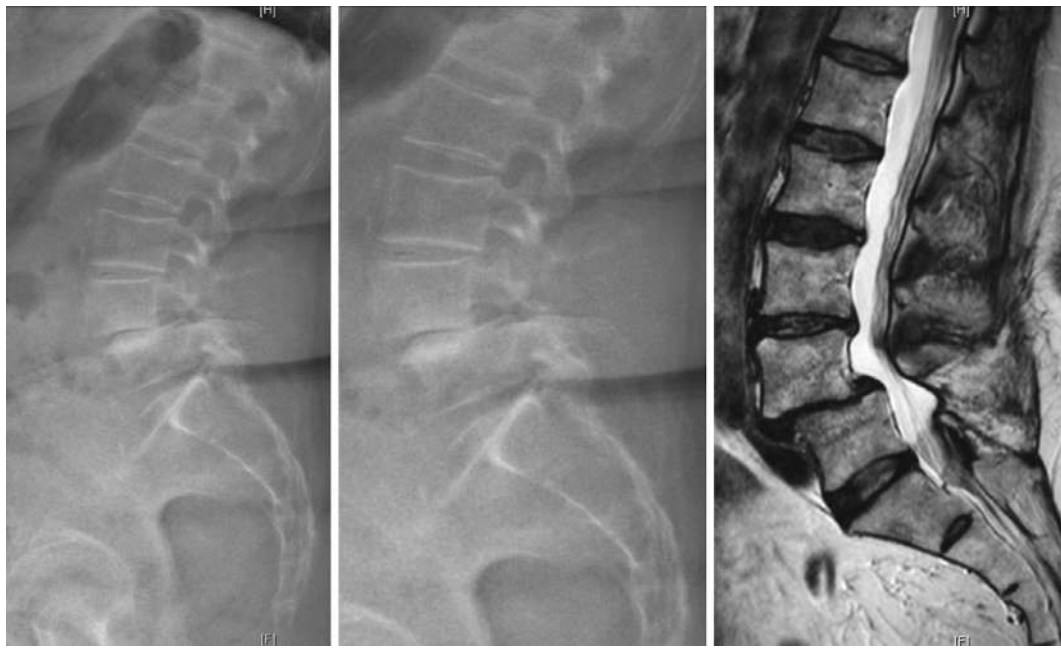
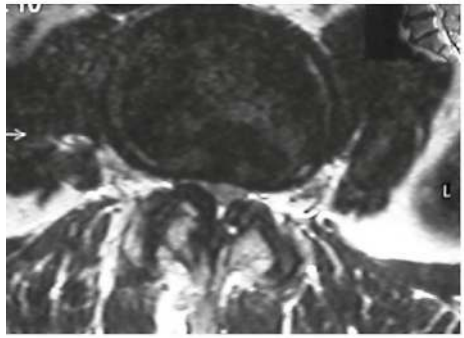


Fig. 6.13 Ankylosed degenerative spondylolisthesis. No variation is observed between standing X-rays and lying MRI. The disc is completely collapsed



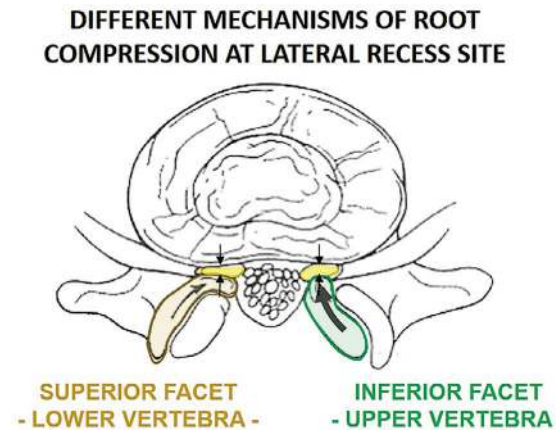


Fig. 6.14 Mechanisms of nerve roots compression into the lateral recess at DS level. The cause of root compression at the site of lateral recess is optimally evaluated on axial MRI. This may be consecutive to the sub-luxation of the inferior facet (green, right part of the illustration) but also to the hypertrophic arthritic changes of the superior facet (brown, left part of the illustration)

Lateral stenosis with respect to the central canal represents a frequent situation for DS (Fig. 6.15).

In severe cases, the DS may result in both lateral and central stenosis of the canal. Antero-posterior translation, hypertrophy of the yellow ligament and bilateral hypertrophy of facets may induce central stenosis with the risk for the patient to develop chronic cauda equina syndrome (Fig. 6.16).

Otherwise, at the advanced stage of the degenerative process with complete disc collapse, DS is often associated with a foraminal stenosis at the index level. Thus, for L4–L5 DS the foraminal stenosis is observed at L4–L5 with compression of the L4 nerve roots. Foraminal stenosis is multifactorial and consecutive to different mechanisms including disc collapse, osteophytes from the superior facet and/or antero-posterior translation of the vertebra (Fig. 6.17).

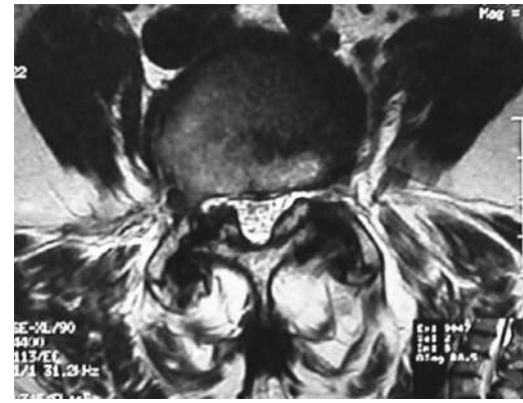


Fig. 6.15 Lateral stenosis with no stenosis of the central part of the canal. On the left side, compression is due to the sub-luxation of the facet and, on the right side, compression is consecutive to the osteophytes coming from the superior facet

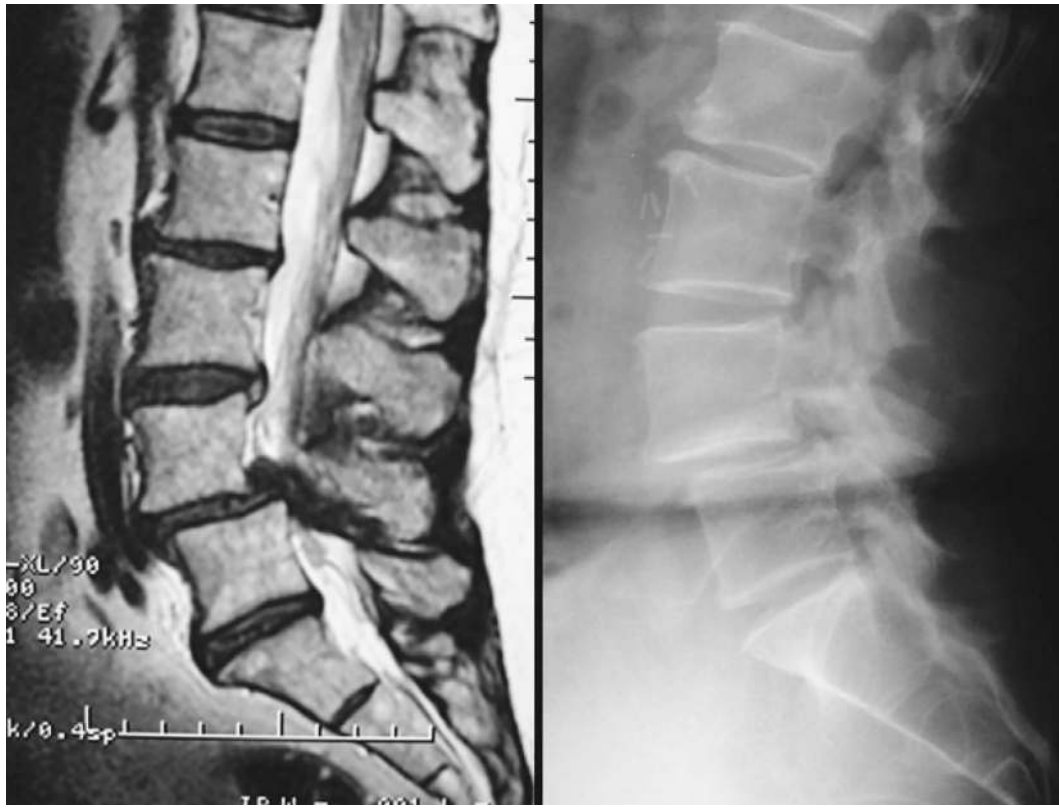


Fig. 6.16 Degenerative spondylolisthesis associated with a severe stenosis of the central canal

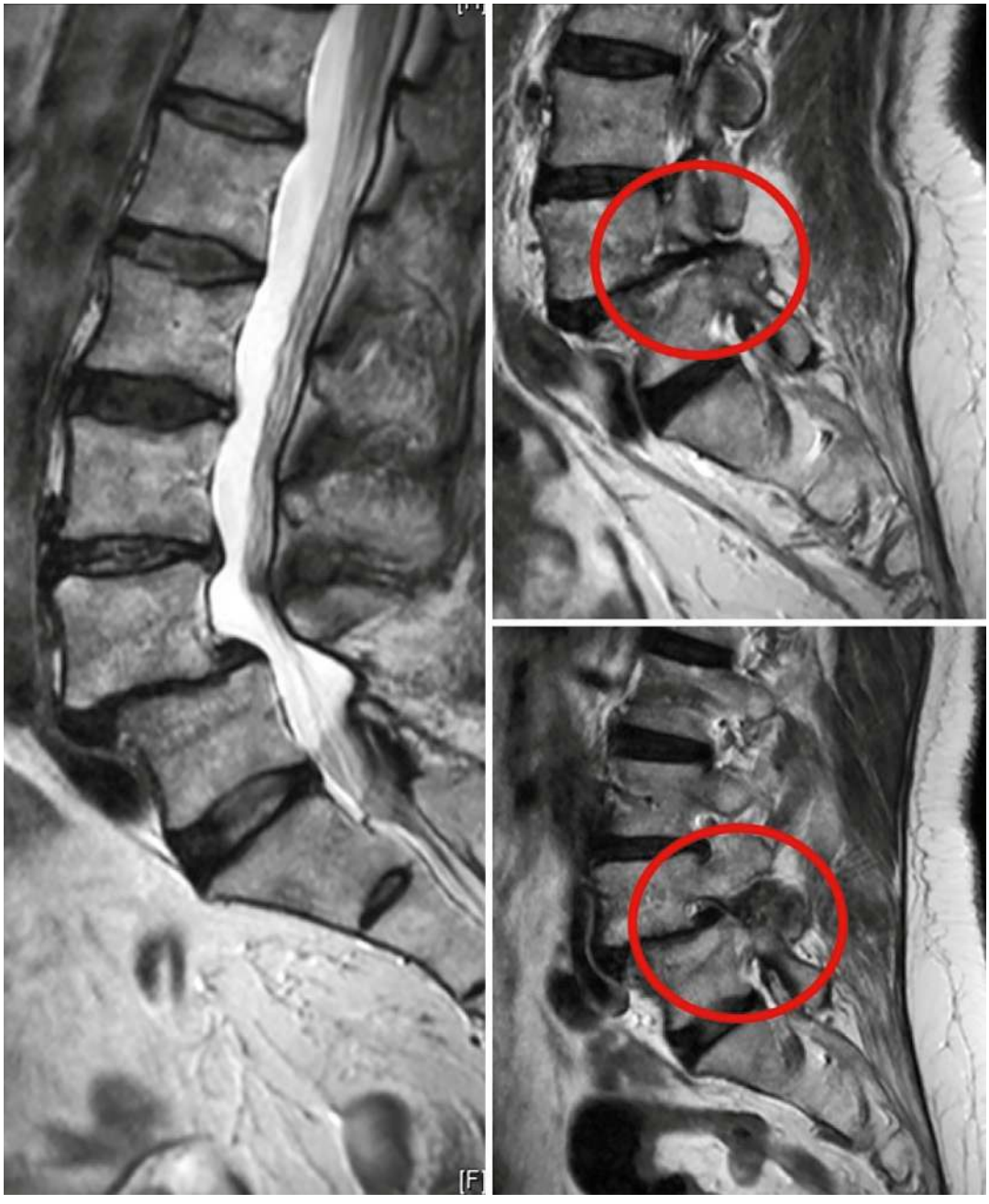


Fig. 6.17 Degenerative listhesis associated with severe and bilateral foraminal stenosis

6.6 Management of Degeneratvie Spondylolisthesis

6.6.1 General Considerations

DS represents a stenotic and kyphotic disease of the lumbar spine and, therefore, both these two issues have to be addressed during management, especially during surgical treatment.

Conservative treatment remains the first-line treatment in management in the absence of neurological deficit and severe stenosis. Matsunaga [13] studied the fate of 110 symptomatic patients for 10 years. It has been reported that, in patients with radiculalgia, conservative treatment combined with natural progression allows for total sedation of pain in 86% of cases but with a high recurrence rate of 35%. In the case of neurological deficit (cauda equina syndrome, sphincter disorders, motor weakness), surgery should be considered rapidly.

6.6.2 Decompression Alone—Recent RCT

There is no real consensus about degenerative spondylolisthesis surgery in the literature for symptomatic grade I associated with spinal stenosis regarding the need for systematic instrumentation of the spine.

Recently, in 2016, Ghogawala et al. [38] reported a randomized study (the SLIP study for Spinal Laminectomy Instrumented Pedicle Study) published in the NEJM and consisted of a multicentre US RCT with 4 years FU and 66 patients included in the study. The authors found no significant difference in terms of functional outcomes between patients with DS treated by decompression and fusion vs. decompression alone but higher risk of slipping progression and reoperation rates at 4 years (14% vs. 34%, respectively) in case of isolated decompression. In addition, the fusion group was associated with slightly greater but clinically meaningful improvement of SF36 score (physical component).

The advantage of decompression alone is represented by its relative simplicity with a low complication rate due to the absence of implants [39], but it should be reserved only for patients who cannot undergo fusion surgery. In fact, one must pay attention that adequate nerve root decompression, even achieved minimally, implies partial facetectomy which is associated with the risk of progression of slippage over time. In case of decompression alone, the surgeon has to be prepared to reoperate 1/4 patient during the first 2 years and at the index level [38, 40, 41].

The results of the observational comparative study from the Norwegian registry [41] compared decompression vs. decompression + fusion with 260 patients in each group. The authors could not conclude that decompression was as good as fusion, seeing that decompression alone was associated with more residual leg pain and back pain at 1 year postop.

Another RCT, published in the New England in 2016, from Sweden, the SSSS—the Swedish Spinal Stenosis Study [42], with approximately 120 patients in each group (fusion vs. decompression alone), did not find any significant difference between the 2 groups concerning the ODI and functional scores at 2 and 5 years. Limitations of this study were that the study was first originally focused of central spinal stenosis and consequently patients with lateral stenosis, which is a frequent scenario in DS patients, were not included in the study; and secondly fusion was achieved using postero-lateral instrumentation only without interbody graft, which is not the optimal way to achieve lumbar fusion, especially in terms of fusion rates and for restoration of disc height and segmental lordosis.

More recently, another Nordic RCT was published, from Finland, comparing decompression vs. fusion for DS reporting no difference in quality of life and functional scores at 2 and 5 years and quite similar reoperations rates [43]. Once again, a large majority of patients in the cohort (>60%) was operated with simple postero-lateral instrumented fusion without any interbody device.

6.6.3 Posterior Fusion Techniques

The rationale to consider fusion as the first option is supported by the physiopathology and the natural history of the disease and also by the data from the literature [38–41].

Traditionally, instrumented postero-lateral fusion (PLF) has been considered the gold standard for treating spondylolisthesis, initially described in 1953 by Cloward and has been continuously improved by more efficient fixation systems and especially since the introduction of pedicles screws-based fixation instrumentation. The main limitations of this technique are represented by the rates of fusion, which is lower compared to the interbody techniques, and by the difficulty to restore adequality the local lordosis (Fig. 6.18).

Since the 90′ interbody fusion techniques have increasingly gained popularity for treatment of spondylolisthesis due to the purported benefit of providing anterior column support, optimal bone grafting and 360-degree fusion. It also allows restoration of a satisfactory local lordosis which is an important point seeing that DS represents a kyphotic disease of the lumbar spine. Not restoring the adequate balance may result into an increased incidence of adjacent syndromes.

6.6.4 Lateral-PLIF

Our favoured technique to treat DS is represented by the lateral-PLIF with cages inserted through the transitional zone between the central canal and the foramen [44, 45] (Fig. 6.19). The patient is placed in a ventral position on a table. Surgical access to the intervertebral disc is obtained from a midline posterior direction trough the IV foramen after complete facetectomy on each side. Once the spiny process and the laminas at the appropriate levels are identified, complete facet resection is achieved. The dura-mater must be gently retracted medially to expose the lateral part of disc. The joint surfaces can then be prepared for implant or graft insertion. We use PLIF cages inserted bilaterally through the lateral part of the disc place (typically 20 mm of length, 10° of lordosis and 10 mm of height). The technique has been recently fully described in details in the paper by Capo and Barrey [44, 45].

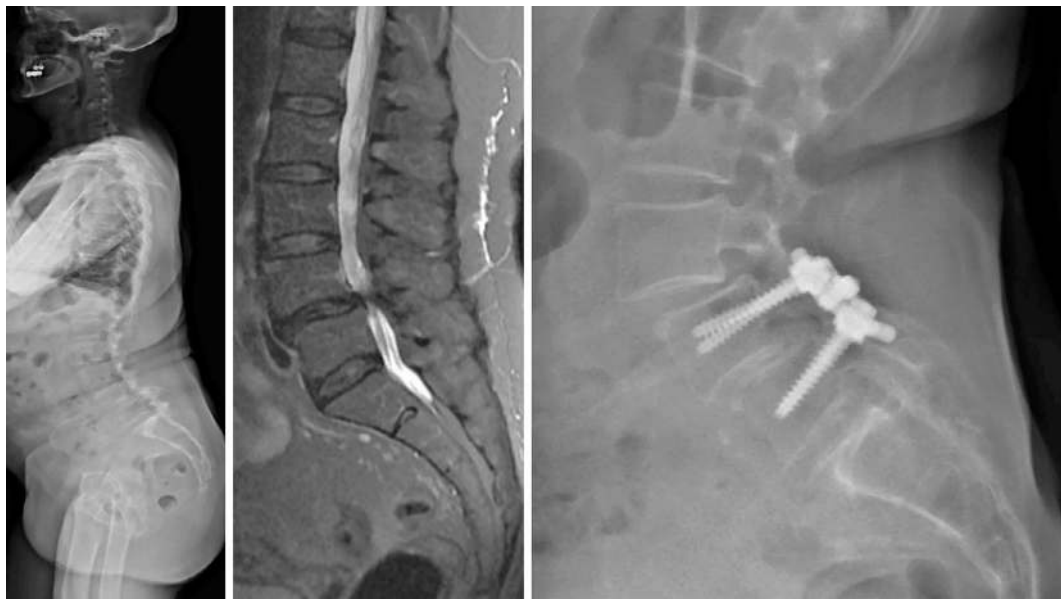


Fig. 6.18 Failure of PLF to restore the segmental lordosis after instrumentation of L4-L5 DS. Due to the lack of anterior support, this technique should be avoided

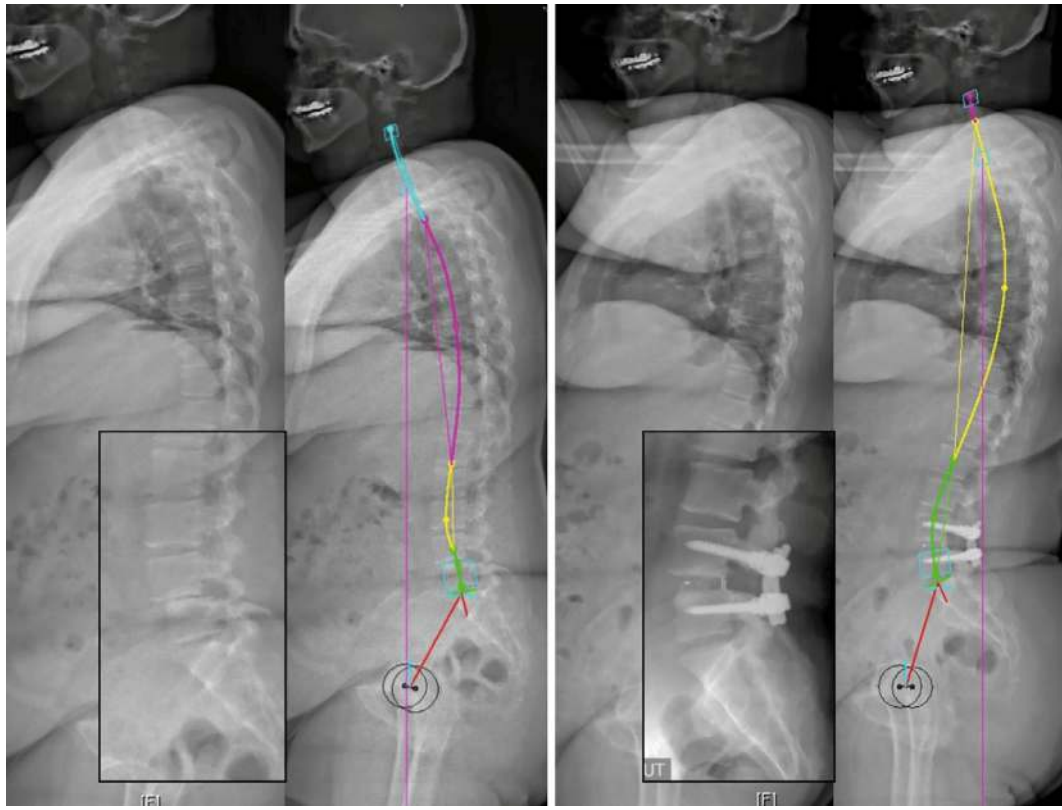


Fig. 6.19 L4–L5 DS treated by lateral-PLIF technique permitting adequate restoration of local lordosis with no need for an extensive instrumentation

There are several advantages associated with this modified lateral-PLIF technique. First, this approach consists of the traditional posterior lumbar approach that most spine surgeons are well trained and comfortable in its performance. A posterior exposure allows an excellent visualization of the nerve roots without compromising the blood supply to the graft. Placing anterior support allows adequate restoration of interbody height and local lordosis with a mean gain around 8–10° which is typically enough at L4–L5 (Fig. 6.20). In addition, posterior fusion surgery also allows a potential 360-degree fusion through a single incision.

Comparing with classical TLIF technique, our modified technique permits to optimize the grafting and the biomechanical stability of the construct by placing 2 interbody cages and also to ensure the adequate nerve root decompression with the bilateral approach. Moreover, the distraction is optimally achieved very progressively from the intervertebral space while the cage is inserted on the contralateral side.

Comparing with the classical PLIF technique, lateral-PLIF technique avoid complete laminectomy and permits to limit the risk of nerve root injury and dural tear due to the fact that the cages are inserted through the transitional part of the canal between the central canal and the foramens. In the literature, the risk of nerve damage is estimated to 7.8% with PLIF vs. 2% for TLIF; and the risk of Dural tear 17% vs. 9%, respectively.

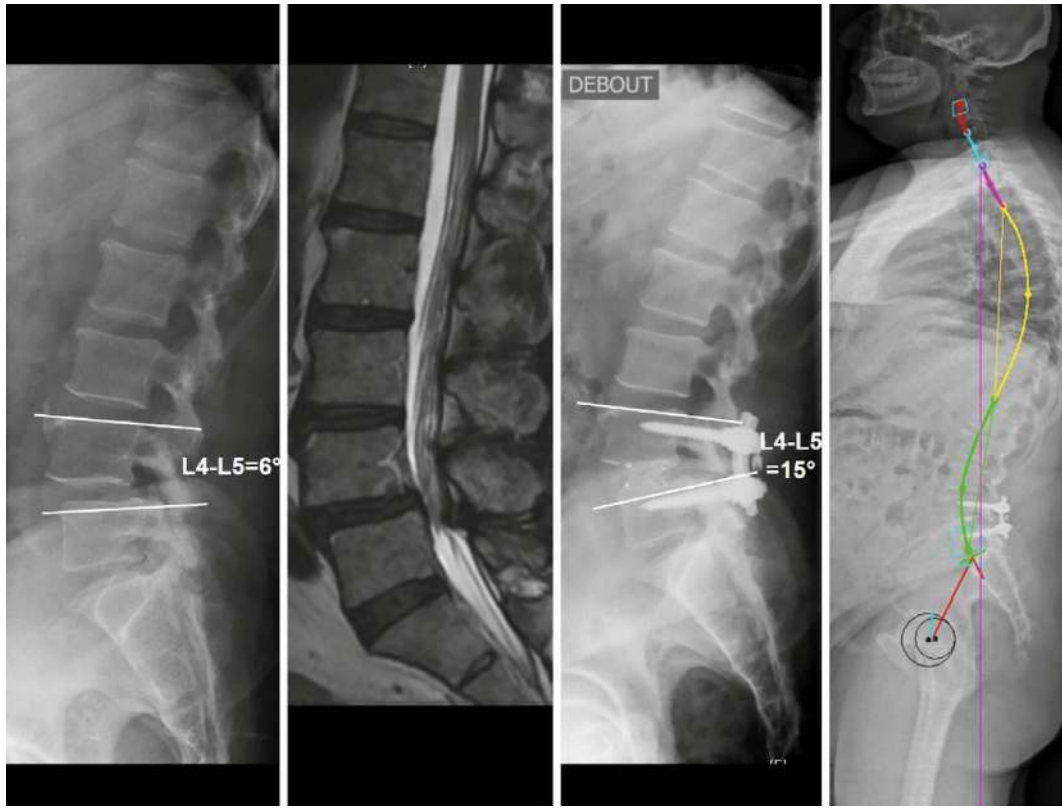


Fig. 6.20 Case 2 with L4-L5 DS treated by lateral-PLIF technique permitting adequate restoration of local lordosis increasing from 6° preoperatively to 15° postoperatively

Comparing with the XLIF/OLIF techniques, our technique permits to decompress the lateral portion of the canal, especially the lateral recess, on both sides. Antero-lateral techniques are efficient to restore the foraminal size or decompress the central canal but with poor effect on the lateral recess enlargement. In fact, lateral recess is bordered by bony structures including the facet, the pedicle and osteophytes coming from the superior facet and, consequently, simple distraction is unlikely to decompress adequately this area, which is very frequently stenotic in DS. In our opinion, in most cases of DS opening of the lateral recess should be achieved.

6.6.5 Complex Degenerative Spondylolisthesis

Three situations have to be identified and separated as complex situations regarding the need for an extensive surgery:

- Multilevel DS.
- DS with local kyphosis.
- DS associated with adjacent DDD.

All these 3 situations result in a severe loss of lordosis, global sagittal imbalance requiring extensive corrective surgery (Figs. 6.21 and 6.22) and in some cases osteotomy surgery.

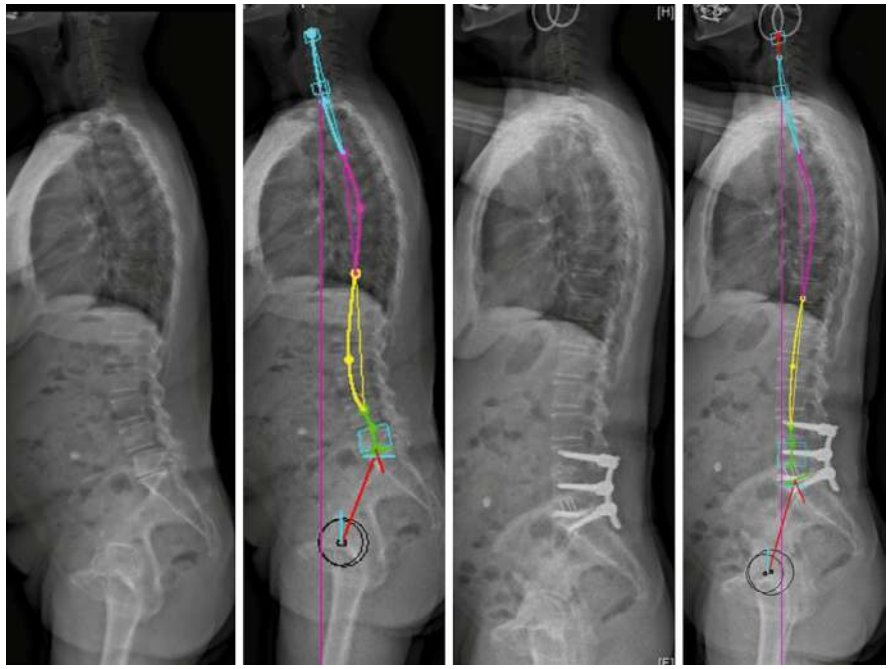


Fig. 6.21 L4-L5 DS associated with total collapse of L5S1 disc. The two problems result into a severe kyphosis in the lower lumbar part requiring adapted corrective surgery. The case was treated by combined surgery with ALIF at L5S1 and bilateral modified TLF at L4–L5

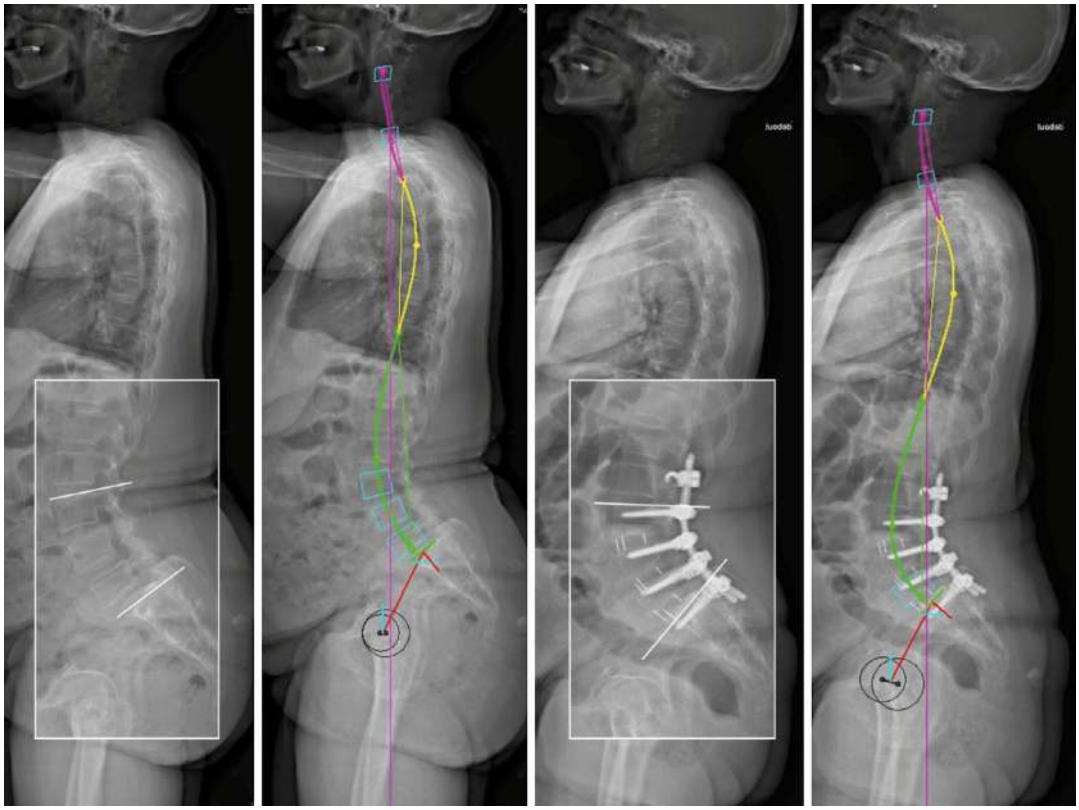


Fig. 6.22 Multilevel DS (L3–L4, L4–L5 and L5–S1) requiring an extensive instrumentation of the lumbar spine (L2-sacrum) to correct the spinal deformity and rebalance the patient

6.7 Conclusion

DS represent a stenotic and kyphotic degenerative disease of the lumbar spine. Surgical management of DS have to deal with these two concerns. The stenosis affects predominantly the lateral part of the canal, i.e. the lateral recess, due to the arthritic hypertrophy and sub-luxation of posterior facets. In general, direct opening of the lateral recess has to be considered to achieve adequate nerve root decompression. Otherwise, in most cases, the local loss of lordosis due to DS is limited and the compensation provided by slight extension of the adjacent spine above works very well. The global balance is typically preserved, and, in such cases, limited stabilization of the DS represents the first surgical option permitting to solve the problem regarding both the stenosis and local kyphosis. Our preferred option is the bilateral modified TLIF technique as described in the chapter.

Situations at risk for global imbalance (complex DS) must be kept in mind and are represented by multilevel DS, DS associated with multilevel DDD and DS associated with severe local kyphosis. These situations represent a spinal deformity surgery generally requiring aggressive surgical treatment to rebalance the patient.

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7 Endoscopy for Lumbar Spine Surgery

Henri d'Astorg, Xavier Castel, and Marc Szadkowski

7.1 A Brief History of Endoscopic Spine Surgery

Spinal endoscopic surgery has gained worldwide popularity over the past few decades. Its development spans a long, international history, with certain milestones still subject to historical and medical debate. In the 1910s, Professor Takagi pioneered the concept of arthroscopy by using a cystoscope to examine the knees of patients with tuberculosis, laying the foundation for minimally invasive techniques.

The earliest mention of spinal endoscopy in scientific literature dates back to the 1930s, when Burman et al. [1] published a study describing the use of an arthroscope to visualize the spinal canal and perform myeloscopy. This marked the beginning of a technique that has since undergone substantial technological advancements. A few years later, Pool et al. and Ooi et al. [2] published studies exploring nerve root visualization using "myeloscopes," though their initial research was limited to cadaveric specimens.

The first in vivo studies appeared in the 1970s, conducted by Kambin and Sampson [3] as well as Hijikata [4]. Kambin's contributions became foundational, with the "Kambin triangle" an anatomical landmark critical for spine surgeons performing transforaminal approaches. Both Kambin and Hijikata are considered pioneers of modern percutaneous spine endoscopy, using monoportal fluoroscopy and cannulas. The first reported monoportal percutaneous discectomy under direct visualization was published in the 1980s by Kambin et al. [5] and Schreiber et al. [6].

In the 1990s, Yeung et al. [7] introduced the first commercially available systems incorporating a continuous saline irrigation system, enabling a monoportal, cannula-assisted endoscopic technique. In the 2000s, Ruetten et al. [8] further refined the concept of full endoscopy. Meanwhile, other minimally invasive spine surgery techniques, such as tubular retractor systems, gained global traction. However, the adoption of these advanced methods required time, specialized training, and specific equipment, including microscopes for tubular retractors and dedicated endoscopes.

Later, a technical note from De Antoni et al. [9] introduced a biportal endoscopic technique using two separate incisions—one for the arthroscope and another for instruments—primarily for treating disc herniation. Their clinical experience, published 2 years later [10], is considered the first trial on spinal biportal endoscopy. In the 2010s, Soliman HM et al. [11, 12] reported the first series on disc herniation and lumbar stenosis, employing techniques similar to today's standards. In 2012, Osman et al. described thoracic discectomy with interbody fusion [13]. Biportal

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endoscopic surgery gained significant momentum in Korea, where Choi et al. first used the term "biportal" in 2016 [14]. Since then, Korean researchers have led innovations in Unilateral Biportal Endoscopy (UBE), publishing key technical advances for various conditions, including lumbar stenosis [15], far-lateral disc herniation [16], and spinal abscesses [17].

In France, the history of spinal endoscopy is relatively recent, originating in Bordeaux and expanding after the 2000s to major centers. Since its initial description, continuous technological advancements have significantly enhanced spinal endoscopic surgery, driving its evolution and broader implementation.

7.2 The Transforaminal Technique

The transforaminal technique represents a paradigm shift in spinal surgery due to its "ultra-minimally invasive" nature. Unlike traditional approaches, its operative strategy focuses on directly targeting the compressive element while minimizing tissue disruption. This means avoiding unnecessary arthrectomy or flavectomy, thus preserving healthy structures.

The key objective is to reach, remove, and verify the decompression of the affected nerve root with maximum precision and minimal collateral damage. In this chapter, the authors describe the transforaminal "out-in" approach, with reamer-assisted foraminotomy.

7.3 Indications

Pathologies treated	Disc herniation (foraminal, extraforaminal, and endocanalar with proper targeting) Foraminal stenosis Ideal for revision surgeries after previous interlaminar endoscopic or open approaches, helping to avoid scar tissue
Surgical considerations	Ensure the foramen is accessible near Kambin's triangle Verify the absence of a low-lying root or anomalies in root emergence Avoid starting with endocanalar migrations extending beyond the pedicle of the vertebra below Classify stenosis based on its location within the foraminal quadrant

7.4 The SANTY Technique (Transforaminal Technique)

Prone Position.

7.4.1 Preparation and Initial Steps

- *Anesthesia and Positioning.*
  No muscle relaxants are required. The patient is positioned prone, with careful attention to spinal alignment to facilitate optimal access and visualization.
- *Skin Landmarks* (Fig. 7.1).
  1. *Frontal Markers*: Identify and draw the midline and the disc level.
  2. *Oblique Line for Pedicle Alignment*: Draw an oblique line connecting the highest point of the pedicle of the ipsilateral vertebra below with the lowest point of the pedicle of the vertebra beneath it.
  3. *Lateral Marker*: Draw another oblique line that passes through the posterior recess of the vertebral body of the vertebra below and extends to the superior articular process. The intersection of these two lines marks the entry point.
- *Needle Insertion and Preparation.*
  Insert the needle at the identified entry point, ensuring it is positioned at the midline of the pedicle recess. After confirming correct placement, make a horizontal skin incision and insert the guidewire. Progressively increase

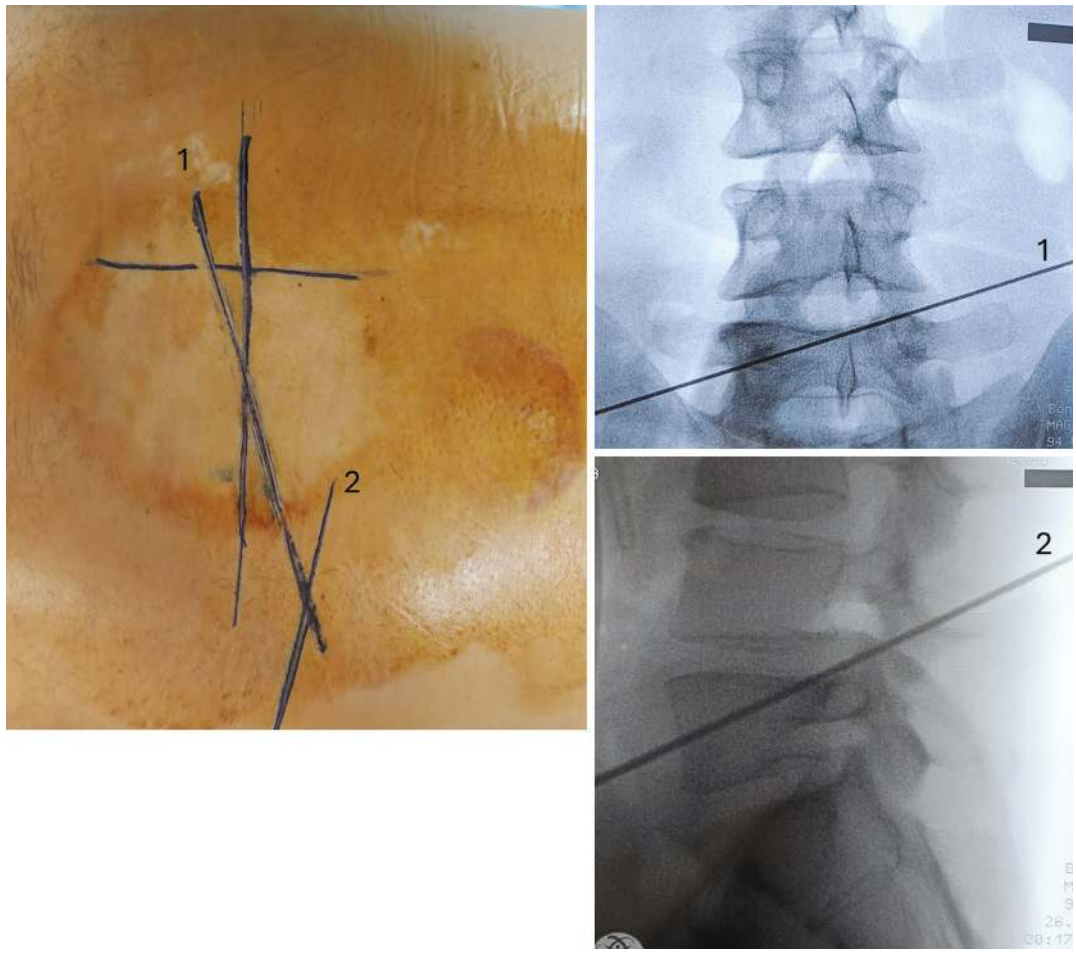


Fig. 7.1 Skin Landmarks: We draw a cross reproducing the axis of the disc and the lines of the spinous processes. Then 2 lines: 1. The first passing from the top of the pedicle of the lower vertebra to the lower part of the opposite pedicle. 2. The second on lateral view representing the projection under the posterosuperior edge of the vertebra below

the size of the cannulas and reamers, as demonstrated in Fig. 7.2.

7.4.2 Endoscopic Stage

Begin by using the radiofrequency probe to clear the reamed tissues. The radiofrequency probe is also essential in verifying that the nerve root is not too close to the area of interest. Initially, outline the bone contours by drawing the arch formed by the upper pedicle and the anterior part of the superior articular process. This creates a clear view of the recess and foramen, with the disc forming the floor and the superior articular process forming the ceiling. The lateral boundaries are defined by the pedicle on one side and the root outlet on the other.

In cases of recess stenosis, the superior articular process can be safely and efficiently resected using an outside-in, caudal-cranial technique. This approach allows for sufficient exposure of the nerve roots once the compressive elements have been removed. Confirm the decompression by checking for pulsatility of the nerve roots. Once verified, perform hemostasis and close the skin with a suture.

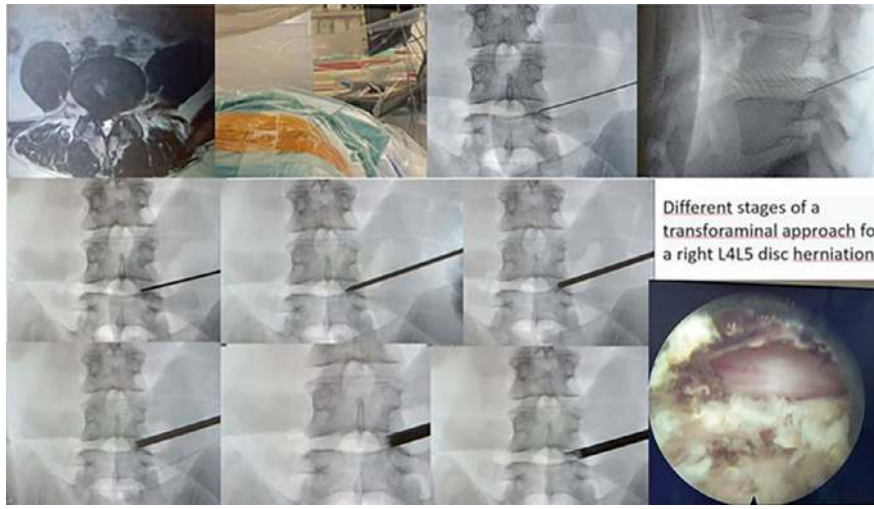


Fig. 7.2 Different stages of a transforaminal approach for a right L4L5 disc herniation

7.5 Specific Complications

Injury to the exiting foraminal root	Reflects the critical importance of precision in radioguidance and meticulous preoperative planning. Injury can result in sensory disturbances and, in severe cases, may lead to temporary or permanent neurological damage
Renal injuries	Higher targeting, particularly in the prone position, poses a risk to the kidneys. To mitigate this, some surgical teams recommend using the lateral decubitus position, which allows the abdomen to drop away from the retroperitoneal space, offering additional protection to the kidneys

7.6 The Interlaminar Technique

The interlaminar technique is less disruptive than the transforaminal approach, making it an easier choice for surgeons familiar with tubular or microscopic techniques. Key advantages include the ability to rotate the scope (typically a 15° scope), allowing the surgeon to visualize challenging corners, as well as the absence of muscle detachment. This technique is versatile and can be applied to all three spinal regions: cervical, thoracic, and lumbar. In this chapter, we focus on both uni- and bilateral approaches for the lumbar region, with or without drilling.

Interlaminar technique—recommendations	
Indications	A wide range of indications depending on the surgeon's experience in endoscopy
Initial cases	Start with easier cases, such as L5-S1 posterolateral disc herniation
Progression	Gradually progress to more cranial levels
Further indications	Unilateral recess stenosis Migrated disc herniations Bilateral central and lateral stenosis

7.7 The SANTY Technique (Interlaminar Technique)

Prone Position.

7.7.1 Preparation and Initial Steps

- *Anesthesia and Positioning*: No muscle relaxants are required. The patient is positioned prone, with careful attention to spinal alignment to facilitate optimal access and visualization.
- *Skin Landmarks Frontal Markers:* Draw the midline and disc level.
- *C-Arm Setup:* Use an AP view. The X-ray will show the interlaminar window, which projects

more caudally than the disc level at higher vertebral levels.
- *Target Point:* Identify the junction between the medial border of the facet and the interlaminar window, midway between the upper and lower lamina (Fig. 7.3a).
- *Skin Incision and Cannula Insertion:* Make a vertical skin incision, insert the guidewire, and progressively insert larger cannulas. Use a lateral C-arm view to ensure the working tube reaches the facet (Fig. 7.3b).

7.7.2 Endoscopic Stage

1. *Soft Tissue Clearance:* Use a radiofrequency probe to remove soft tissue from the capsule and ligamentum flavum.
2. *Crossing the Ligamentum Flavum:*
   - *Option 1:* Cut it horizontally (Fig. 7.3c).
   - *Option 2:* Divide it vertically with an elevator until the dura or epidural fat is visible.
3. *Recess Stenosis Management:*
   - Drill the medial part of the inferior articular process using a dedicated intermediate-speed burr (10,000 rpm).
   - Follow by drilling the medial part of the superior articular process before removing the ligamentum flavum.

7.7.3 Disc Herniation Removal

- *Root and Dura Exposure:* Once compressive elements are removed, the ipsilateral root and dura become visible.
- *Disc Access:* Use a palpator to gently retract the root medially, exposing the disc (Fig. 7.3d).
- *Working Channel Positioning:* Advance the working channel to the disc level and rotate it to protect the retracted root (maximum 10 min, Fig. 7.3e).
- *Herniation Removal:* Extract the disc herniation and perform hemostasis using the radiofrequency probe (Fig. 7.3f).

7.7.4 Contralateral Stenosis Management

- Use the "over-the-top" technique to access the contralateral side.
- Drill and remove the contralateral ligamentum flavum until the contralateral root is decompressed and visualized.
- *Drill Options*
  - Use a 4.5 mm diamond burr for precision.
  - For extensive bony work, consider using bone-cutting burrs, noting their higher efficiency but increased risk when the ligamentum flavum is already open.

7.7.5 Final Steps

- *Decompression Confirmation:* Check for pulsatility of the dura and/or nerve roots to confirm adequate decompression.
- *Hemostasis and Closure:* Perform hemostasis and close the skin with a suture (Table 7.1).

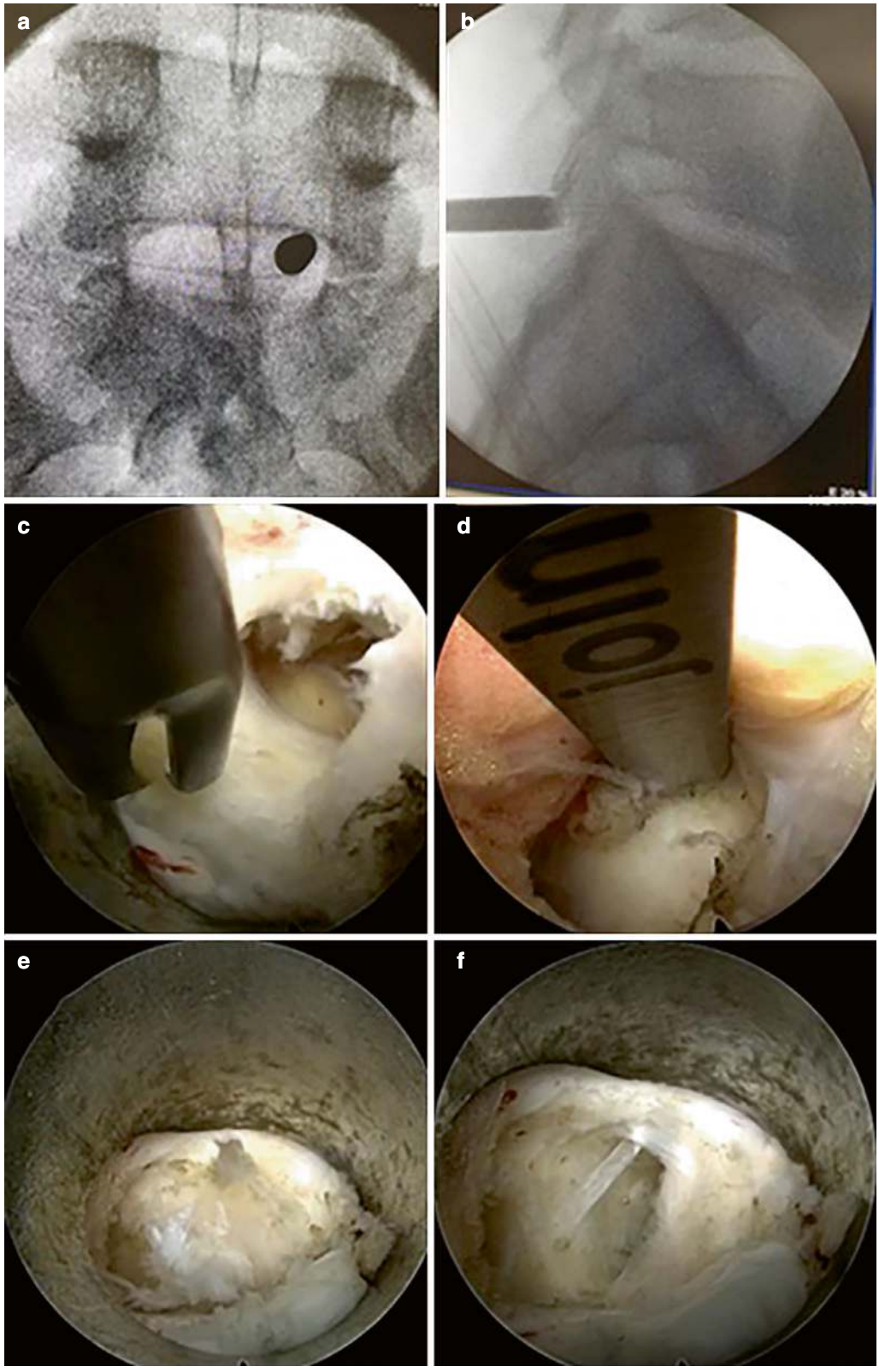


Fig. 7.3 Inter laminar technic for L5S1 disc herniation

Table 7.1 Key surgical considerations

Step	Details
Positioning	Prone, no muscle relaxant
Imaging setup	AP and lateral views with C-arm
Target point identification	Medial border of the facet & interlaminar window midpoint
Ligamentum flavum management	Horizontal incision or vertical division
Disc access	Use a palpator to expose the disc
Root protection	Rotate the working channel, max 10 min
Drilling	Use 4.5 mm diamond or bone-cutting burrs
Decompression check	Confirm nerve root pulsatility
Closure	Hemostasis and skin suture

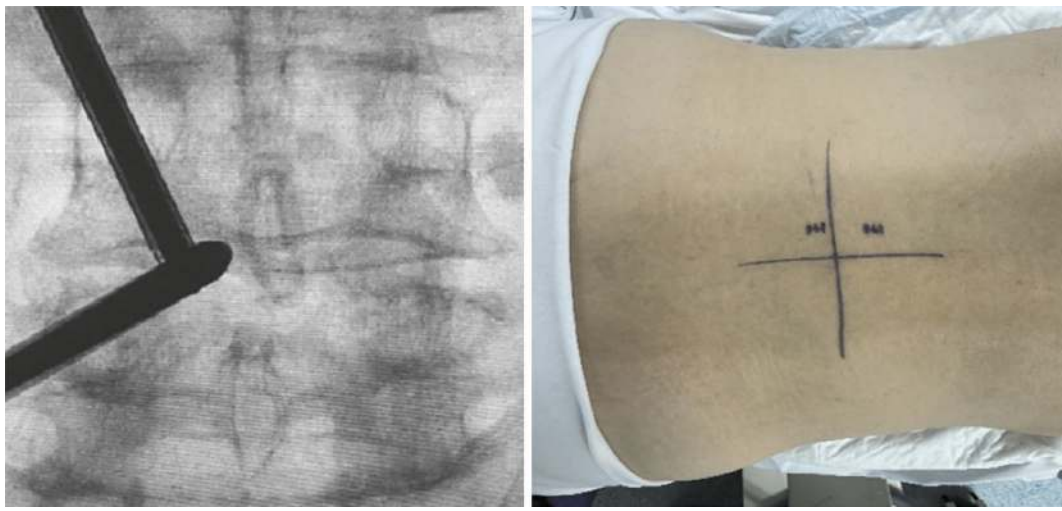


Fig. 7.4 Skin landmaks and UBE docking point

7.8 Complications

The potential complication types are similar to those encountered in an open approach and include epidural hematoma, dural tear, neurological injuries, inadequate decompression. The infection rate seems to be diminished with endoscopy [18].

Complication	Management
Dural tear with rootlet herniation	Conversion to an open approach is required for direct dural suturing
Small dural defects (< 5 mm)	Apply a hemostatic patch directly through the cannula and place it over the defect to promote sealing and healing

7.9 Unilateral Biportal Endoscopic Technique

7.9.1 Indications

The indications for biportal endoscopic surgery align with those of interlaminar, transforaminal, or traditional open and minimally invasive techniques. This technique is particularly recommended for bilateral decompression or cases involving significant bony work (Fig. 7.4) (Table 7.2).

Table 7.2 Indications for biportal endoscopic surgery

Indications	Details
Bilateral decompression	Ideal for addressing bilateral pathologies
Extensive bony work	Suitable for cases requiring significant bone removal
Standard indications	Similar to interlaminar, transforaminal, open, or minimally invasive techniques

7.9.2 Materials Required

- *Spine Endoscope:* 0° 15° or 30°.
- *Radiofrequency Probe:* For tissue ablation.
- *Dilator Bougies:* For gradual tissue dilation.
- *Saline Irrigation:* Gravity-fed, positioned 1 meter above the patient.
- *High-Speed Drill*: 4 mm diamond burr.
- *Surgical Instruments:* Kerrison punch, nerve root retractor, pituitary forceps, elevator, and hook.

7.10 Operative Technique

7.10.1 Preparation and Initial Steps

- *Patient Position:* Prone.
- *Incision Side:* Ipsilateral to the side of the pain (some surgeons prefer contralateral for L2-L3 and L3-L4 herniations).
- *Beginner Tip:* Left-sided disc herniations are easier for right-handed beginners.
- *Endoscope Recommendation:* Use a 0° or 15° endoscope.

7.10.2 Surgical Level Identification

- Use an *anteroposterior C-arm view* to identify the surgical level.

7.10.3 Incisions

- *Number:* Two incisions:
  - *Cranial Incision*: For arthroscope insertion.
  - *Caudal Incision:* For instrument access.
- *Incision Placement:*
  - 2–3 cm apart.
  - Vertical (craniocaudal) incisions recommended for beginners to allow easy conversion to an open approach.
  - Slight offset in the muscle fascia for ergonomic access.
  - Ensure effective *saline irrigation* and fluid outflow from the caudal incision (Fig. 7.5).

7.10.4 Dilator Insertion and Working Space Creation

- Insert dilators through both incisions.
- Detach muscle from the lamina, facet joint, and spinous process.
- *Target:* Base of the lamina (triangulation target).
- *Working Zone:* Beneath the multifidus and longissimus muscles within the "Son space" (fatty tissue sheath).

7.10.5 Endoscopic Insertion

- Insert the endoscope through the cranial incision and surgical instruments through the caudal incision.
- Perform a *fluoroscopic check* to confirm the vertebral level.

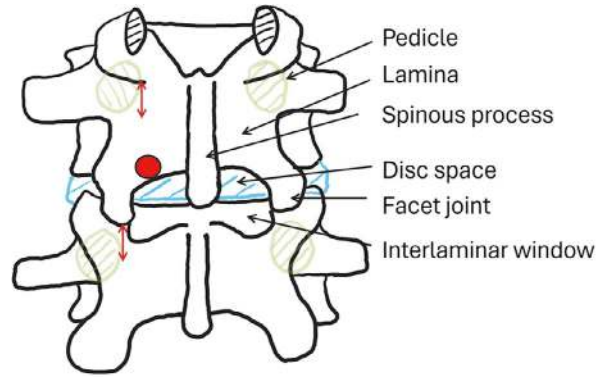
7.10.6 Surgical Exposure

1. Use the *radiofrequency probe* to expose the ipsilateral cranial vertebra's lamina.
2. Ensure *optimal fluid outflow*:
   - Inadequate outflow → Bloody field, poor visibility.
   - Excessive outflow → Chamber collapse.

7.10.7 Bony Decompression

- *Expose:* Cranial lamina, medial facet joint, interlaminar window.

Fig. 7.5 landmark for UBE technic



- *Drill:* Use a high-speed drill (20,000 rpm) with a diamond burr for minimal tissue injury.
- *Resect Bone:*
  - Drill the lamina and medial facet joint border until inner cortical bone is visible.
  - Use a *Kerrison punch* to complete the approach.
  - Extend bony resection cranially until the attached ligamentum flavum is exposed.
  - Extend laterally to the lateral border of the passing nerve root.
  - Complete all bony decompression *before opening the canal* to avoid dural injury.

7.10.8 Ligamentum Flavum Removal

- *Expose:* Cranial and lateral insertion of the ligamentum flavum.
- *Enter Canal:*
  - Remove the ligament gently with *pituitary forceps*.
  - Complete removal using a *Kerrison punch*.
  - *Visualize:* Clear view of the lateral border of the nerve root.

7.10.9 Disc and Nerve Root Release

- Perform *epidural space dissection* with a spatula.
- *Identify:* Disc and compressed nerve root.
- *Goal:* Release the nerve root from any inflammatory tissue.

Unilateral biportal endoscopic technique—operative technique—key steps

Step	Action	Details
Patient positioning	Position prone	Incision side: Ipsilateral to pain Beginner tip: Left-sided disc herniations are easier for right-handed beginners
Surgical level identification	Use C-arm (AP view)	Confirm surgical level
Incisions	Two vertical incisions	Cranial: arthroscope; caudal: instrument
Dilator insertion	Insert dilators to create working space	Target: Base of lamina (Son space)
Endoscopic insertion	Insert endoscope through cranial incision	Fluoroscopic check for level
Surgical exposure	Use radiofrequency probe to expose structures	Maintain optimal fluid outflow
Bony decompression	Drill lamina, medial facet, interlaminar window	Use Kerrison punch for removal
Ligamentum flavum removal	Remove ligamentum flavum with pituitary forceps	Complete removal with Kerrison punch
Disc and nerve root release	Dissect epidural space, identify disc and root	Release nerve root from compression

7.11 Summary

Spine endoscopy has revolutionized the treatment of degenerative lumbar disease by enabling increasingly minimally invasive procedures. This approach reduces postoperative pain, shortens hospital stays, and lowers complication rates. Various techniques can be employed, including the transforaminal approach, interlaminar monoportal endoscopy, and Unilateral Biportal Endoscopy.

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8 Circumferential Lumbar or Lumbosacral Fusion by Posterior Approach: Minimal-Invasive Transforaminal Lumbar Interbody Fusion (Mis TLIF) and Posterior Lumbar Interbody Fusion (PLIF)

Nathan Beucler, Kaissar Farah, and Stéphane Fuentes

8.1 Introduction

Since the 1990–2000s, circumferential lumbar interbody fusion has emerged as a possible surgical treatment of back pain associated with radicular pain of the lower limbs [1]. Among the different surgical techniques available for lumbar spine fusion, posterior lumbar interbody fusion, abbreviated PLIF and transforaminal lumbar interbody fusion, otherwise called TLIF, both allow for slight correction of sagittal imbalance of the lower lumbar spine by restoring segmental lordosis [2, 3], but mostly for direct posterior decompression of the nervous elements. Recent evidence has shown slight functional benefit and better spine fusion of posterior lumbar spine fusion with decompression over lumbar decompression alone for degenerative back pain associated with radicular pain of the lower limbs [4, 5].

Here, we briefly describe the surgical indications for PLIF and TLIF and provide some technical tips in order to ease challenging surgical steps, notably foramen decompression and interbody cage placement during minimal-invasive TLIF.

8.2 Indications

PLIF and TLIF are well suited for the following indications:

- Mechanical lower back pain associated with radicular pain of the lower limbs caused by low-grade degenerative lumbar spondylolisthesis [1, 6–9],
- Symptomatic lumbar canal stenosis associated with degenerative spinal instability [2, 5],
- Recurrent symptomatic lumbar disc herniation [8].

These surgical procedures can also be performed for the following clinical situations:

- Degenerative discogenic back pain, especially at L3L4 and L4L5 level thanks to the horizontal character of the disc space of the middle

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lumbar spine, even though PLIF or TLIF can also be performed at L5S1 level despite the more vertical character of the disc space there [1, 8, 10],
- And more rarely for cases of radicular pain from single-level foraminal stenosis in the setting of thoracolumbar degenerative scoliosis [2].

8.3 Preoperative Work-Up

Patients should undergo complete work-up of the lumbar spine including the following:

- CT scan in order to anticipate the aspect of the hypertrophic zygapophyseal joint and the posterior bone spurs of vertebral endplates which can hamper TLIF cage insertion,
- MRI to evaluate the discopathy and to anticipate the need for spinal canal decompression,
- Dynamic-profile X-ray of the lumbar spine in flexion and extension in order to confirm degenerative instability for spondylolisthesis,
- Standing full-spine EOS radiographs in order to anticipate the correction required for frontal and sagittal imbalance,
- Electromyography of the lower limbs can be helpful in case of bilateral radicular pain of the lower limbs in order to decide the side of arthrectomy or to confirm long-term radicular damage for legal issues.

8.4 Surgical Procedure

For both procedures, the patient lies prone, ideally on a spine table allowing to relieve mechanical pressure on the abdomen, thereby decreasing epidural venous congestion which will facilitate proper discectomy and placement of the interbody implant.

8.4.1 Open PLIF

Classic open posterior approach to the lumbar spine is performed, centred by the affected disc (Fig. 8.1a). Pedicular screws are placed (Fig. 8.1b). Bone decompression includes the lower two-thirds of the upper lamina (Fig. 8.1c) and the upper one-third of the lower lamina (Fig. 8.1d), which corresponds to the insertion of the ligamentum flavum. Hypertrophic ligamentum flavum is completely resected down to the lateral recess. This first surgical step corresponds to classic open lumbar spinal stenosis decompression. Once the interlaminar bone window seems sufficient, partial medial resection of a third of the hypertrophic articular processes provides direct visualization of the intervertebral foramen, thus making sure the exiting nerve roots are free from mechanical compression.

Resection of the mesial part of the articular processes also provides direct access to the disc space without requiring excessive traction on the dural sac nor the shoulder of the passing nerve root. Epidural venous plexus are controlled using bipolar cautery. Then, discectomy is carried out using Cushing intervertebral disc rongeur first, followed by ring curettes (Fig. 8.1e). In order to optimize endplates preparation, cartilage is removed using shavers and reamers.

Once the lower and upper vertebral endplates are properly prepared, the intervertebral space is progressively expanded using trial cages of increasing thickness. Then, the desired interbody TLIF implant can be placed, using a 10–20° slightly convergent angle (Fig. 8.2a). It should measure 2 mm less than the largest trial implant used in order to decrease the odds of endplate fracture and cage subsidence. Temporary contralateral distraction with rod and screws may ease the insertion of the cage, and the same manœuvre can be performed for the other side once the first cage has been placed (Figs. 8.2a, b). The cage should be placed anteriorly enough, i.e. right behind the anterior longitudinal ligament, in order to restore segmental lordosis. Interbody grafting is placed between the two PLIF implants (Figs. 8.2c, d). Last, contraction manœuvres on the two rods provide supplementary segmental lordosis (Fig. 8.2e).

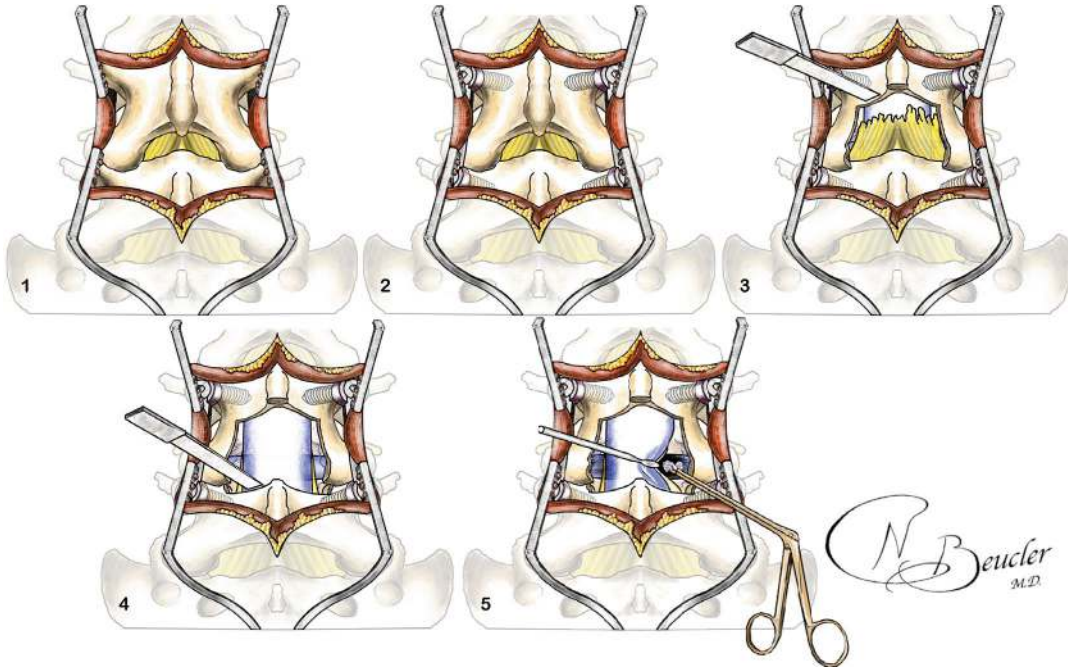

Fig. 8.1 Artistic view of surgical steps during PLIF, part 1 (**a**). Surgical exposure (**b**). Open pedicle screw positioning (**c**). Bone decompression of upper lamina (**d**). Bone decompression of lower lamina (**e**). Discectomy

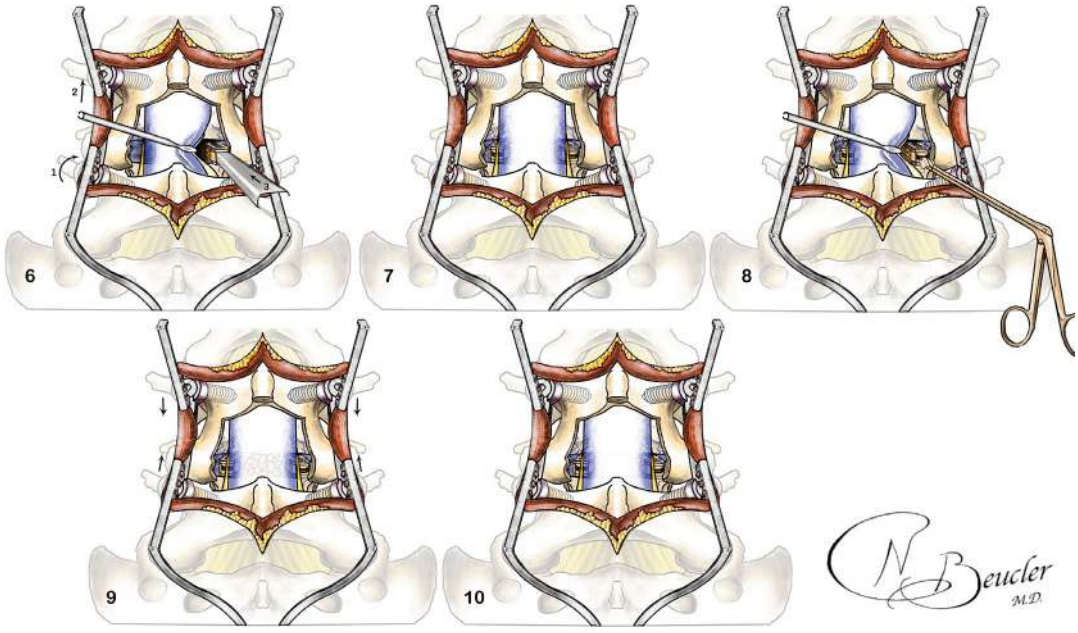

Fig. 8.2 Artistic view of surgical steps during PLIF, part 2 (**a**). Contralateral distraction to ease ipsilateral TLIF cage insertion (**b**). PLIF cages in place (**c**). Gentle dural sac and nerve root retraction for intersomatic bone grafting (**d**). Bone graft in place, contraction of posterior instrumentation (**e**). Final aspect

8.4.2 Minimal-Invasive TLIF

8.4.2.1 Percutaneous Pedicle Screws

K-wires are placed in the pedicles through Jamshidi needles under anteroposterior fluoroscopy control (Fig. 8.3a), then the fluoroscopy is definitively placed for profile guidance only. Percutaneous screws are placed on the less symptomatic side (Figs. 8.3b, 8.4a and 8.5a). On the most symptomatic side, *the K-wires are maintained during the whole procedure against the surgical field* using gauze dressings and 10 cm foliodrape® OP-tape (Fig. 8.3b). A paramedian 5 cm skin incision is performed between these two K-wires, 2.5 cm from the midline (Figs. 8.3b and 8.5e).

Under profile fluoroscopy guidance, a transmuscular minimal-invasive Wiltse approach is performed using sequential tubular dilators allowing to place a retractor, for example the Quadrant® (Medtronic) system, which provides direct exposure of the zygapophyseal joint from the upper to the lower pedicle (Figs. 8.3c, 8.4a and 8.5b).

8.4.2.2 Arthrectomy

Using the operative microscope, subperiosteal dissection using a monopolar with a long blade provides clear visualization of the upper lamina, isthmus, inferior articular process of the upper vertebra and superior articular process of the lower vertebra. Foraminal exposure can now be performed by resecting the zygapophyseal joint.

The first step consists of removing the lower articular process of the upper vertebra. For this purpose, the surgeon will remove a *right-angled*

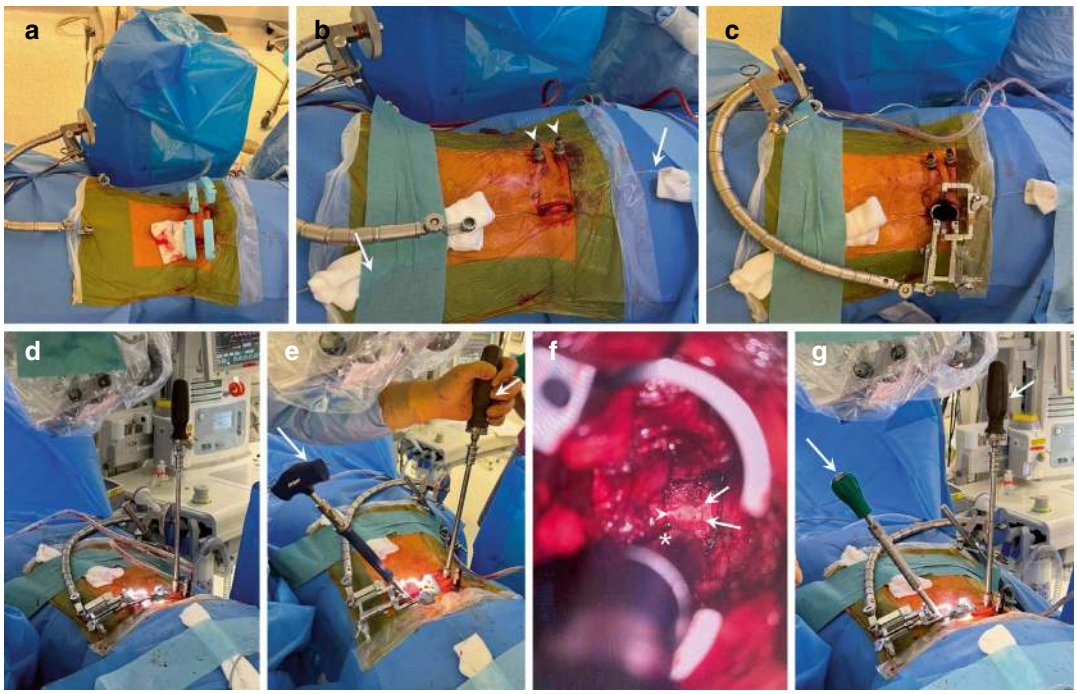

Fig. 8.3 Intraoperative photographs. (**a**) Pedicle trajectory using Jamshidi needles. (**b**) Contralateral percutaneous pedicle screws (white arrowheads), K-wires maintained against surgical field with OP-tape (white arrows), 5 cm paramedian incision between k-wires. (**c**) Tubular retractor quadrant® placed. (**d**) Screw driver kept on contralateral side to perform contraction or distraction manœuvres whenever necessary. (**e**) Shavers and trials of increasing size are placed through the 30° MIS TLIF approach (large white arrow), please note the contralateral screwdriver for intersomatic distraction (small white arrow). (**f**) Posterior bone spur (lower white arrow) of superior endplate of lower vertebra is removed using misonix® bone scalpel (white star) to ease access to disc space (white arrowhead), please note upper vertebra lower endplate (upper white arrow). (**g**) TLIF cage insertion (large white arrow)

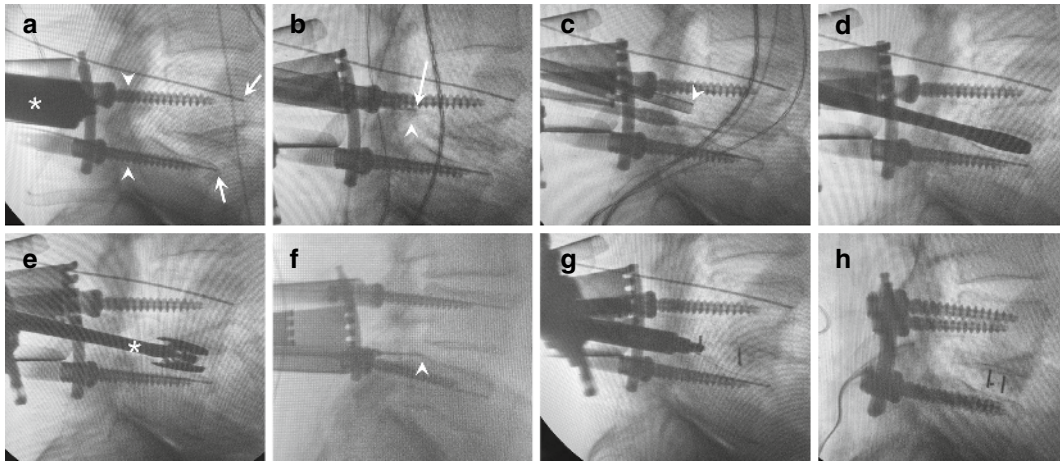

Fig. 8.4 Intraoperative profile fluoroscopy guidance. (**a**) Ipsilateral K-wires (white arrows) allow insertion of dilators (white star) for placement of tubular retractor, please note the placement of contralateral screws (white arrowheads). (**b**) Misonix® bone scalpel cuts the isthmus (white arrow) down to the anterior bone cortex of lamina (white arrowheads), right below the inferior cortex of pedicle. (**c**) Suction in the unroofed foramen (white arrowhead). (**d**) Intersomatic space dilatation. (**e**) Dynamic intersomatic dilatation device (white star). (**f**) Removal of posterior bone spur of superior endplate of inferior vertebra using misonix® bone scalpel to ease TLIF cage insertion. (**g**) TLIF cage insertion. (**h**) TLIF cage rotation, please note that radiopaque markers of the cage are almost aligned

bone corner, the horizontal cut concerning the *isthmus right below the inferior aspect of the upper pedicle* (Figs. 8.4b, c and 8.5c), and the vertical cut concerning *the lamina a few millimetres lateral from the spinous process*. This osteotomy can be performed using either a blunt ultrasonic bone blade such as the misonix®, or a 1 cm straight bone osteotome. Profile fluoroscopy guidance can help the surgeon making the horizontal cut right below the lower aspect of the upper pedicle (Fig. 8.4b). It is also useful for pushing the osteotomy deep enough, at least down to the anterior cortex of the lamina. This allows for monobloc removal of the inferior articular process.

Osteotomy of the superior articular process of the lower vertebra is then conducted using either the osteotome *placed horizontally right above the upper cortex of the lower pedicle using profile fluoroscopy guidance* (Fig. 8.6a), or a Kerrison bone rongeur.

Optimal exposure from pedicle to pedicle helps reducing nerve root traction during TLIF cage insertion (Fig. 8.6b).

8.4.2.3 Spinal Canal Decompression

Once the foramen has been unroofed, the surgeon can either choose to perform unilateral flavectomy with the large Kerrison rongeur in case of unilateral foramen stenosis (Fig. 8.5d), or to conduct an *over-the-top complete flavectomy* by *tilting the operative microscope and tubular retractor 45° medially* in case of associated central canal stenosis.

8.4.2.4 Access to Disc Space

Once the dural sac is free within the spinal canal, the *landmarks of Kambin triangle* are identified: the exiting nerve root circumventing the inferior aspect of the upper pedicle superolaterally, the upper endplate of the lower vertebra inferiorly, and the dural sac medially now that the articular processes have been removed [11].

Epidural veins are cauterized before opening the posterior longitudinal ligament and accessing the disc (Fig. 8.6d). During MIS TLIF, curved curettes are very useful to access the contralateral side of the disc space through the 30° unilateral transforaminal approach. Profile fluoroscopy

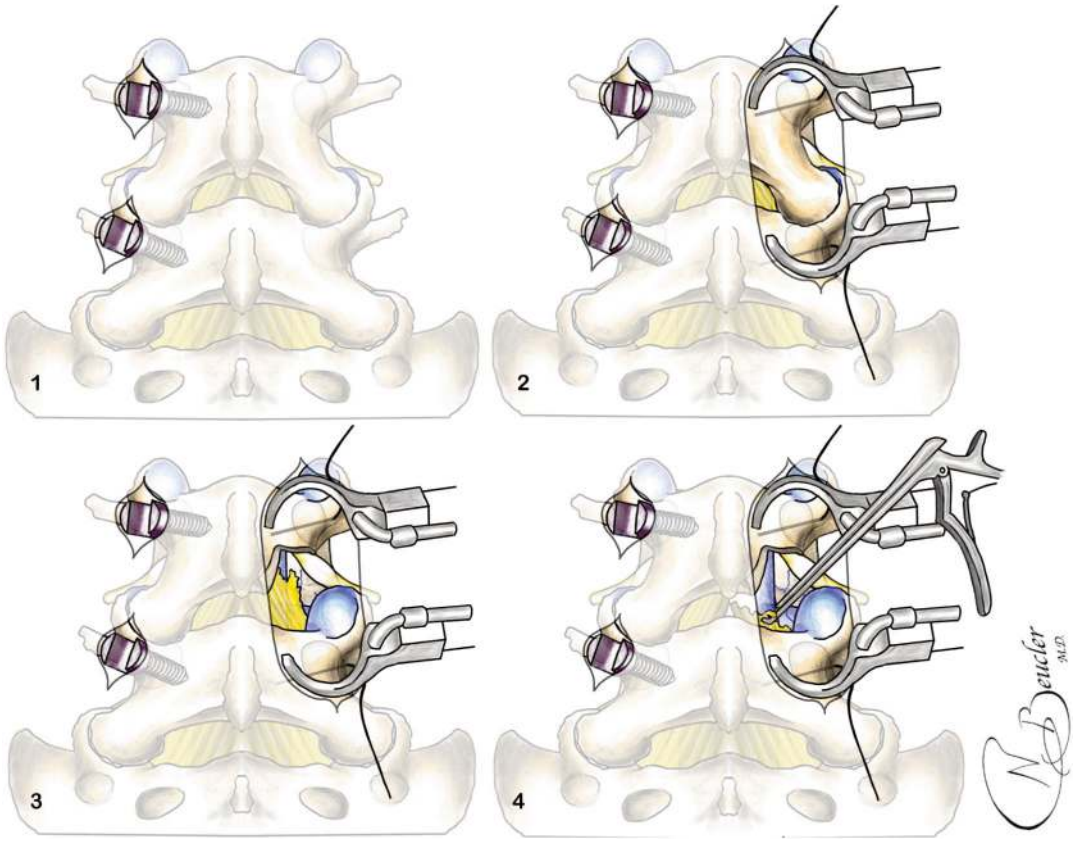

Fig. 8.5 Artistic view of surgical steps during MIS TLIF, part 1 (**a**). Contralateral percutaneous pedicle screws placement (**b**). Ipsilateral pedicle K-wires and tubular quadrant® retractor placed (**c**). Right-angled corner osteotomy of inferior articular process (**d**). Flavectomy for spinal canal decompression

helps guiding the surgeons in order to carry out discectomy down to the anterior longitudinal ligament without risking vascular injury. If necessary, rasps and shavers can be used for proper endplate preparation in order to reduce the odds of pseudarthrosis.

8.4.2.5 Placement of Intersomatic Implant

Trials of increasing size are inserted flat within the disc space and then tilted 90° in order to relax the ligaments and dilate the intersomatic space. The larger trial should measure 2 mm more than the desired TLIF cage (Figs. 8.3e and 8.4d). Dynamic dilatation of the intersomatic space can performe by the surgeon is properly equipped (Figs. 8.4e and 8.6e). Once the surgeon is satisfied with the new intersomatic height on profile fluoroscopy, *bone graft is inserted* deep into the disc space, *right behind the anterior longitudinal ligament*.

The TLIF cage is filled with bone harvested from arthrectomy. Before definitive TLIF implant insertion, *bone spurs of the superior endplate of*

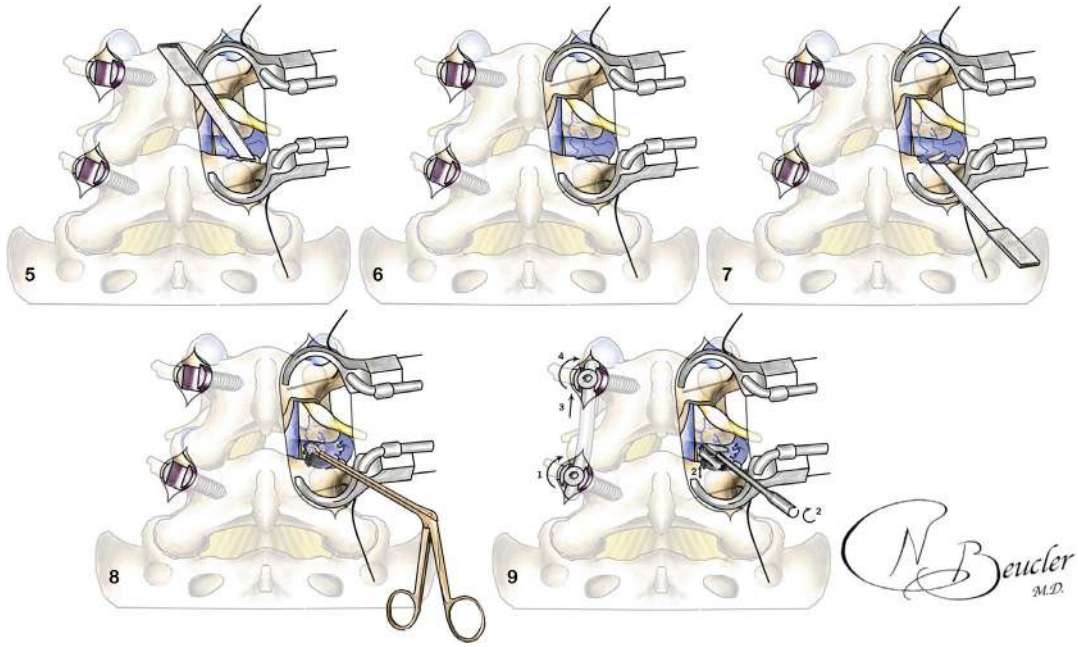

Fig. 8.6 Artistic view of surgical steps during MIS TLIF, part 2 (**a**). Osteotomy of superior articular process of inferior vertebra right above pedicle (**b**). Arthrectomy completed (**c**). Removal of bone spurs of superior enplate of inferior vertebra (**d**). Discectomy (**e**). Intersomatic dilatation using dynamic device with the support of contralateral distraction

inferior vertebra are removed, thus providing larger visual access to the intersomatic space (Figs. 8.3f, 8.4f and 8.6c). During cage insertion, if necessary, the surgeon can protect the dural sac medially using either a Penfield number 4 or a neurosurgical patty to reduce the risk of durotomy (Figs. 8.3g, 8.4g and 8.7a). *Contralateral distraction* on a temporary rod placed on the screws can also help *opening the intersomatic space*. Once the TLIF cage reaches the anterior longitudinal ligament, the operator releases the cage holding forceps. Then, the TLIF cage is *rotated* by pushing its bottom anteriorly and laterally with an *implanter held as medially as possible* (Figs. 8.4h and 8.7b). Ideally, the radiopaque markers of the TLIF cage should be aligned on profile fluoroscopy (Fig. 8.7c).

After TLIF cage insertion and once the surgeon has made sure that there is no epidural bleeding, the ipsilateral screws are placed and the K-wires are removed (Fig. 8.7d). Bilateral posterior contraction with rods and screws, associated with a TLIF implant properly positioned right behind the anterior longitudinal ligament, pro-

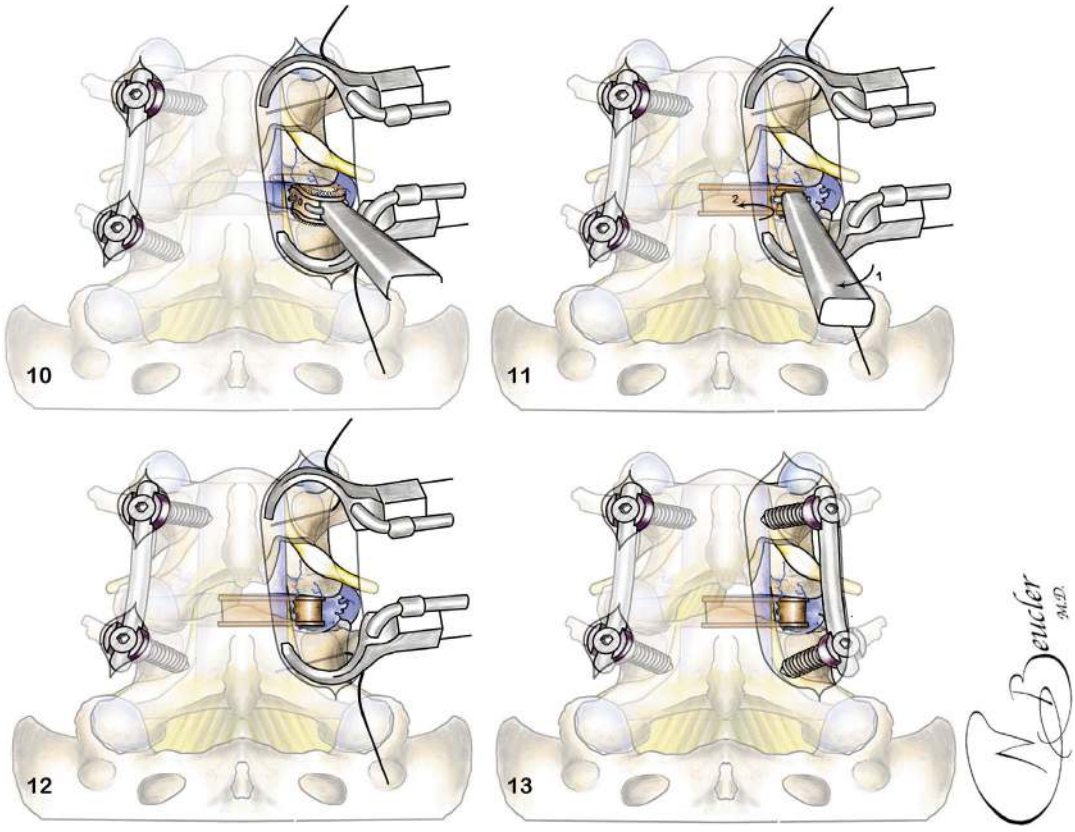

Fig. 8.7 Artistic view of surgical steps during MIS TLIF, part 3 (**a**). 30° TLIF cage insertion (**b**). Holding the implater medially (step 1) help rotating the TLIF cage laterally (step 2). (**c**) TLIF cage properly positioned. (**d**) Placement of ipsilateral screws

vides the desired segmental lordosis. The fascia and the skin are closed without drainage.

8.5 Postoperative Course

After MIS TLIF, the patient is encouraged to stand up and walk with the help of the physiotherapist at postoperative day 1, according to the principles of enhanced recovery after spine surgery. CT scan of the spine confirms optimal positioning of cage and screws, and sufficient foraminal decompression. Full-spine standing EOS radiographs can check for correction of sagittal balance if the facility is equipped for. The patient is discharged at postoperative day 4–5 in case of uneventful postoperative course.

The 1-month follow-up consultation confirms proper wound healing, beginning of functional improvement, and correction of sagittal balance on full-spine EOS radiographs. The 6-month to 1-year follow-up consult confirms long-term bone fusion.

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Surgical Technique for Anterior Lumbar Interbody Fusion

9

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9.1 Introduction

While the posterior lumbar spine approach was long the most frequently adopted to perform fusion, anterior approaches, first introduced in 1906 [1], are increasingly used.

This trend is due to:

- Proven efficacy;
- Low morbidity and mortality, notably thanks to the development of minimally invasive approaches [2–6], on condition that the technique and especially vascular risk are well mastered [7, 8].

We will describe the details of the surgical approach to perform anterior lumbar interbody fusion (ALIF) and the best way to obtain a good discectomy, endplates preparation, efficacious bone graft and instrumentation to promote a successful stabilization of the operated vertebras leading to fusion.

9.2 Patient Positioning on the Operating Table

The patient is in simple supine position or with arms and legs spread. Two options can be used: both legs in maximal abduction with the surgeon lying between both or both legs side by side with the surgeon on the side. In our experience, this second solution may cause surgeon back pain and more fatigue. It is very important to check before the skin incision that efficient AP and lateral views of the operated level can be performed with the fluoroscopic device. Except in case of BMP graft use, the left or right anterior iliac crest has to be included in the operating area.

9.3 Surgical Approach

The skin incision may be medial horizontal (Pfannenstiel) for L5S1 or medial vertical. In case of L2L5 ALIF, medial vertical incision has to be performed. Some authors use a pararectal vertical approach, but this heightens the risk of rectus abdominis denervation and atonia. The fascia is incised between the two abdominal muscles (Fig. 9.1).

The retroperitoneal approach is performed between the deep side of the rectus abdominis and the peritoneum, either right or left for L5S1 and left for upper levels. The rectus abdominis is raised for lateral access. The Douglas arcade is

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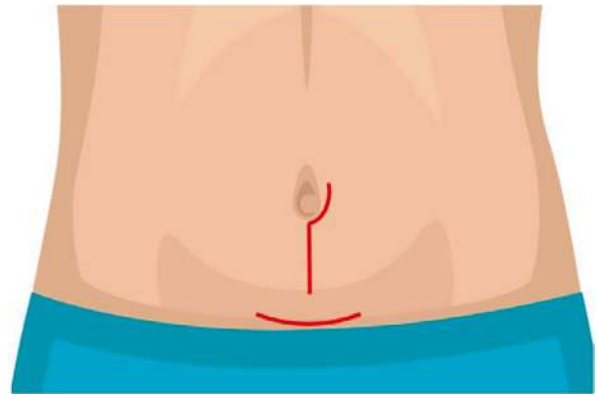

Fig. 9.1 Different types of skin incisions

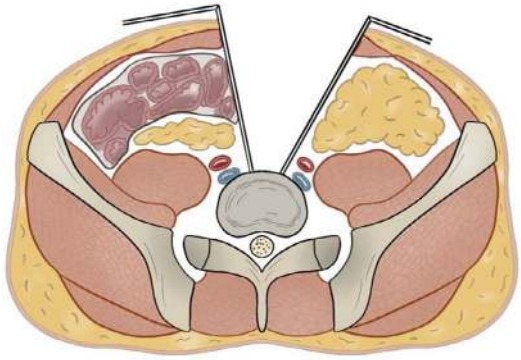

Fig. 9.2 Spine is reached by moving inward the peritoneal sac

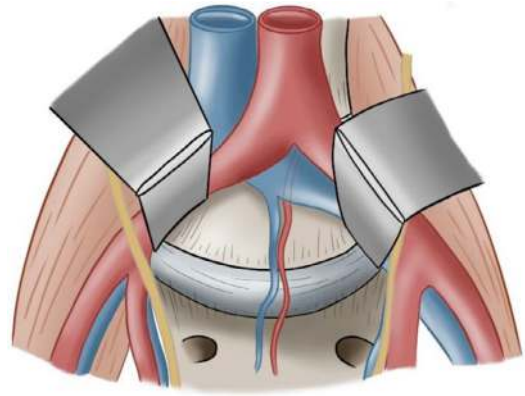

Fig. 9.3 Level L5S1: Iliac vessels are retracted laterally and presacral vessels are controlled and sectioned

released and incised vertically; release is continued laterally and the peritoneal sac is moved inward until the psoas is identified (Fig. 9.2).

In L5S1, approach on the right side has the advantage that the iliac vein is at its most lateral; the superior hypogastric plexus is naturally shifted leftward and approach on the left side is left untouched for any subsequent procedure on the overlying discs, where it avoids the obstacle of the right iliac vein. Walls are much more resistant in arteries than veins, and their accidental lesions are very rare. The peritoneal sac is progressively pushed back by a tampon and valves. The psoas muscle is an essential landmark and is easily identified by its vertical fibres and convex shape; its anterior side is carefully followed to the midline, displacing the peritoneal sac. The common iliac artery usually masks the vein, descending in front of it. To the right, the vein is more lateral and usually not visible. The ureter adheres to the peritoneum and is displaced along with it, avoiding undue and prolonged compression by a valve. In case of doubt, ureter can be recognized by pinching it with pliers because it makes it creep. Once the ureter and iliac vessels have been located, the disc is visible in the aortic bifurcation. The anterior side, in front of which the presacral vessels and superior hypogastric plexus descend, is carefully dissected. The disc is exposed from right to left, shifting the hypogastric plexus towards the accompanying aorta. No electrocoagulation, whether uni- or bi-polar, should ever be applied on the anterior side of the disc to avoid causing hypogastric plexus dysfunction; rather, presacral vessel haemostasis is achieved by clips or ligatures before sectioning the vessels to facilitate mobilization of the left iliac vein (Fig. 9.3). Management of the risk of intra-operative iatrogenic damage of the iliac

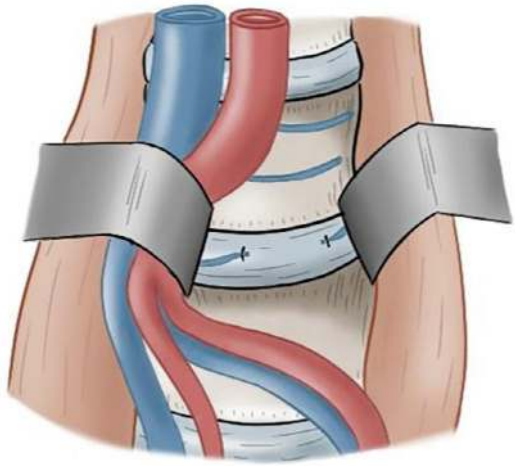

Fig. 9.4 Levels L2 to L4: Vessels are retracted from the left to the right. Ascending lumbar vein or ilio-lumbar veins must be controlled

vessels leads some spine surgeons to delegate the spinal approaches to vascular surgeons [7, 8]. Nevertheless, the spine surgeons have not to forget that vascular surgeons usually operate old vascular patients with aortic aneurysm or arteritis diseases and retrograde ejaculation is not a key point of their surgical technique. This is why they have to adapt their practice to our younger patients.

In L2L5 anterior interbody fusion, the approach is performed at the left side of the left iliac vessels, with the spine appearing on the medial side of the psoas. Care must be taken to spare the genitofemoral nerve descending in the angle between the spine and the psoas. In L4L5, it is essential to locate, ligature or clip, then section the ascending lumbar vein so as to be able safely to shift the common iliac vein towards the midline, as rupture could lead to major uncontrollable haemorrhage with the stump retracting under the psoas (Fig. 9.4). To limit 'sympathectomy effects', no electrocoagulation, whether uni- or bi-polar, should be applied on the anterolateral side of the spine where the plexus descends. Exposure is maintained by Steinmann nails in the vertebral bodies or by autostatic valves mounted on a metal ring fixed to the operating table (Fig. 9.5).

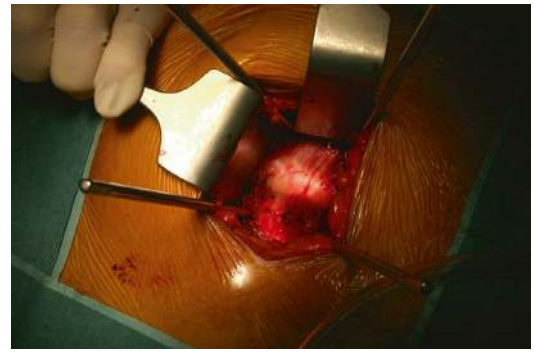

Fig. 9.5 L4L5 disc exposed. Vessels are maintained using Steinmann nails

9.4 Discectomy and Deformity Reduction

The anterior side of the disc is incised as widely as possible, using a cold blade to allow extensive discectomy. This is performed using a raspatory, disc forceps and curettes, taking care to respect the endplate cortex to avoid secondary impaction. We advise systematically opening the posterior vertebral ligament to facilitate correction of any deformity and restoring disc height if necessary. Deformity is mainly corrected under fluoroscopic controls by restoring tension in the capsule-ligament system and lateral annulus by ligamentotaxis, using dilation bougies and/or specific distractor devices, which automatically realign the vertebras. An improvement of the lumbar lordosis can be performed while using the operating table angulation (in this case, its articulation has to be in front of the operated level during the preop patient positioning).

9.5 Anterior Cage Fusion Technique

Interbody cages are classically in polyether ether ketone (PEEK), although 3D printing now mainly uses titanium. Design varies and fixation stability accordingly [9]. They are used with or without integrated fixation devices, according to design: anchors or screws. The instrumentation may be

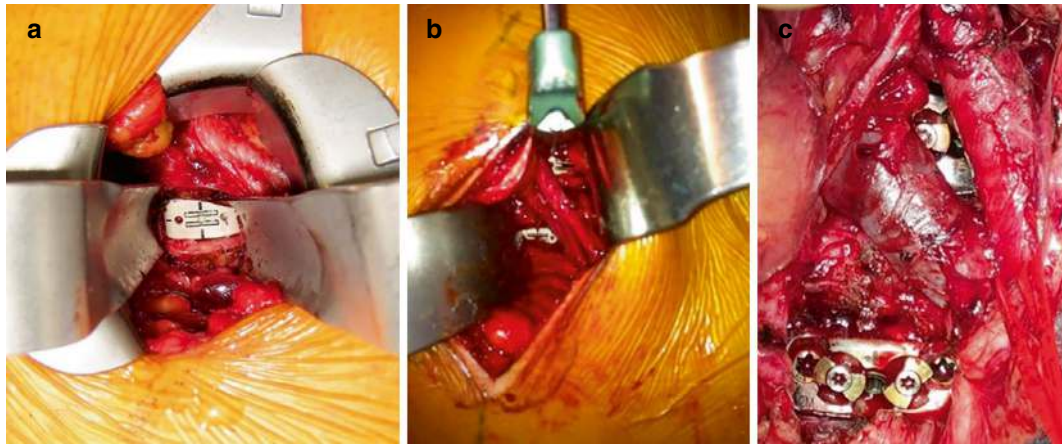

Fig. 9.6 Low profile cages after being inserted: one-level PEEK cage (**a**), two-levels PEEK cages (**b**), two-level 3D-Ti cages with a transperitoneal approach (**c**)

'stand-alone' or associated to an anterior screwed plate or posterior internal fixation (Fig. 9.6).

Choice of implant depends on the pathology, objectives and surgeon's habits. Usually, however, the cage with the widest base on the endplates will be chosen, to avoid intra-body penetration by spreading stress over the widest possible area, although without any overhang into the foramen, which could incur radicular impingement [10]. For the same reason, cages with posterolateral convexity are to be avoided. Metal templates are introduced after the reduction manoeuvres, with hard friction but not too much force as it would damage the endplates. Small bougies can be let in the lateral interbody area to maintain the intervertebral distraction during the cage insertion. The cage needs to fit the two-endplate surfaces as perfectly as possible, both frontally and laterally on the fluoroscopic controls.

Lumbar fusion uses autologous bone graft (cancellous bone) or bone morphogenetic protein (BMP); no other kinds of osteoinductive or osteoconductive bone substitute or allograft have proven sufficient efficacy. Bone marrow can be strived with a Jamshidi trocar and combined with osteoconductive bone substitute before its insertion in the cage. Unlike in the cervical spine, where the distance between endplates is just 5 mm, the 10–16 mm distance in the lumbar spine is too great to allow fusion without autologous or BMP graft.

The final step before introducing the cages is to freshen the endplates. This should not be done before the retractor and trial implants have been introduced, to avoid endplate lesions or the template penetrating the endplate. Freshening should not be too aggressive, so as not to damage the cortical bone, with risk of secondary cage subsidence. If the aim is stand-alone instrumentation, shavers should not be used. At the same time, freshening should not be too superficial, to prevent non-union. The best procedure is to use a fenestrated curette to achieve a uniform surface while still reaching the cancellous bone. In case of very hard or sclerotic bone, bone scissors may be needed. When PEEK cages are used, it is senseless and dangerous to freshen the endplate where the cage walls are going to lie against the vertebra, which could lead to cage subsidence without any gain in osteogenesis. After freshening and checking for bone debris liable to be pushed into the spinal canal, the cage is inserted and stabilized or not into both adjacent vertebral bodies with anchoring plates or screws according to the cage model (Fig. 9.7).

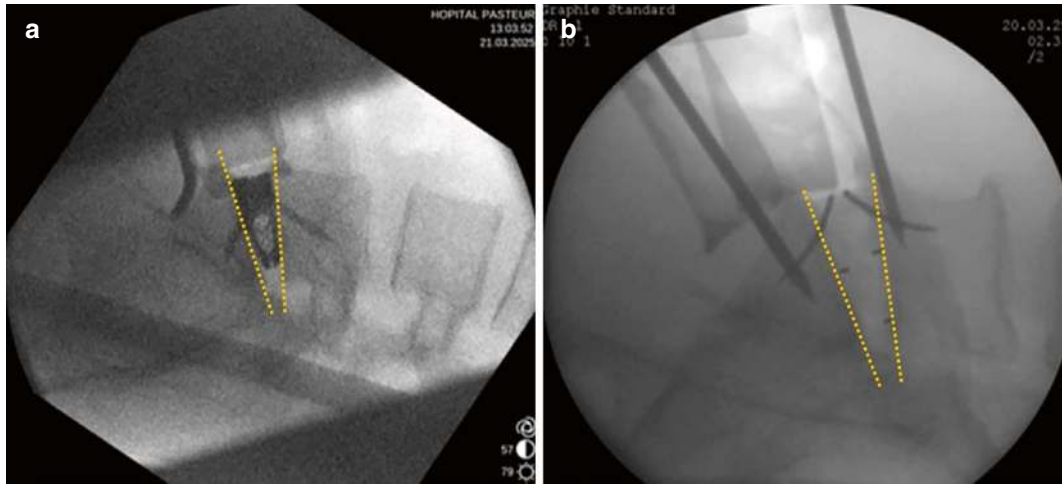

Fig. 9.7 Peroperative X-ray controls: titanium cage with screws (**a**) and PEEK cage with anchors (**b**), both restoring segmental lordosis

9.6 Anterior Lumbar Fusion Technique by Locking Plate

Anterior fusion by locking plate can be isolated or associated to an interbody cage to increase stability. Great care must be taken in drilling the screw-holes and in screwing, as several studies reported higher complication rates when rotating instruments were used in proximity to the prevertebral veins. Sasso, in a series of 471 fusions, comparing impacted versus screwed implants, reported a ten-fold greater rate of complications with screwing: 4.8% versus 0.4% [11]. These risks can be reduced by having perfect exposure of the spine and using protective valves and sleeves. The screw-heads must not protrude, and plate thickness should not exceed 10 mm, to avoid secondary arterial lesions.

The Steinmann nails should be removed with caution, being very sharp. It should be checked that there is no bleeding, which would indicate that the nail had pierced a vein.

Prevertebral drainage is not systematic. It is not necessary to suture the Douglass fascia. The white line should be carefully repaired with a solid No. 2 slow absorption (PDS) or non-absorbable suture.

9.7 Transperitoneal Approach [12]

This older technique is less and less often used, due to risk of injury to the peritoneum and superior hypogastric plexus (depending on the surgeon's experience) [13] and secondary intestinal occlusion around iatrogenic fibrous scar tissue. Performing and closing the approach increases surgery time and often induces paralytic ileus. The technique may nevertheless be useful in patients with history of multiple abdominal surgery in whom retroperitoneal release proves impossible, or in revision of an anterior spinal approach, to reduce the risk of vascular and urologic complications. The anterior peritoneum is opened and the digestive tract loops are pushed back by damp drapes. Once the sigmoid and mesosigmoid have been pushed to the left, physiological saline is injected into the retroperitoneal space to release the posterior peritoneum from the prevertebral vessels and superior hypogastric plexus; it is then incised vertically. The rest of the procedure is as with the retroperitoneal approach.

To sum up:

- The approach is usually retroperitoneal;
- Electrocoagulation should imperatively be avoided, to respect the hypogastric and sympathetic plexi;
- Endplate preparation, bone graft quality and cage size adaptation to the intervertebral disc space are the key points to obtain fusion without subsidence;
- Instrumentation may use interbody cages and/or a screwed plate.

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10 Oblique Lateral and Extreme Lateral Interbody Fusion: Techniques, Indications and Outcomes

Jordan Assaker, Pierre Haettel, Boulos Ghannam, Henri Arthur Leroy, and Richard Assaker

10.1 Introduction

Oblique lateral interbody fusion (anterior to psoas, OLIF) and extreme lateral interbody fusion (transpsoas, XLIF) are two minimally invasive approaches to lumbar spinal fusion that access the spine from the patient's flank [1]. These lateral accesses avoid the extensive muscle dissection of posterior approaches and the large abdominal incision or great vessel mobilization required in anterior lumbar interbody fusion (ALIF). OLIF and XLIF achieve intervertebral fusion via indirect neural decompression (restoring disc height and ligament tension) and can correct deformities with large grafts while preserving the anterior and posterior longitudinal ligaments. OLIF, introduced in the late 2000s (term coined in 2012 by Silvestre et al.), uses an anterior-to-psoas corridor between the psoas muscle and great vessels. This avoids traversing through the psoas, reducing lumbar plexus risk of injury while still allowing deformity correction and indirect canal decompression. XLIF (also known as direct lateral or transpsoas fusion), popularized earlier in the 2000s, accesses the disc space through the psoas muscle from the lateral flank. Both techniques have shown favourable clinical outcomes in degenerative disc disease, spondylolisthesis and adult deformity, with significant pain and disability improvements postoperatively. In this article, we review the surgical approaches, step-by-step procedure, instrumentation and neuromonitoring, indications/contraindications, comparative advantages and limitations, common complications (with avoidance strategies) and clinical outcomes for OLIF and XLIF based on current peer-reviewed literature and surgical texts.

10.2 Surgical Approaches and Patient Positioning

Both OLIF and XLIF are performed with the patient in the lateral decubitus position on a radiolucent table. Typically, surgeons prefer a right lateral decubitus position (left side up) for OLIF, taking advantage of the usual anatomy: the aorta lies to the left of the spine and the inferior vena cava (IVC) to the right, making the left access a safer corridor (Figs. 10.1 and 10.2). In XLIF, the patient is also placed in lateral decubitus (often right lateral decubitus as well), and the operating table may be flexed ('jackknifed') at the hips to increase the space between the iliac crest and the rib cage for levels like L4-L5 (Fig. 10.3). The patient's flank is secured with taped supports, and all pressure points are padded

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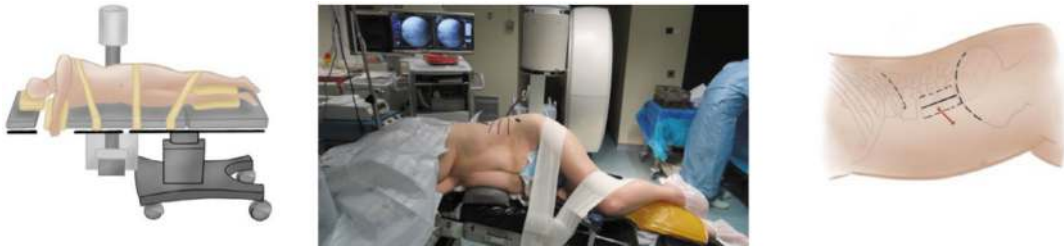

Fig. 10.1 Positionning and skin incision mark

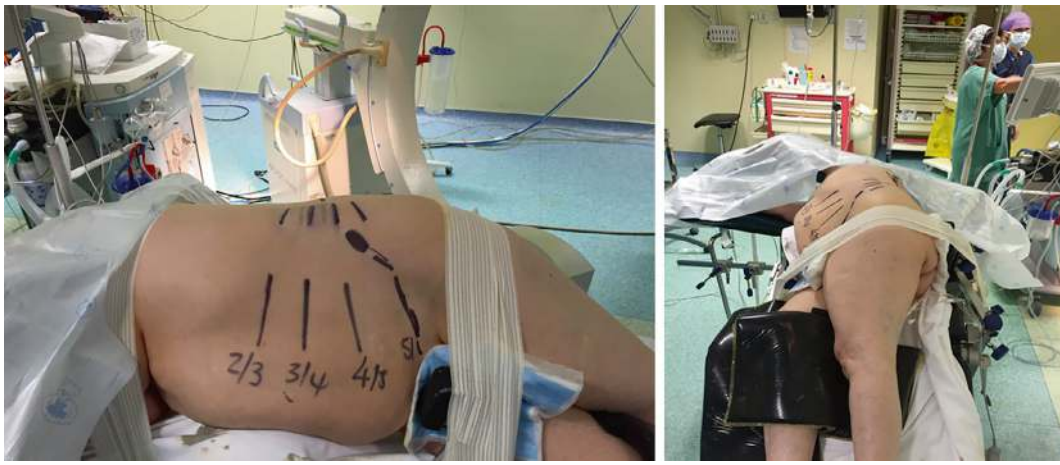

Fig. 10.2 Discs levels marks. Noticed that for a anterior to psoas access the ipsilateral leg is extended

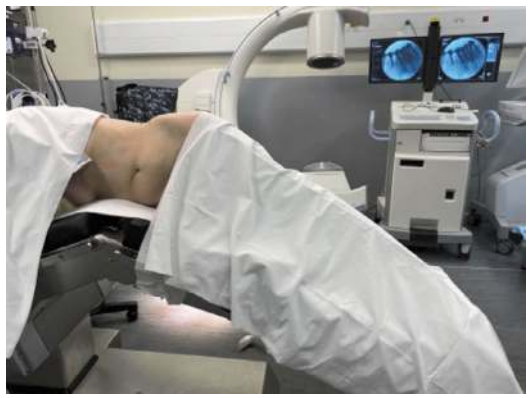

Fig. 10.3 For a transpsoatic access the operating table is flexed

to prevent shifting during the approach. Fluoroscopic imaging (C-arm) is used to identify the target disc level, and a skin mark is made at the level of the disc space on the lateral abdomen (Figs. 10.1 and 10.2).

10.2.1 Anterior to Psoas Approach

The surgeon stands anterior to the patient. An oblique skin incision (typically ~3–5 cm in length) is made on the side of the abdomen, a few centimetres anterior to the mid-disc line on lateral projection Fig. 10.1. The exact incision location is planned using preoperative imaging to account for anatomic landmarks: the '*oblique corridor*' between the peritoneum and psoas. Through this flank incision, the external oblique, internal oblique and transversus abdominis muscle layers are sequentially split in line with their fibres (often by blunt finger dissection). The surgeon carefully opens the transversalis fascia with a finger or blunt instrument, directing forces posteriorly to avoid entering the peritoneal cavity. Once the retroperitoneal space is reached, the peritoneum (with bowel contents and ureter) is gently mobilized anteriorly, while the psoas (and kidney/ureter, if

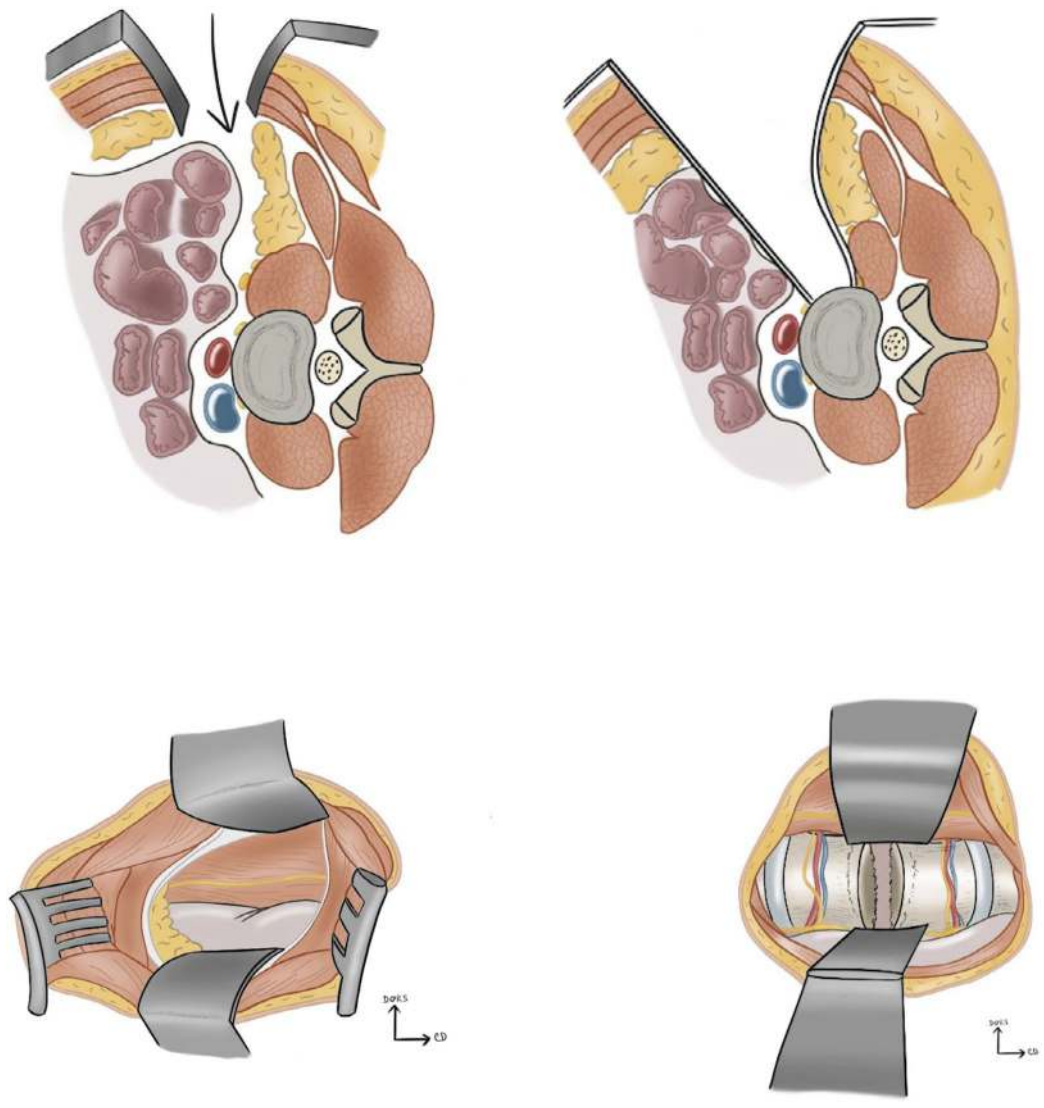

Fig. 10.4 Retroperitoneal approach from the left side

upper lumbar) is retracted posteriorly (Fig. 10.4). This creates a working window between the anterior psoas border and the great vessels—typically the left lateral border of the aorta for levels above L5, or between the iliac vessels for L5-S1. At L4–5, OLIF's more anterior trajectory avoids obstruction by the iliac crest (unlike a pure lateral approach) and does not require breaking the table or cutting through psoas. An important surface landmark in OLIF at L5-S1 is two finger-breadths anterior to the ASIS, which often corresponds to the safe window below the aortic bifurcation.

10.2.2 Transpsoas Approach

In XLIF, the surgeon typically stands posterior to the patient's flank. A true lateral incision (often ~3–4 cm) is made over the target disc, at the mid-axillary line, guided by fluoroscopy. In some cases, a second, smaller posterior incision is made for the surgeon's finger to palpate the retroperitoneal space and guide the initial dilator. The peritoneum and its contents are protected anteriorly, and the surgeon's finger (or a blunt dilator) is used to split the psoas muscle in the safe zone

between its anterior third and middle third—this positioning pushes nerves posteriorly (lumbar plexus lies mostly in the posterior 1/2 of psoas) and keeps the great vessels anteriorly. Intraoperative neuromonitoring probes are used as the dilator advances through psoas, delivering EMG feedback to warn if the dilator is too close to lumbar plexus nerves. Stepwise dilation creates a tunnel through the psoas muscle at the disc level, and then a special lateral retractor is deployed, often fixed to the operating table, to hold the psoas muscle open and maintain a clear path to the disc. By working through the transpsoas corridor, XLIF avoids any incisions in the back muscles or bone, and also does not require direct visualization or mobilization of the aorta or IVC. However, because the psoas must be traversed, patient positioning and neuromonitoring are critical to minimize stretch or injury to the nerves within the psoas.

10.3 Step-by-Step Procedural Details

Anterior to Psoas Technique [2] After establishing the oblique retroperitoneal corridor as described, a series of dilators is inserted towards the target disc space, staying anterior to the psoas border. Fluoroscopy confirms the dilator tip at the disc (Fig. 10.5). A working retractor is then placed over the dilators and can be anchored to the vertebral body with a pin for stability. The retractor blades are oriented obliquely, in line with the approach; this orientation allows an '*orthogonal manoeuver*' during cage insertion—i.e. instruments enter at an angle but can be rotated to a true lateral trajectory across the disc space.

Once exposure is secured, discectomy is performed. An annulotomy is made and disc material is removed using pituitaries, shavers and curettes under direct vision and fluoroscopic guidance (Fig. 10.6).

Care is taken to preserve the posterior longitudinal ligament and avoid over-retraction of the contralateral annulus. A contralateral annular release (using a cobb elevator or similar) is often performed to ensure the far side of the disc is freed, facilitating insertion of a wide cage. (Figs. 10.7, 10.8, and 10.9).

Sequential trial spacers are inserted to distract the disc height, which indirectly decompresses

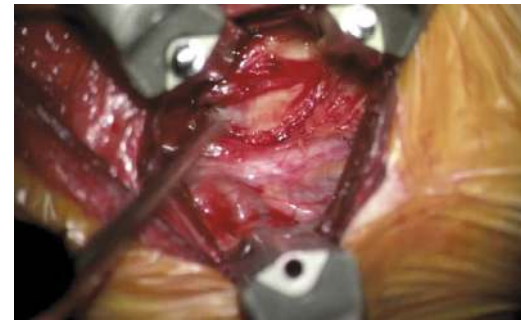

Fig. 10.5 Left side exposure of L4-L5 disc. The sympathetic chain, ureter are seen and protected

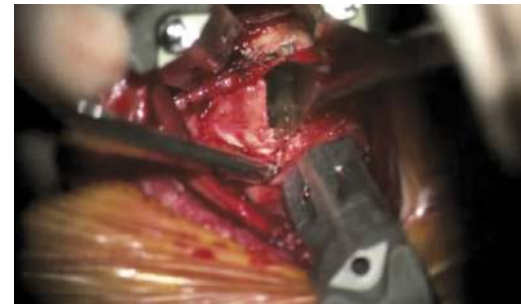

Fig. 10.6 Discectomy is performed using pituitary forceps and curettes

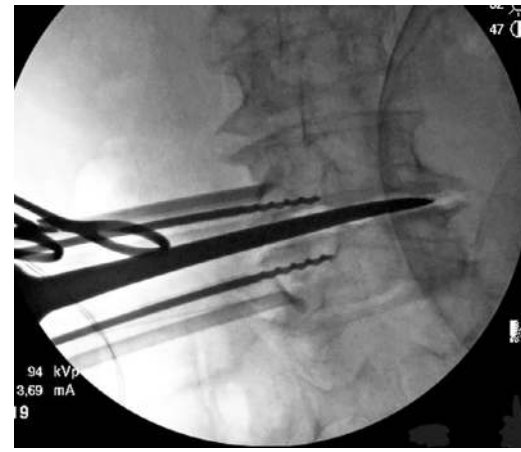

Fig. 10.7 A Cobb curette is used to release the controlateral annulus

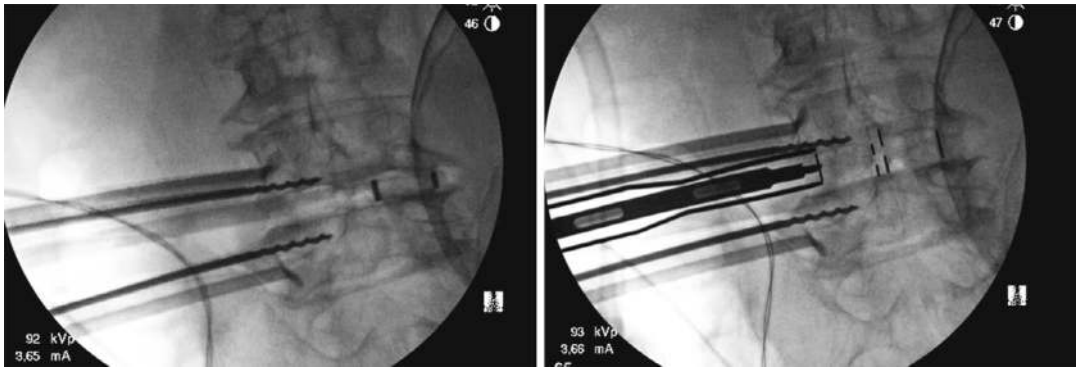

Fig. 10.8 Sequential dilators are used to restore the height followed by cage insertion

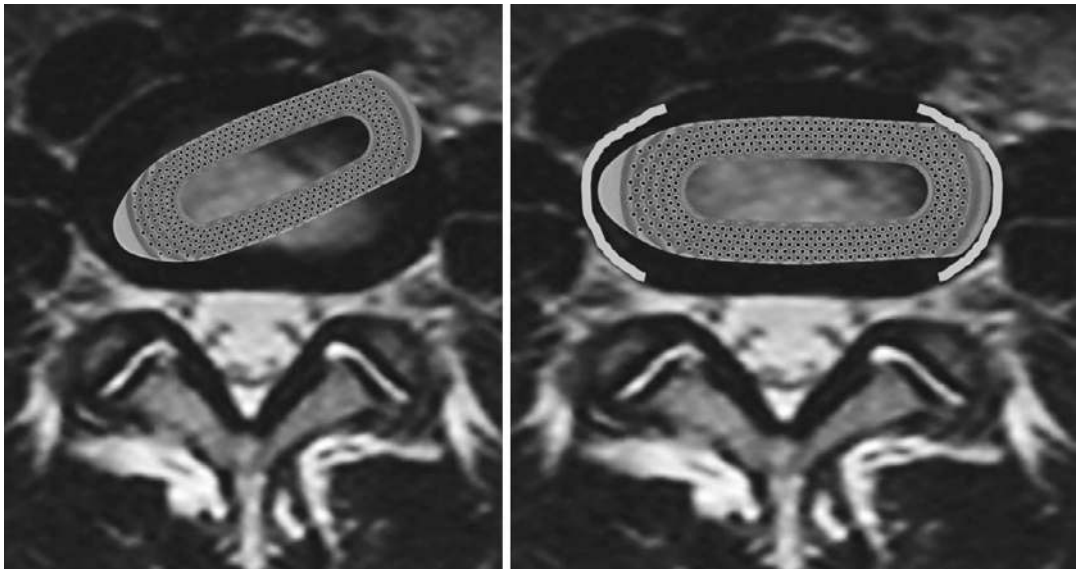

Fig. 10.9 In the ATP, the cage has to be rotated in order to be placed in the disc axis and avoid compromising the contralateral foramen

neural foramina and tensions the ligamentous structures. After selecting the appropriate size, a wide-bodied graft cage filled with bone graft is inserted obliquely and then rotated into a final position spanning the apophyseal ring from lateral to anterior, similar to a cage placed via XLIF. Final fluoroscopy confirms cage position and alignment.

OLIF at L5-S1 (often termed OLIF51) follows a similar step sequence but uses a lower abdominal oblique incision; the surgeon accesses the L5-S1 disc below the bifurcation of the great vessels, often releasing the fibrous layer containing the superior hypogastric plexus to mobilize the left common iliac vein if necessary.

Transpsoas Technique [3] The XLIF procedure can be outlined in three main phases.

First, **Approach and Exposure** After the lateral incision is made over the disc space, blunt dissection through the external and internal oblique muscles leads to the retroperitoneal space, similar to OLIF, but directly lateral. The surgeon's index finger (through either the main incision or a small posterior auxiliary incision) palpates the

psoas muscle and guides the placement of an initial tubular dilator to the lateral surface of the disc. Using continuous lateral fluoroscopy, the dilator is advanced *transpsoas* at the target disc level. Neuromonitoring (EMG) is used with each advancement to confirm no significant nerve irritation, ensuring the path is safely between nerve roots of the lumbar plexus. Once the dilator reaches the disc, sequential dilators (graduated tubes) are passed over it to gently split the psoas fibres and create a working channel. A lateral retractor is then slid over the dilators and deployed. The retractor is often affixed to the table and contains a light source; when opened, it holds the muscle apart and provides a direct view of the lateral disc an.

Second, **Disc Preparation** Through the retractor, the surgeon incises the lateral annulus and removes disc material using pituitary rongeurs and disc shavers/curettes. Typically, the anterior and posterior annulus are left intact to preserve stability. Cartilage is scraped off the endplates to promote fusion, and care is taken to clear disc material from the contralateral (far) side of the disc space as much as possible. Fluoroscopic images may be taken to ensure the disc space is adequately cleaned and released for implant placement.

Third, **Interbody Cage Insertion and Stabilization** After disc clearance, a large-footprint interbody cage (usually 18–26 mm wide and long enough to span the disc) packed with bone graft is inserted laterally across the disc space. Because XLIF allows a wide implant that contacts the strong ring apophysis of the vertebrae, it provides good segmental stability and reduces the risk of subsidence compared to smaller posterior cages. The cage restores disc height and, by its lordotic angle if present, can help reestablish lumbar lordosis. Once the cage is in position (confirmed by X-ray), the retractor is removed and the muscle and skin incisions are closed. XLIF is often supplemented by additional instrumentation—either a lateral plate/screw through the same incision or posterior percutaneous pedicle screws. If posterior instrumentation is planned, it may be done in the same lateral position (with specialized technique) or after repositioning the patient prone.

10.4 Dedicated Instrumentation, Intraoperative Monitoring and Nuances

Both OLIF and XLIF rely on specialized minimally invasive instrumentation.

Retraction Systems XLIF needs sequential dilators and a final hinged retractor, which attaches to the table and holds the psoas open while providing illumination and a pathway for instruments. OLIF uses an oblique retractor system that often includes blades contoured for the anterolateral anatomy; it can be anchored to the vertebral body to maintain the working corridor between psoas and peritoneum. Because OLIF's corridor is anterior to the plexus, neuromonitoring is considered *optional* by some surgeons.

However, many OLIF procedures still employ electrophysiological monitoring to detect any inadvertent pressure on the lumbar plexus (for example, if the psoas is retracted too far posteriorly). In XLIF, neuromonitoring is essential—typically spontaneous and triggered EMG signals guide the safe placement of dilators and retractor within the psoas muscle, helping avoid direct nerve injury. A free-running EMG can alert the surgeon if a dilator is too close to a nerve root.

Imaging Guidance Intraoperative fluoroscopy is used in both techniques for level localization, proper disc space targeting and confirming cage placement. Some centres utilize O-arm cone-beam CT imaging with navigation to assist in accurate implant positioning. Navigation is especially useful for single-position surgery, allowing percutaneous pedicle screw insertion in the lateral decubitus position with 3D guidance. Recent advances include robot-assisted navigation for screw placement, which can further improve accuracy and reduce radiation exposure to the surgical team.

Implants Both OLIF and XLIF use large footprint interbody cages that span the cortical rim of the endplates, often made of PEEK or titanium, sometimes with integrated screws or lateral plates for additional stability. The typical OLIF/XLIF cage is much wider than a posterior cage (up to ~26 mm), distributing load to reduce subsidence risk. Supplemental fixation is common—either anterior/lateral plate fixation or posterior pedicle screws. If posterior instrumentation is needed, it can be placed percutaneously.

There is a trend towards *single-position surgery (SPS):* performing the lateral fusion and posterior screw fixation without repositioning the patient. In *lateral SPS*, the patient remains in lateral decubitus while the surgeon places pedicle screws from that position; in *prone SPS*, a prone position lateral fusion is done, which mimics XLIF but with the patient prone to allow easier simultaneous posterior fixation. Each approach has specialized tables or positioning frames and may utilize novel retractor designs to allow prone lateral access.

10.5 Indications and Contraindications

Indications OLIF and XLIF are indicated for a variety of lumbar pathologies requiring fusion. Common indications include degenerative disc disease with low back pain, disc herniations or collapse, grade I–II spondylolisthesis and degenerative scoliosis or other spinal deformities where restoring disc height and alignment is desired. They are frequently used at lumbar levels L1-L5; OLIF can also access L5-S1 in many cases (using the OLIF51 approach). Both techniques enable placement of large cages that can indirectly decompress stenotic spinal canals and neural foramina, so they are indicated in cases of foraminal stenosis or mild to moderate central stenosis due to disc collapse. They are also useful in multi-level fusion constructs for adult deformity correction, often combined with posterior instrumentation. Infections or tumours requiring anterior column stabilization can be approached laterally in select cases, and trauma or pseudoarthrosis (failed previous fusion) are potential indications if anatomy permits. Generally, these lateral approaches are best suited for patients who have failed conservative management and in whom a large interbody graft is needed to restore alignment or stability.

Contraindications and limitations Not all patients are candidates for XLIF/OLIF.

Anatomical constraints play a major role. XLIF is *contraindicated at L5–S1* because the iliac crest and lumbosacral plexus obstruct the lateral route to that disc. At L4–L5, XLIF is feasible but more challenging if the iliac crest is very high; OLIF's oblique trajectory has an advantage here by approaching anterior to the crest.

Vascular anatomy is critical for OLIF—patients with anomalous vessel anatomy (e.g. a left-sided IVC, or aorta that does not sufficiently drift leftward at the target level) may be poor candidates due to a narrowed corridor. Significant atherosclerotic disease or vascular stents near the target level are relative contraindications for OLIF because of the risk of vascular injury during retroperitoneal dissection.

Prior retroperitoneal or abdominal surgery can cause scarring that obscures tissue planes; a history of major abdominal surgery may increase the difficulty or risk of OLIF/XLIF. Similarly, extreme obesity can limit the surgeon's reach and visualization through a lateral incision and may increase complication rates.

Neurologic Considerations Pre-existing neuropathy or lumbar plexus irritation might caution against XLIF, since traversing the psoas could exacerbate these issues. Severe central canal stenosis with significant neural compression might not be adequately addressed by indirect decompression alone; such cases may require direct posterior decompression (thus lateral-alone fusion would be insufficient).

High-grade spondylolisthesis or gross instability might be contraindicated for standalone lateral fusion, though lateral fusion can be performed in combination with posterior instrumentation in many such cases. Finally, skeletal anomalies like transitional lumbosacral vertebrae

or severe scoliosis can alter the anatomy of the psoas and vessels, requiring careful evaluation—sometimes one approach (OLIF vs XLIF) may be favoured or neither may be safe in extreme cases.

Each patient's *preoperative imaging* must be scrutinized to choose the appropriate approach: surgeons should locate the great vessels relative to the discs, the height of the iliac crest, the course of the lumbar plexus (if visible on MRI), and any congenital variants that could impede safe access.

10.6 Comparative Advantages and Limitations of OLIF Vs XLIF

Each technique offers unique benefits and has distinct limitations [4].

Avoiding Psoas vs. Avoiding Vessels The fundamental difference is the path relative to the psoas muscle. OLIF's anterior-to-psoas route means the lumbar plexus is not directly traversed—this markedly lowers the incidence of neural injuries like femoral nerve or lumbar plexus neuropraxia. Studies show postoperative hip-flexor weakness and thigh numbness are significantly less frequent with OLIF (reported in ~1–14% of cases) than with XLIF (~5–31%, mostly transient). By contrast, XLIF's trans-psoas route completely avoids the anterior great vessels and peritoneal contents—there is virtually no risk of major vessel injury in XLIF (0% in one large series), whereas OLIF, working near the aorta and iliac vessels, carries a small risk (~3% in meta-analysis) of vascular injury. In OLIF, careful preoperative vascular evaluation and gentle retraction of vessels are crucial to mitigate this risk.

In summary, *OLIF trades a higher vascular risk for a lower neural risk, whereas XLIF is the opposite* (higher neural/plexus irritation risk, minimal vascular concerns).

Visualization and Anatomical Access OLIF provides a wider surgical view of anterior structures. The oblique incision and approach allow the surgeon to directly visualize important structures like the ureter, the peritoneal sac and the anterior margin of the disc under direct vision. This can aid in avoiding injury to these structures and in ensuring the cage is placed far enough anteriorly. By seeing the anterior disc space, OLIF may facilitate more anterior cage placement; in addition, the ALL could be intentionally cut, which can enhance lordotic correction. XLIF, working through a narrower tubular retractor, offers a more limited field of view (essentially the disc space and immediate margins) and relies heavily on fluoroscopic imaging for guidance. However, XLIF allows extremely direct lateral access to the disc, which can make it easier to remove disc material from both sides of the space. In OLIF, because the approach is oblique, there can be a tendency to leave some disc or osteophyte on the far contralateral corner if not thoroughly released. A study comparing the two noted a slightly greater amount of unremoved disc remnants on the contralateral side in OLIF cases, though clinical impact of this is unclear.

Segmental level and Alignment OLIF has an advantage at the L4-L5 level (and the ability to do L5-S1), as it avoids the iliac crest obstruction; no table break is needed in OLIF, and the approach naturally clears the high crest by coming in more anteriorly. XLIF at L4–5 often requires aggressive table flexion or may be impossible in short individuals with a high pelvis. Conversely, XLIF (or lateral LLIF) can be performed at upper lumbar and even thoracolumbar levels (L1–2, T12–L1) by carefully working around the lower ribs, whereas OLIF at L1–2 may be limited by the ribs and the deep location of the corridor. In terms of sagittal alignment, both techniques can use lordotic cages to increase lumbar lordosis. OLIF cages can often be placed very anteriorly, which biomechanically yields good lordosis. Some reports suggest OLIF achieved equal or slightly greater segmental lordosis restoration than XLIF, though meta-analyses show no statistically significant difference. XLIF, if done in a prone position (prone lateral fusion), might allow additional lordosis due to gravity and easier posterior osteotomy if needed.

Stability and Fusion Potential Both OLIF and XLIF use large interbody devices that confer high stability and fusion rates. By spanning the apophyseal ring, these cages minimize subsidence compared to smaller posterior cages. Neither approach requires cutting spinal posterior elements, which preserves stability. XLIF and OLIF have similarly high fusion rates reported (often on the order of 90 + % at 1–2 years in degenerative cases), especially when combined with supplemental fixation and bone grafting. No clear advantage of one vs the other in fusion success has been demonstrated in comparative studies—outcomes are more surgeon- and case-dependent. Both techniques, by virtue of indirect decompression, rely on disc height distraction; so in cases of very stiff collapsed discs, achieving adequate release might be challenging. OLIF's ability to also approach L5-S1 in the lateral position can be seen as an advantage in performing *complete L2-S1 fusions* in a single lateral position surgery.

Operative Time and Learning Curve Learning curves for both are significant but XLIF was developed earlier and adopted widely, meaning many surgeons are familiar with it. OLIF, being a newer variation, may not be as widely practiced outside specialized centres. However, some surgeons find OLIF's workflow (especially at L4–5) more straightforward since neuromonitoring isn't constantly dictating instrument position. XLIF can sometimes be quicker at a single level due to a more direct path; on the other hand, OLIF in experienced hands is also rapid and can access two levels through one incision by angling up and down the spine. Evidence directly comparing operative times is limited, but one review noted no significant difference in surgical time between OLIF and XLIF groups for single-level fusions.

In summary, *OLIF's key advantages* include avoidance of traversing the psoas (lower nerve injury risk), ability to access L5-S1 and good visualization of anterior anatomy. Its downsides are the need to work near major vessels and slightly more complex access at higher levels. *XLIF's key advantages* include a safe distance from major vessels, a well-established technique with robust neuromonitoring support, and efficient lateral access to mid-lumbar levels; disadvantages are the risk of psoas muscle/plexus injury and inability to reach L5-S1. Both achieve similar biomechanical and clinical goals, and the choice often comes down to patient anatomy and surgeon preference.

10.7 Common Complications and Avoidance Strategies

Both OLIF and XLIF are associated with specific approach-related complications, in addition to general risks of lumbar fusion (infection, bleeding, dural tear, etc.).

Neurological Injuries As noted, transient thigh sensory changes or hip-flexor weakness are relatively common after transpsoas XLIF due to retraction or injury of the lumbar plexus (femoral nerve, lateral femoral cutaneous nerve, etc.). In most cases these are temporary and resolve within weeks, but permanent nerve deficits are possible. Meticulous neuromonitoring and avoidance of excessive retraction time can mitigate this risk. Surgeons limit the duration of psoas retraction (often <30 min) and will reposition or slightly relax the retractor if EMG signals drop. Choosing the ideal dilator trajectory (usually at the posterior one-third of the disc space for XLIF) helps keep the plexus safely behind the instruments. If patients report significant anterior thigh pain or weakness postoperatively, steroids and neurologic assessments are done; in nearly all cases, these deficits improve as the psoas edema resolves. OLIF largely avoids direct plexus injury, but it is not immune from neural issues: retraction of the psoas (especially upper lumbar levels) can still cause stretch injury to the genitofemoral or ilioinguinal nerves that run on or near the psoas, or even the sympathetic chain that lies on the anterior spine. Injury to the *lumbar sympathetic chain* (which may occur during the lateral approaches) can result in temporary sympathectomy symptoms such as warm foot or ejaculation changes in men, but these are rare and often transient. To avoid sympathetic injury, sur-

geons identify and gently mobilize the sympathetic trunk off the disc space in OLIF exposures (it appears as a whitish filament on the anterolateral vertebral body).

Vascular Injuries In OLIF, the proximity of the iliac arteries and veins, and the great vessels, means there is a risk of vessel laceration during exposure. Major vascular injury is the most feared complication, potentially life-threatening. Injury can occur to the common iliac vein or artery during L5-S1 OLIF, or to segmental vessels or the aorta/IVC during higher levels. To prevent this, a preoperative vascular workup is essential: review CT/MRI to map out the vessels' positions relative to the spine. Some surgeons obtain vascular surgery standby for higher-risk patients. Intraoperatively, gentle blunt dissection and use of malleable retractors to protect vessels are key. The surgeon should stay directly on the anterior spine (where the vessels' adventitia can often be gently swept off the disc). If significant vessels overlie the disc space (as with an aberrant IVC or iliac vein), abandoning the lateral approach or switching sides (as in the case of a left-sided IVC, using a right-side OLIF) is prudent. XLIF's transpsoas route has a very low incidence of injuring the big vessels, but at L4-L5 there is some risk to the ascending segmental vessels or iliolumbar vessels if instrumentation strays too anterior—maintaining the dilator in the mid-lateral position on the disc helps avoid this. Both approaches carry a small risk of bleeding from segmental arteries or venous plexus; careful cautery and tamponade are used if this occurs.

Visceral and Other Injuries Entering the peritoneum inadvertently is possible in both approaches (especially OLIF). Proper oblique trajectory and keeping the dissection plane just above the transversalis fascia help avoid the peritoneal cavity. Surgeons will recognize retroperitoneal fat as a sign they are in the correct plane; encountering bowel indicates a wrong plane. If the peritoneum is opened, it is usually managed with direct suture repair and does not preclude completing the surgery (unless bowel injury occurred, which is exceedingly rare). The ureter can potentially be injured during the mobilization in OLIF. To mitigate this, a preoperative contrast CT or ureteral stent placement can be considered in high-risk cases to map the ureter's course. Once in the retroperitoneum, identifying the ureter (a subtle peristaltic tubular structure) and keeping it with the anterior peritoneal contents prevents harm. In XLIF, bowel or ureter injury is rare since the peritoneum is usually not entered at all—it is held anterior by the surgeon's finger as the psoas is traversed.

Orthopedic Complications Endplate damage or cage misposition can occur with either technique. Because lateral cages are large, forceful insertion can occasionally cause an endplate fracture or retropulsion of a fragment. Thorough disc space release (especially contralateral annulus) is important to reduce insertion force. Using an appropriate size trial to gradually open the space and choosing a slightly smaller height cage if resistance is high can prevent fracture. Cage subsidence is a known complication; however, it is less common in OLIF/XLIF compared to TLIF/PLIF due to better endplate coverage. Optimally, cages should be placed spanning the apophyseal ring and care taken not to excessively gouge the endplates during preparation (to avoid weakening them). If a cage is seen to subside significantly on imaging, posterior fixation can help offload and stabilize it.

Infection and Others Both OLIF and XLIF are muscle-splitting, small-incision surgeries, so infection rates are low compared to open fusion. Still, standard prophylaxis and sterile techniques are followed. If infection occurs, it may present as an abscess in the psoas or retroperitoneum; CT-guided drainage is often effective in addition to antibiotics, since instrumentation is often already in place. A rare but reported complication in XLIF is psoas hematoma (bleeding into the psoas), which can cause femoral nerve compression—avoiding uncontrolled dilation and using hemostasis for any muscle bleeding prevents this. Postoperative ileus (transient bowel slowdown) can happen, particularly with OLIF, since manipulation of the peritoneum can irritate the bowel. This is usually

managed with bowel rest and fluids until resolution. Patients are typically kept NPO (nothing by mouth) until they have bowel sounds after an OLIF to monitor for ileus. Early ambulation and limited use of opioids help reduce ileus risk.

To *avoid complications*, surgeons employ several strategies: thorough preoperative imaging review (vessels, bone anatomy, and if possible, MRI to infer plexus position); careful patient selection (avoiding lateral approach in unsuitable anatomy); use of neuromonitoring and staged dilation in XLIF to protect nerves; gentle, correct-plane dissection in OLIF to protect vessels and peritoneum; and limiting retractor time and periodic release to allow tissue perfusion. With proper technique, most approach-related complications are infrequent and transient.

10.8 Clinical Outcomes and Evidence

Multiple studies, including comparative analyses, have evaluated the clinical and radiographic outcomes of OLIF and XLIF. Overall, both techniques yield *significant improvements in pain and function* for patients. Typical outcomes include large drops in Visual Analog Scale (VAS) back and leg pain scores and improvements in the Oswestry Disability Index (ODI) after surgery, with success rates (per patient satisfaction and fusion achievement) generally high. For example, XLIF has been shown to significantly improve VAS and ODI in patients with degenerative conditions, often accompanied by high fusion rates at 12 months (≥90% in many series). OLIF likewise demonstrates excellent outcomes: recent reports show improvements in VAS and ODI comparable to XLIF, with the added benefit of lower incidence of certain approach-related morbidities. A 2023 meta-analysis compared single-level OLIF versus XLIF (at L1–L5) across 24 studies: it found *no significant differences* in radiographic outcomes (disc height restoration or segmental lordosis achieved) or in clinical outcome scores between OLIF and XLIF. Both techniques effectively increased disc height by about 4–5 mm and improved segmental lordotic angle by a few degrees on average. Patients in both groups had major reductions in pain and disability scores, with no statistically significant difference in final outcomes.

Where differences did emerge was in the *complication profiles*, as discussed: XLIF had a higher rate of transient neurologic complaints (especially thigh numbness or weakness), while OLIF had a higher rate of vascular injuries. However, the overall incidence of serious permanent complications in both is low. Importantly, both OLIF and XLIF rely on *indirect decompression*, and studies confirm that this mechanism can adequately relieve neural compression in many cases. Radiographic measures post-surgery often show increased foraminal height and canal area due to disc height gain. If indirect decompression proves insufficient (e.g. in a subset of patients with severe stenosis), additional posterior decompression can be performed—in the meta-analysis, there was no significant difference in reoperation rates between OLIF and XLIF groups, suggesting both are equally durable as fusion techniques.

Fusion success is high with both approaches when bone graft and supplemental fixation are used. Some series have reported fusion rates approaching 95–100% at 1–2 years for single-level XLIF or OLIF with posterior instrumentation [5]. In standalone cases (cage with no posterior screws, typically augmented with lateral plate), fusion might be slightly lower, but still comparable between OLIF and XLIF. Clinical success (improvement in symptoms and no need for revision) is likewise high and similar for both. One advantage of these lateral fusions is the earlier mobilization and shorter hospital stay compared to traditional open fusions. Many patients ambulate on postoperative Day 1 and are discharged within 1–4 days barring complications. Comparative studies note that both OLIF and XLIF patients benefit from reduced blood loss and length of stay versus posterior fusion approaches.

In degenerative scoliosis or sagittal imbalance, lateral interbody fusion has become a powerful tool. OLIF and XLIF can provide coronal plane correction by asymmetric cage placement and restore lordosis with lordotic cages. Studies

in adult deformity patients have shown significant Cobb angle corrections and sagittal alignment improvements with lateral fusions as part of a staged strategy. What is clear from the literature is that lateral access fusion in general (LLIF) is an effective MIS alternative to traditional fusion, with fewer perioperative complications compared to open surgery and equivalent if not superior radiographic outcomes.

In conclusion, evidence to date supports that OLIF and XLIF are complementary lateral fusion techniques with comparable fusion and clinical success. Proper patient selection and surgeon familiarity with the nuances of each approach are critical to maximizing outcomes while minimizing complications. Future prospective studies and randomized trials will further clarify any subtle differences, but current literature indicates that both OLIF and XLIF achieve the goal of a solid fusion with indirect decompression and offer patients a less invasive road to spinal stability.

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11 Indications for the Treatment of Painful Degenerative Lumbar Disc Disease with Disc Prosthesis

Jacques Beaurain

11.1 Introduction

Degenerative lumbar disc diseases are structural alterations of the intervertebral disc primarily associated with ageing but influenced by a combination of genetic, environmental and biomechanical factors [1, 2]. The loss of intervertebral disc function can lead to pain and dysfunction in the spine, sometimes significantly affecting quality of life [3]. Conservative treatment including physiotherapy, analgesics and injections remains the first-line approach [4]. In cases of treatment failure, surgical intervention may be considered if sufficient evidence has been gathered to confirm that the degenerated disc is the primary pain generator [5]. Intervertebral fusion is still regarded as the gold standard, despite its associated side effects, such as adjacent segment degeneration and alterations in the biomechanical conditions of the lumbar spine [6]. Non-fusion techniques, developed in the 1980s, aim to alleviate pain while preserving physiological motion, thus reducing adjacent-level degeneration [7]. Disc arthroplasty replaces the degenerative intervertebral disc with an artificial prosthesis, preserving mobility and potentially slowing the degenerative process in posterior facet joints while maintaining spinal balance [8]. However, this procedure should only be considered when compelling evidence supports that the pain originates predominantly from the degenerated disc and that other potential sources of pain have been adequately ruled out.

11.2 Historical Background

Early Attempts (1950s–1970s)

In 1966, Ulf Fernström implanted stainless steel spheres in lumbar and cervical disc spaces. Inspired by joint arthroplasty, his work highlighted the feasibility of motion preservation but faced challenges such as implant subsidence and extrusion [9].

First Prototypes of Disc Prostheses (1980s)

Modern prosthetic discs emerged with the SB Charité intervertebral disc prosthesis developed by Dr. Karin Buettner-Janz and Dr. Kurt Schellnack in 1982. This design incorporated two metal endplates and an interposed, sliding polyethylene core. The construct was designed to preserve the motion-sparing features of earlier models while offering enhanced stability at the interface between the prosthesis and the native vertebral endplates [10].

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Next-Generation Prostheses (1990s–2000s)

Prostheses evolved, incorporating improved biomechanics and durability, including:

- ProDisc-L (Aesculap (B. Braun) Germany) developed in the late 1980s by Dr. Thierry Marnay, a French orthopedic surgeon— keel fixation for enhanced osseointegration.
- Maverick (Medtronic, USA)—metal-on-metal design to reduce polyethylene wear.
- Mobidisc (LDR Medical, France) developed in France—mobile core mimicking physiological movement and reducing facet joint stress.
- FlexiCore, ActivL and LP-ESP—designed for enhanced mobility and load distribution.

Early clinical trials were conducted, leading to the Food and Drug Administration (FDA) approval in the United States (US) for the Charité Artificial Disc in 2004 and for the ProDisc-L in 2006. Prospective, randomized, multicentre FDA Investigational Device Exemption (IDE) studies reported overall favourable noninferior results for patients in comparison to anterior lumbar interbody fusion (ALIF) with similar incidence of complications and no more adverse events at 24 months follow-up [11, 12]. While all the novel devices became available outside of the United States, few received FDA approval and were discontinued or withdrawn from trial [13].

Currently, only two FDA-approved devices are commercially available in US: the Prodisc-L (Centinel Spine) approved in 2006 for one-level use and in 2020 for two-level use—the activL Artificial disc (Aesculap Implant Systems) approved for one level in 2015.

In France, the reimbursement of lumbar disc prostheses was officially established by the decree published in the Journal Officiel on December 15, 2011. Initially three prostheses were approved: ProDisc-L (Synthes A), Mobidisc (LDR Medical) and Maverick (Medtronic France) [14]. The corresponding procedure was listed In the French 'Common Classification of Medical Procedures', under the description: 'Replacement of a lumbar intervertebral disc with a total prosthesis, via laparotomy or lumbotomy' [LFKA001].

Three prostheses are yet included in the List of Reimbursable Products and Services (LPP 24/01/2025. Version: 816) [15].

- ProDisc L® Prosthesis distributed by CENTINEL SPINE SCHWEIZ GmbH (Switzerland)

The prosthesis consists of three components: two anchoring endplates made of cobalt-chromium-molybdenum (Co-Cr-Mo) alloy and a polyethylene core. Articulation occurs between the polyethylene core and the inferior surface of the superior endplate. The metallic endplates are equipped with serrated keels to ensure primary stability of the implant within the vertebrae. These endplates are coated with a porous titanium layer to promote bone integration with the implant surface, ensuring long-term stability of the prosthesis. The polyethylene insert includes radiopaque tantalum markers (Fig. 11.1).

https://www.centinelspine.com/prodisc_l.php

- Mobidisc® Prosthesis. Now distributed by Highridge Medical

The Mobidisc® prosthesis is composed of an upper and lower prosthetic endplate (with the lower endplate optionally lordotic), a polyethylene insert and a fixation system-utilizing fin-like structures. The prosthesis consists of two endplates made of cobalt-chromium-molybdenum alloy, coated with titanium and hydroxyapatite and an insert made of ultra-high-molecular-weight polyethylene (UHMWPE). The fixation system includes fin-like structures made of cobalt-chromium-molybdenum alloy or anchors made of surgical titanium alloy (TiAl6V4 ELI) (Fig. 11.2).

https://thespinemarketgroup.com/mobidisc-l-lumbar-disc-prosthesis/

- LP-ESP® Prosthesis. Distributor: Orthofix (France)

The LP-ESP® prosthesis was approved in France in 2014. It is a monobloc implant composed of two titanium alloy endplates separated by a

Fig. 11.1 Prodisc L®

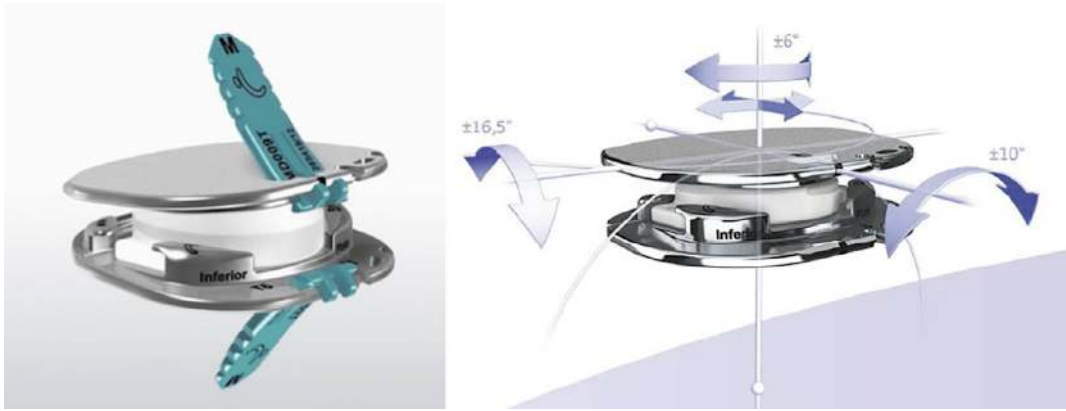


Fig. 11.2 Mobidisc®

deformable component designed to allow the natural movements of the intervertebral disc. The prosthesis features raised anchoring pegs and is coated with hydroxyapatite (HAP) on a layer of pure titanium (T40), which is porous and textured. It has a durable and watertight junction between the soft and rigid components. The deformable part consists of a soft cushion made of polycarbonate urethane and a central core made of silicone embedded with compressible beads. Internal pegs fixed to the titanium endplates control mobility, particularly rotational deformation and the deformability of the peripheral cushion. The central core includes two metallic components, male and female, interlocked within the soft material to regulate vertical shock absorption. Regardless of the implant size, the viscoelastic mechanism remains identical; only the thickness of the metallic endplates varies (Fig. 11.3).

Fig. 11.3 ESP®

https://thespinemarketgroup.com/lp-esp-disc-prosthesis/

11.3 Indications

The primary indication for disc prosthesis is disabling chronic low back pain caused by isolated degenerative disc disease in patients who have not responded to at least 6 months of conservative treatment. The pain should be well localized to the disc, with minimal or no radicular pain [16].

Discogenic pain remains challenging to diagnose accurately. Clinical examinations, radiological imaging (particularly MRI) and medical history have low sensitivity and specificity in identifying discs as the primary source of spinal pain [17].

- Clinical features

Low back pain (LBP) can have multiple origins, including muscular, ligamentous, articular and psychological factors. However, in young individuals with severe, chronic and disabling low back pain, lumbar disc disease—characterized by progressive degeneration of one or more intervertebral discs—is often the primary cause.

The main symptoms include:

- Horizontal lumbar pain, aggravated by physical exertion, prolonged static positions (both sitting and standing) and driving. The pain tends to worsen with trunk flexion and exhibits an impulsive characteristic during coughing and sneezing.
- Morning stiffness is also present, often requiring an extended period of movement to 'warm up' before engaging in daily activities.
- Sharp, electric shock-like pain or stabbing sensations in the lower back during specific movements.
- Episodes of movement restriction, particularly when bending forward, often described as a feeling of impending spinal 'blockage'.
- Possible sciatic leg pain, which may occur if disc herniation accompanies the degenerative process [18].

Discogenic pain is typically described as dull, aching and gnawing. While primarily localized to the lower back, it may also present with referred pain in the lower extremities, particularly above the knees, in a non-dermatomal pattern. When present, referred leg pain is often perceived as a deep, pressure-like discomfort radiating in a sclerotomal distribution, covering broad, indistinct areas [19]. Although the boundaries of the pain are often unclear, patients are generally able to identify its central or core location with confidence.

A clinical presentation combining central deep low back pain, painful forward flexion, impulsive pain and pain reproduction with abdominal palpation of the lumbar disc is highly suggestive of a discogenic origin.

- Radiological features

While X-rays can provide indirect signs of lumbar discopathy such as disc space narrowing and endplate sclerosis, they are not sufficient for a definitive diagnosis. MRI remains the gold standard for assessing disc degeneration. However, X-rays are valuable in ruling out other spinal pathologies and evaluating spinal alignment, instability and spondylosis.

MRI reveals a loss of T2 signal and a reduction in disc height [20] as well as subchondral bone lesions described in Modic's classification [21].

- *Modic Changes (MC) and Low Back Pain (LBP)*

Various studies have reported that the prevalence of MC in LBP patients varies from 8 to 80.1% [22]. However, among the three types, Modic 1 has been most associated with LBP [23]. Recent literature, however, indicates a poor association between MC and LBP [24]. Chen et al. failed to establish a statistically significant association between any type of MC or their sizes and prevalence and/or severity of LBP and/or activity limitation [25]. A recent study evaluated the significance of vertebral end plate (VEP) changes as possible indicators of surgery. In their study involving 1085 patients with LBP and 445

patients without LBP (controls), the odds ratio of the need for surgery was found to be high (OR = 5.2) in patients with disc-endplate-bone marrow complex (DEBC) changes [26].

- *Articular block test*

Articular block tests can be used to eliminate doubt about facet joints involvement in pain.

- *Discography*

In combination with the specific signs and symptoms identified during physical examination, discography can serve as a test for confirming the diagnosis of disc degeneration associated with chronic and severe discogenic pain. Introduced in the 1950s, discography is a minimally invasive diagnostic procedure, typically performed provocatively by injecting contrast agents into the disc to reproduce the patient's pain (diagnostic discogram). Alternatively, it can involve the injection of a small dose of anesthetic to alleviate pain (functional anesthetic discogram) [27]. Provocative discography is often paired with computed tomography (CT discogram) to precisely locate and assess the extent of annular disruption. Over 70% of painful discs exhibit posterior and/or posterolateral annular radial and/or concentric fissures that extend to the outer annular fibres (e.g. grade 3 out of 4 severity) [28]. The false-positive rate of low-pressure discography (<20 psi) has been reported to be as low as 6% [29]. A systematic review conducted in 2018 [29] illustrates that lumbar provocation discography performed according to IASP (International Association for the Study of Pain) criteria may be a useful tool for evaluating chronic lumbar discogenic pain [30].

- *Magnetic resonance spectroscopy (MRS)*

More recently, specialized MRS has demonstrated the ability to identify chemically painful lumbar discs. This advancement has been linked to significant improvements in patient-reported outcomes following surgery for discogenic low back pain [31]. Such developments may provide a valuable diagnostic tool, enabling clinicians to better select patients and treatment levels.

11.4 Conditions for Use for Lumbar Disc Prostheses in France According to HAS Recommendations

In France, the use of disc replacement prostheses is limited and must follow the recommendations set forth by the Haute Autorité de Santé (HAS) [32].

The approved indication is chronic, disabling discogenic low back pain that is resistant to well-conducted medical treatment for at least 6 months, in adults under 60 years of age with symptomatic lumbar or lumbosacral disc disease. A single pathological disc should be replaced with a lumbar disc prosthesis.

The indication for the procedure must result from a collaborative decision made by a multidisciplinary team (composed of: two spine surgeons; a physician experienced in psychosocial, professional and chronic low back pain assessment such as a rheumatologist, physical medicine and rehabilitation specialist or pain management specialist; a radiologist or another physician with expertise in spine imaging; on a case-by-case basis, a psychiatrist and a vascular surgeon) and determined following the completion of standard radiographic imaging (full-spine X-rays in anteroposterior and lateral views, and lumbar spine imaging), dynamic radiographs, MRI and potentially discography if there remains persistent doubt after MRI evaluation. Dynamic radiography assesses segmental mobility, and full-spine radiographs evaluate the patient's postural balance.

11.5 Contraindications for Use for Lumbar Disc Prostheses in France According to HAS Recommendations

The Haute Autorité de Santé (HAS) outlines contraindications which are similar to those specified in the FDA's Summary of Safety and Effectiveness

Data for Total Disc Replacement [33]. These include:

- Non-discogenic low back pain, predominant radicular pain
- Multilevel disc disease
- Deformities (scoliosis and spondylolisthesis)
- Severe vertebral instability
- Lumbar spinal canal stenosis
- Morbid obesity
- Osteoporosis and metabolic bone disease
- Advanced degenerative lesions of the facet joints
- Recent lumbar vertebral trauma
- Sequestered disc herniation
- Recent radicular deficit
- History of local infections
- Unfavourable psychological conditions
- Recurrent professional difficulties (e.g. frequent or prolonged work absences)

Although not listed in the contraindications by the HAS, certain situations may be considered as relative contraindications.

- *Severely Collapsed Discs (< 3 mm)*

A clinical analysis of lumbar disc prostheses based on initial disc height highlights the importance of restoring disc height for optimal clinical outcomes [34]. Patients with preserved or moderately reduced disc height before surgery generally achieve better postoperative function, whereas those with severely reduced preoperative disc height may experience less favourable results. Significant disc height loss is often associated with advanced degeneration of adjacent spinal structures, potentially limiting the benefits of disc arthroplasty.

- *Previous operated disc herniation*

A prior disc herniation surgery does not necessarily rule out the implantation of a disc prosthesis. Patients with a history of surgery often experience improved functional scores and significant relief from low back pain. However, they may continue to experience radicular pain for several months following the procedure [34].

- Spinal morphotype

Certain spinal curvature types may affect postoperative outcomes [35]. According to the Roussouly classification [36], type 4 is associated with poorer clinical and radiological results, including a higher incidence of residual lower back pain compared to types 2 and 3. This may be attributed to increased mechanical stress on the facet joints caused by lumbar hyperlordosis in type 4, potentially explaining the less favourable outcomes [37].

11.6 Surgical Techniques

The implantation of lumbar prosthetic discs is performed via an anterior approach of the lumbar spine. The pathological disc is excised. The vertebral endplates and spinal ligaments are preserved, as they contribute to maintaining the stability of the implant. The disc prosthesis is positioned between the adjacent vertebral bodies after meticulous preparation of the intervertebral space, with the goal of restoring optimal disc height and lordosis. A specific surgical toolset is provided to the surgeon to guide and secure the insertion of the implant. The choice of the correct implant size is critical and has significant implications. An undersized implant increases the risk of subsidence into the vertebral endplates. An oversized implant can lead to postoperative pain due to excessive tension on the facet joints or neurological complications from nerve root overstretching. Careful implant selection and precise placement are essential to optimizing outcomes and minimizing complications. Incorrect positioning within the intervertebral space can disrupt segmental biomechanics, altering the natural kinematics of the spinal segment and potentially leading to mechanical dysfunction or postoperative complications. Fluoroscopic guidance ensures accurate implant placement, minimizing the risk of malposition.

There are two types of anterior approaches for disc prosthesis implantation:

- Retroperitoneal approach: Right or left-sided for L5-S1 and most often left-sided for L4-L5 and levels above.
- Transperitoneal approach: Used when the retroperitoneal approach is not feasible (e.g. due to prior surgical history).

The retroperitoneal approach is generally preferred due to its lower risk of visceral complications, peritoneal adhesions and postoperative ileus. Additionally, it reduces the likelihood of superior hypogastric plexus injury, thereby minimizing the risk of retrograde ejaculation in men and vaginal dryness in women [38].

These approaches have their own contraindications [39].

- Severe vascular abnormalities (e.g. abdominal aortic aneurysm, iliac artery disease, or extensive atherosclerosis) that increase the risk of major vascular injury.
- Prior extensive retroperitoneal surgery or radiation that may cause severe adhesions, making safe dissection difficult.
- Previous anterior spinal surgery (e.g. ALIF, abdominal surgery) as obesity represents relative contraindications.

Proper preoperative imaging— such as CT angiography, MRI or Doppler ultrasound— is recommended for patients with suspected vascular abnormalities or a history of abdominal surgery. Additionally, consultation with a vascular surgeon is advised to assess the feasibility and risks of an anterior lumbar approach.

To ensure patient safety and optimize surgical outcomes, the French National Authority for Health (HAS) has established specific requirements for surgeons and surgical teams [32]:

- Specialization in spine surgery: The primary surgeon must specialize in spinal procedures, with at least 50% of their practice dedicated to spine surgery.
- Expertise in the anterior approach: The surgeon must either be trained in the anterior approach or delegate this aspect to a vascular or visceral surgeon.
- Supervised learning period: A dedicated training phase is required, during which the surgeon should operate under guidance.
- Hands-on training: Practical training, including anatomical specimen practice, is essential.
- Vascular expertise availability: A surgeon with vascular expertise must be present or on standby to intervene if needed.
- Postoperative patient monitoring: A cohort follow-up of implanted patients must be established to evaluate:
- The effectiveness of the procedure (functional outcomes at the operated level).
- The absence of adjacent-level degeneration requiring reoperation.
- Long-term complication tracking.
- Comprehensive surgical team: The procedure is performed by a spine surgeon trained in the technique, supported by:
- A surgical assistant and a scrub nurse trained in implant instrumentation.

11.7 Results

Among the pioneering studies on lumbar disc arthroplasty, several were conducted in France and published in the early 2000s [40–44]. One of the largest prospective, multicentre studies took place in France between November 2003 and December 2008, involving 411 consecutive patients who received the Mobidisc® disc prosthesis [45, 46]. Key findings at 5 years post-surgery included: Significant reduction in the Oswestry Disability Index (ODI), as well as in low back and radicular pain. Notable improvement in SF-36 scores, for both mental and physical health components. Decreased medication consumption over time. Improved professional status, with an increase in employed patients and a decrease in sick leave. An overall reoperation rate of 14.6%.

While Europe initially led the way in disc arthroplasty research, most highly cited studies on the subject have since come from the United States. In the 2000s, prospective, randomized, multicentre FDA Investigational Device Exemption (IDE) trials for the Charité and Prodisc prostheses generated significant enthusiasm regarding the clinical and economic potential of total disc replacement (TDR). Some researchers even predicted that TDR could replace up to 50% of spinal arthrodesis procedures, with the U.S. disc arthroplasty market projected to surpass $2 billion by 2008 [47]. This growing interest was reflected in the exponential rise of publications in the United States between 1999 and 2008, including 102 surgical outcome studies, 63 clinical reviews and 46 biomaterial and biomechanical reports.

- Comparative Outcomes: TDR vs. Fusion

A meta-analysis by Zigler et al. [48], including four RCTs with long-term follow-up, reported improved ODI scores, lower reoperation rates and higher patient satisfaction with TDR compared to fusion. Another meta-analysis by Rao et al. [49], analysing seven RCTs with 2-year follow-up, found better ODI and VAS scores in the TDR group and shorter hospital stays compared to fusion. However, Ding et al. [50] reported conflicting evidence, suggesting that while TDR remains a viable alternative to fusion, its superiority remains uncertain in the long term.

These findings reinforce lumbar TDR as a valuable alternative to spinal fusion, particularly for appropriately selected patients, with positive long-term outcomes and functional improvements.

11.8 Complications and Reoperations of Lumbar Total Disc Replacement (TDR)

Complication rates range from 1–17.5%, and reoperation rates are reported at 2.3–10% for short-term follow-ups. Studies, including a meta-analysis by Wei et al. [51], show lower complication rates for TDR compared to fusion. Complications are usually categorized as:

- Surgical approach-related: Examples include hematoma, vascular injuries and retrograde ejaculation…
- Device-related: as subsidence and dislocation.
- Postoperative: Adjacent segment degeneration (ASD) remains common concerns.

- *Adjacent Segment Disease*

Several studies have examined the incidence and prevalence of adjacent segment degeneration (ASD) following lumbar total disc replacement (TDR) compared to spinal fusion. Harrop et al. reported a significant reduction in the incidence of adjacent segment degeneration (9% vs. 34%) in lumbar TDR patients compared to those who underwent fusion [52]. Zigler et al., analysing data from a prospective multicentre study, found fewer changes in adjacent-level degeneration in the TDR group than in the fusion group (9.2% vs. 28.6%) at five-year follow-up [53]. In a meta-analysis of 13 studies, Ren et al. further confirmed a lower prevalence of ASD and a decreased reoperation rate in lumbar TDR patients compared to fusion at both short-term and long-term follow-up [54].

A recent large retrospective study compared the rates of adjacent segment disease (ASD) following lumbar disc arthroplasty (LDA) and anterior lumbar interbody fusion (ALIF) in 1625 matched patients. The results showed that LDA was associated with a lower risk of ASD (relative risk: 0.932, $*P* < 0.001$) and revision within 30 days (relative risk: 0.235, $*P* = 0.007$) compared to ALIF, with no differences in overall surgical or medical complications [55].

These findings suggest that lumbar TDR may contribute to a lower risk of adjacent segment pathology compared to fusion, supporting its role as a motion-preserving alternative in appropriately selected patients.

- *Lumbar Total Disc Replacement Device Removals and Revisions*

Reoperation rates range from 0% to 39.3%, with causes including device failure, persistent pain or adjacent segment pathologies. Revision strategies vary and include posterior fixation, prosthesis replacement or anterior fusion. However, anterior revision is associated with higher risks, while lateral approaches can reduce complications [56]. A large consecutive study shows a 1.26% removal/revision rate for TDRs over a 20-year period, demonstrating the safety of the devices [57]. Among 2141 patients, device removal occurred in 24 patients (1.12%), while three patients (0.14%) underwent revision. Timing analysis revealed that 37% of removals/revisions occurred within 1 month of implantation. Additionally, 40.7% of these cases occurred in the first 25 procedures performed by individual surgeons. One significant vascular complication was reported in a trauma-related TDR removal, the only case among 258 patients with ≥15 years of follow-up who required removal or revision.

11.9 Multilevel Use of Lumbar Total Disc Replacement (TDR)

The concept of multi-level lumbar disc replacement has been explored in the literature since 2005, when Bertagnoli et al. [58] described hybrid constructs incorporating two- and even three-level lumbar artificial disc replacement. In 2009, Erkan et al. published research on the biomechanics of two-level lumbar disc replacement, further contributing to the understanding of its feasibility and outcomes. In 2011, Delamarter et al. [59] published a 2-year outcome analysis from the Investigational Device Exemption (IDE) study comparing ProDisc-L total disc replacement (TDR) to circumferential arthrodesis. Their findings demonstrated: maintained range of motion at both implanted levels, comparable or superior VAS and ODI scores compared to fusion patients, statistically significantly fewer reoperations in TDR patients (2.4% vs. 8.2%, P = 0.0497), and significantly lower narcotic usage rates in the TDR group (36.4% vs. 61.0%, P = 0.0017). In April 2020, the FDA approved the expanded use of ProDisc-L to include the treatment of up to two consecutive lumbar spinal levels (L3-S1) [60].

11.10 Hybrid Constructs

Total disc replacement may also be used in hybrid constructs for treating two-level degenerative disc disease.

A prospective cohort study comparing mid- to long-term patient-reported outcome measures among three surgical treatments for symptomatic degenerative disc disease: single-level total disc arthroplasty (TDA), multi-level TDA and hybrid constructs (a combination of TDA and anterior lumbar interbody fusion across multiple levels) included 950 patients who underwent surgery for single-level or multi-level DDD [61]. All groups demonstrated statistically and clinically significant improvements in pain and function. With careful preoperative evaluation and accurate diagnosis, clinically and statistically equivalent outcomes can be achieved for symptomatic DDD using single-level TDA, multi-level TDA or hybrid constructs. These improvements were maintained in the mid- to long-term follow-up.

In a 2017 study, Andrieu et al. conducted a multicentre, prospective observational analysis comparing two-level total disc replacement (2TDR) with hybrid constructs (HC) in patients suffering from two-level degenerative disc disease [62]. The hybrid constructs combined a total disc replacement at one level with an anterior lumbar interbody fusion at the adjacent level. The study included 72 patients, with 48 undergoing 2TDR and 24 receiving HC, and had a minimum follow-up period of 2 years. The study concluded that both two-level total disc replacement and hybrid constructs are effective surgical options for treating two-level degenerative disc disease, providing similar outcomes in terms of pain relief, functional improvement and preservation of segmental mobility over a minimum 2-year follow-up period. The choice between 2TDR and HC should be individualized based on specific patient characteristics and surgeon expertise.

The choice between a hybrid construct (HC) and two-level total disc replacement (2TDR) depends on several clinical, biomechanical and practical considerations. A HC might be preferred when one of the two levels has facet degeneration, instability or a high risk of failure with TDR. It combines the motion-preserving benefits of disc replacement at one level with the stability of fusion at the other, offering a balanced solution for two-level degenerative disc disease. The final choice depends on the patient's specific pathology, surgeon experience and financial considerations.

11.11 Challenges in Adoption

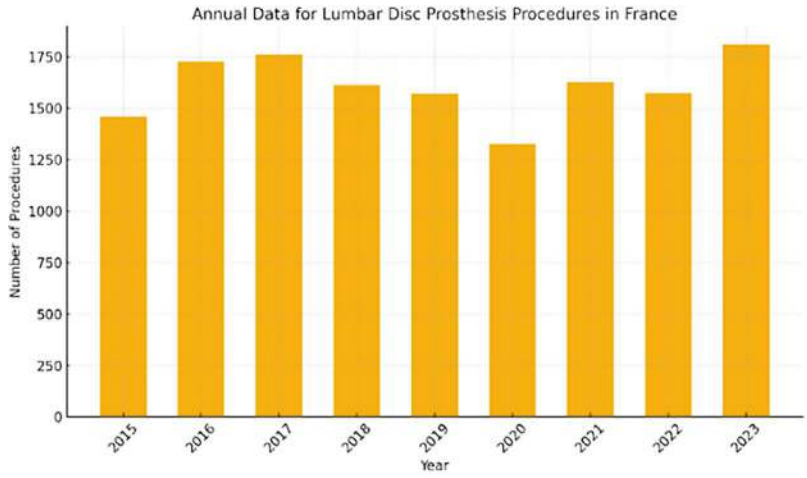
A nationwide survey conducted by Hart et al. found that a large proportion of US spine surgeons had not adopted the procedure despite having the appropriate training and experience, citing limited indications, concerns regarding long-term complications, technical challenges in revising a failed prosthesis, and poor coverage by insurance providers [63]. Spinal fusion continues to be the preferred treatment in most cases with an increasing global trend over recent decades. Reisener et al. attribute this rise to advancements in surgical techniques, innovative implants and expanded indications for fusion surgery [64]. Despite its advantages, LDP remains underutilized due to limited indications, a lack of consensus on long-term benefits, higher technical demands and economic factors [65].

Nevertheless, recent studies, including meta-analyses, continue to demonstrate positive long-term outcomes and advantages over fusion [66].

11.12 Conclusion

A substantial body of clinical research, including high-quality Level I and II evidence with long-term follow-up, supports lumbar total disc replacement (TDR) as a viable alternative to spinal fusion in carefully selected patients. While some studies stem from industry-sponsored trials, rigorous governmental oversight, independent evaluations and peer review processes ensure the credibility of published findings. Long-term follow-up studies, extending beyond 10 years, have consistently demonstrated favourable outcomes, confirming the procedure's safety and efficacy in appropriately chosen cases. As research progresses and surgical techniques continue to evolve, lumbar TDR may gain wider acceptance as an optimal motion-preserving treatment for degenerative lumbar disc disease.

'Annual Data for France (LFKA001: Replacement of a lumbar intervertebral disc with a total prosthesis via laparotomy or lombotomy):' Source: https://www.scansante.fr/



Yearly trends demonstrate fluctuations in the number of procedures, with an overall increase from 2020 to 2023. The decline observed in 2020 is likely attributable to the COVID-19 pandemic and its impact on elective surgeries.

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Sagittal Balance and Small Construct

12

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12.1 Introduction

Jean Dubousset defined spinopelvic alignment as a "cone of economy" in which the axial skeleton balances in line above the feet, lower limbs and pelvis [1]. Accordingly, the significance of a well-balanced spine is now widely acknowledged, and during the past few decades, a comprehension of several significant sagittal alignment factors has surfaced in the literature on adult spinal deformities [2–4]. However, when planning surgeries for degenerative spinal disease, thorough examination of the sagittal plane was not extensively considered in the field of degenerative spine. This paradigm has started to change recently, and it is now more well acknowledged how crucial sagittal alignment is to the diagnosis and care of patients with degenerative spinal disorders. Alignment concepts are developing as potential solutions to enhance the longevity and results of short construct fusions, given the rise in lumbar fusion volume and the need for better short- and long-term patient outcomes [5–9].

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In fact, the debate on whether or not patients with certain degenerative spinal diseases should be fused. While some studies report better postoperative patient-reported outcome measures when decompressing and fusing spondylolisthesis and lumbar spinal stenosis, other studies do not show additional benefits of fusion [10–12]. Fusion is usually recommended in cases of revision surgery, instability, considerable deformity, symptomatic spondylolysis, adjacent segment disease, refractory degenerative disc and in cases of extensive intraoperative decompression [13]. However, the fusion itself can be associated with adverse events. In addition to increasing operative time, and blood loss and if not done properly, fusion can result in extensive and complex reoperations [10, 14]. Looking at the European Spine Study Group database, nearly half of their adult spinal deformity surgeries were revision surgeries that frequently required more invasive procedures often due to under correction of segmental lordosis goals [15]. A significant problem in spine care is revision brought on by iatrogenic adult spinal deformity, which can result from under correction during first surgery or by loss of alignment after surgery. Decades of research have demonstrated that sagittal alignment restoration and maintenance in adult spinal deformity patients can prevent flatback syndrome and lumbosacral kyphosis which could be very intolerable for the patient [16–21].

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Several surgical strategies exist to manage these patients presenting with degenerative spinal disease such as decompression alone, interspinous or pedicular stabilization and solid fusion with each technique indicated depending on pathology, symptoms and the sagittal balance of the patient.

12.2 Ageing of the Spine and Compensatory Mechanisms

In the ageing spine, sagittal deformity typically begins with a loss of lumbar lordosis and ultimately results in the trunk tilting forward and a positive sagittal malalignment. In the degenerative spine, the lumbar lordosis frequently flattens due to the intervertebral discs' squaring from their prior dorsal wedging and their degeneration to a more kyphotic alignment, which changes the segmental lordosis [22–25]. As a result, measurements of the segment of interest's intervertebral disc lordosis and vertebral body wedging will help determine the kind of interbody device needed in terms of the segment's height, endplate contact location, lordosis magnitude and posterior compression requirement [26]. In general, the degree of lordosis in the level of interest and surrounding segments should always be considered when performing a short-segment lumbar fusion. In order to preserve sagittal alignment, degenerative alterations that modify the degree of lordosis in one segment cause compensatory modifications in adjacent segments. Global lordosis may therefore seem normal, but careful examination will show that the cephalad and caudal segments do not have the optimal lumbar distribution [27–29]. This concept may explain some biomechanical failures in short lumbar fusions that encompass both pathologic segments and those in compensated positions [5].

To maintain full body alignment in this ageing spine, patients often trigger a chain of compensatory mechanisms including thoracic hypokyphosis, hyperextension of adjacent segments, retrolisthesis, pelvic retroversion, knee flexion and ankle dorsiflexion. In fact, by reducing the thoracic kyphosis, the anterior translation of the axis of gravity can be limited. This seen especially in the young adult population because when the spine becomes more rigid in old patients, it is not possible for the patient to reduce the magnitude of the thoracic curve [20, 30]. As for the hyperextension of adjacent segments, the latter limits the consequences of lumbar kyphosis on the shift of the gravity axis. Prior research showed that individuals with low back pain had more proximal lumbar lordosis (i.e. greater extension of the upper lumbar spine), a more vertical sacrum and less distal lordosis [31, 32]. Hyperextension can occur locally (mono/bi-segmental) or globally (multi-segmental) with the former increasing the strain on posterior structures, increasing the risk of retrolisthesis and potentially leading to interspinous hypertension, accelerated facet joint arthritis and occasionally isthmic lysis. Retrolisthesis is usually confined to 2–3 mm of slippage in the lumbar spine and can cause severe foraminal stenosis and, less frequently, central stenosis. They are frequently seen at the L5-S1 region, which is one of the lower or upper adjacent segments of the kyphotic degenerative illness.

In the pelvis, the main compensatory mechanism is pelvis retroversion which is defined by an increase in the pelvis tilt and corresponds to a posterior rotation of the pelvis around the femoral heads. This compensatory mechanism is made possible by the hypolordotic spine's rigidity that is transferred to the pelvis, causing the sacrum to be positioned posteriorly in relation to the coxo-femoral heads. This mechanism allows for the adjustment of anterior translation of the axis of gravity by increasing the sacro-femoral distance and bringing back the sacral plate. Indeed, several investigations have shown that individuals with lumbar degenerative disease and chronic low back pain have increased pelvic tilt and decreased sacral slope [20, 31–34]. As for lower limb compensations, it is characterized by knee flexion and ankle dorsiflexion. Knee flexion is a well-known compensatory mechanism for patients with severe degenerative spine and adult spinal deformity [35]. Ankle dorsiflexion is another compensatory mechanism seen in severe

degenerative spine and adult spinal deformity patients and was shown to play a role in the induction of posterior pelvic shift [36].

12.3 Sagittal Balance in the Degenerative Spine

In degenerative spinal disease, patients often lose their ability to maintain optimal segmental sagittal balance as the spine degenerates, and this malalignment often contributes to their symptoms. Studies have shown that degenerative spondylolisthesis (DS) affects the distal lordosis, where most of the LL is present, in 70% of the cases [20]. Patients with DS were more anteriorly translated (had a higher sagittal vertical axis (SVA)), had a higher pelvic tilt (PT) decreased sacral slope (SS) and a lower LL, when compared to a control population matched for PI [20]. Furthermore, the DS population had a higher PI rendering them to suggest that a high PI may predispose patients to the development of DS [20]. Reduction and fusion of the slipped vertebra in low- and mid-grade isthmic spondylolisthesis had improved outcomes when the correct values spinopelvic parameters such as PT, SS, SVA and spinosacral angle (SSA) were restored [37, 38].

When it comes to degenerative disc disease (DDD), correlations between MRI T2 values of the anterior annulus fibrosis (AF) and spinopelvic parameters including LL, SVA, PT and SS, with AF degeneration being related to a low LL, high SVA and posterior inclination of the pelvis [39]. When studying the sagittal alignment of a population suffering from degenerative lumbar stenosis (DLS) and compared it to an ASD population [40], DLS patient with mild/moderate sagittal malalignment was shown to have a lower LL with an increased truncal inclination and a recruitment of posterior pelvic shift instead of PT, helping them achieve neural decompression and symptom-relief [40]. However, when the malalignment becomes severe, the compensatory mechanisms showcased were similar to that of the ASD population with a predominance of pelvic retroversion [40]. Patients with CLBP were shown to have lower SS and LL associated with a small PI, further presenting the question of whether or not there is a relationship between this specific pattern of spinopelvic parameters and LBP when comparing the sagittal alignment of 198 patients with CLBP to that of 709 asymptomatic subjects [41].

Sagittal alignment is affected by spinal degeneration; however if restored post-operatively, it is correlated with better surgical outcomes. Importantly, this does not always necessitate arthrodesis depending on the spinal pathology. Eighty eight patients who underwent lumbar decompression for DLS had a post-operative improvement in LL, thoracic kyphosis (TK), SVA, PT and PI-LL [42]. They further concluded that isolated decompression without fusion could induce a reactive improvement in both lumbar and global sagittal alignment [42]. However, when patients have a PI-LL > 10° after fusion for DS, they were shown to have a 10-times higher risk of revision surgery for adjacent segment disease [43]. Other studies showed that for each 1° increase in PI-LL mismatch, the odds for developing adjacent segment disease increase 1.4-fold [44]. The relationship between PI-LL mismatch and adjacent segment disease development was also validated by Matsumoto et al. [45]. A similar relationship was shown between the risk of revision surgery and a low post-operative contribution of L4-S1 to global LL (i.e. low lordosis distribution index) [45–47].

12.4 Sagittal Balance Operative Goals (Fig. 12.1)

Schwab et al. published a current-concepts review in 2010 highlighting the key parameters in assessing alignment and surgical planning [48]. They noted that restoring sagittal vertical axis and pelvic tilt values are crucial objectives for corrective surgery in adult spinal deformities. Furthermore, they emphasized that it should be paired with a proportionate lumbar lordosis to pelvic incidence, introducing what became a highly-cited formula LL = PI ±9° [48]. In fact, it was demonstrated that increased pelvic incidence–lumbar lordosis (PI-LL) mismatch (i.e.

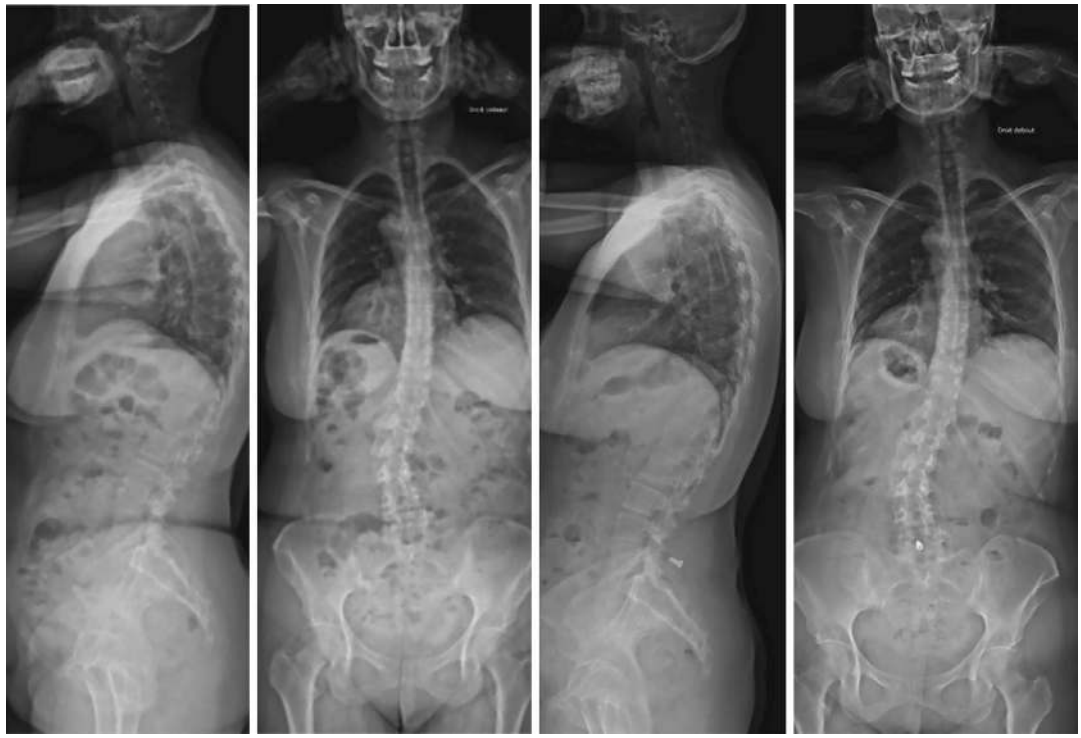

Fig. 12.1 When the alignment is preserved and doesn't need any correction, an interspinous osteosynthesis to prevent iatrogenic destabilization associated to a fenestration is a good option to relieve radicular pain

LL should be within 10° of PI) is associated with adverse patient-reported outcomes [49–51]. With this work, the focus of sagittal realignment expanded to encompasses both global and regional parameters. Been et al. performed radiograph measurements on humans and macaques, reporting that the discs and not the vertebral bodies are what contributes mostly to the lordosis [52]. In addition, they showed that lordosis decreases from distal to proximal levels with L4-S1 contributing to 62% of the lordosis [52]. Pesenti et al. further reported that L4-S1 (distal lordosis) was PI-independent, and only L1-L4 (proximal lordosis) positively correlated with PI [53]. Therefore, when PI increases, the contribution of L4-S1 to the global lordosis decreases [53].

Recently, lumbar lordosis was assessed on the segmental level with Diebo et al. defining sagittal alignment targets for segmental assessment of lumbar vertebra [4]. In their study, they examined the alignment in 510 patients with adult spinal deformity and developed an ideal segmental alignment for 6 classes of PI [4]. Based on their classification, they showed that over-corrected patients had higher risks of proximal junctional failure (PJF), and under-corrected patients had higher rates of revision for implant failure [4]. Singh et al. validated this classification on the degenerative spine disease patients showing that having a L4-S1 lordosis outside the ideal interval of 35° to 45° after transforaminal lumbar interbody fusion had a higher rate of adjacent segment disease and revision at 2 years post-operatively [54].

Another classification that is as helpful in restoring sagittal balance is the Roussouly classification. In 2020, Sebaaly et al. published a multicenter study comparing outcomes after adult spinal deformity surgery in patients operated on following their suggested algorithm (based on the Roussouly classification) to patients operated not according to said algorithm [2]. The algorithm was used to operate on 66% of the

patients, of which 22.5% experienced a mechanical complication, while the remaining 34% of patients experienced a mechanical complication rate of 46.8%. In fact, operating according to the algorithm reduced the chance of experiencing a mechanical complication by 3 times [2]. This classification was further validated on degenerative spine disease patients showing that restoring the sagittal balance in short fusions according to the Roussouly classification reduced the chance of experiencing an adjacent segment disease [55, 56]. Therefore, a view of the entire spine can be more beneficial compared to using constrained angles and simplified calculations. A simple formula utilizing a fixed angle and the LL or a more complicated formula involving some portion of the lumbar lordosis (L4-S1) should not be used by surgeons to manage the entire spine [2].

12.5 Consequences of Malalignment in Short Fusions (Fig. 12.2)

Even with our thorough knowledge of the best surgical practices and our use of contemporary instrumentation, up to 53.7% of previous spine fusions require revision for deformity correction [57–59]. This revision could be due to numerous reasons, including insufficient prior correction, pseudoarthrosis, implant failure, adjacent segment disease or proximal junctional kyphosis [57, 60]. Kumar et al. were one of the firsts to assess the consequences of malalignment in short lumbar fusions [60]. With a follow-up of up to 5 years, they showed that patients with abnormal C7 plumb line and/or sacral inclination immediately after short lumbar fusion had higher rates of adjacent segment disease compared to patients having both of these parameters within the normal range [60]. In fact, in a recent study, 45.3% of the 510 adult spinal deformity patients were revision fusions [14]. Of these revisions, 27% were implant-related failure with pseudoarthrosis being the most common, 40% junctional-related failure with PJK being the most common, 73% malalignment-related failures with sagittal malalignment being the most common and 28% neurologic-related failures with radicular pain being the most common, often caused by adjacent segment disease [14]. When assessing the segmental lordosis of these revision patients, 93%, 88% and 62% were shown to be under corrected at LL, L1-L4 and L4-S1, respectively. In addition, when looking at baseline patient-reported outcome measures compared to primary patients, patients with failing short fusions reported more back and leg pain, more disability, and worse SRS appearance, mental and total scores. As for their surgery, this same cohort of patients had a higher number of 3-column osteotomies and more invasive surgeries compared to primary patients [14]. Other studies revealed increased costs in patients undergoing revision surgeries compared to primary patients. For instance, Zuckerman et al. calculated that the average cost of surgery for adult spinal deformity was between $60,000 and $80,000, and that the cost of revision procedures increased by over $50,000 to $87,000 [61]. Furthermore, this population has shown increased incidence of procedure-related problems, including surgical site infections, and repeat revisions (almost 21%) [62–66].

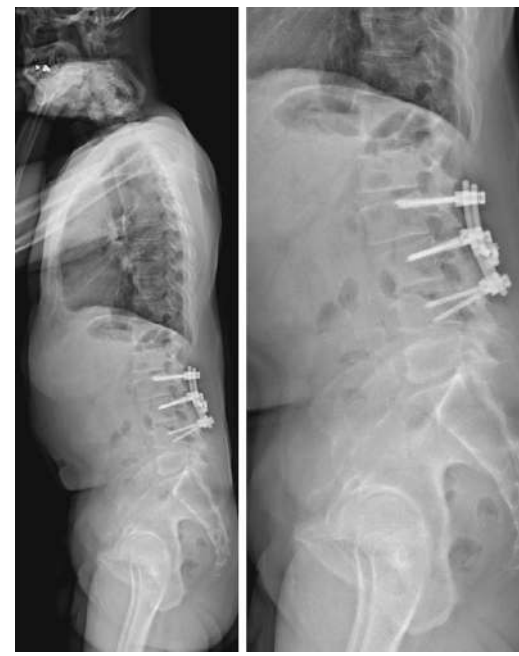

Fig. 12.2 Spinal fusion in a kyphotic position worsens the anterior malalignment and the patient's disability

12.6 Lumbar Kyphosis and Small Constructs (Fig. 12.3)

If a short arthrodesis cannot be performed in the correct position, it is often preferable not to fuse the spine. However, certain situations justify osteosynthesis due to instability, which is responsible for clinical symptoms, or to prevent iatrogenic instability resulting from the neurological decompression procedure. Dynamic systems are particularly valuable in cases where global balance is preserved, aiming to stabilize the most pathological segments while avoiding extensive corrective surgeries. The use of dynamic systems in managing adult scoliosis and kyphosis is well-documented and the results are stable over time despite kyphotic conditions) [67].

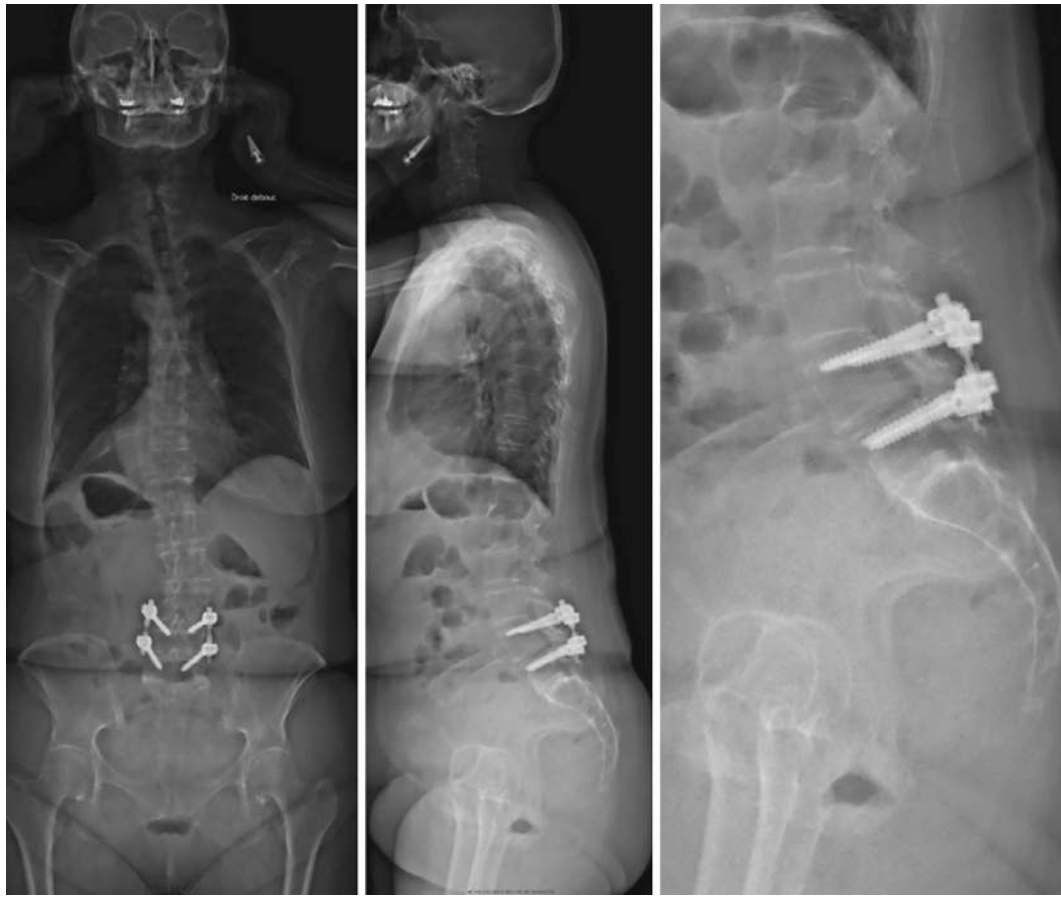

Fig. 12.3 Degenerative spondylolisthesis management in a kyphotic position can be managed with dynamic rods. The SRS-22 score went from 2.8 at baseline to 3.8 at 2 years follow-up

12.7 Conclusion

In conclusion, sagittal alignment of the degenerative lumbar spine is important for spinal surgeons to measure and assess prior to the surgical procedure. Assessment of segmental lordosis and Roussouly spinal shape is necessary in cases requiring fusion. If a spinal fusion in the correct position is not possible or if the goal is not to modify the curvature being instrumented, the use of dynamic osteosynthesis appears to be a relevant option.

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13 Sacroiliac Joint and Lumbar Spine Degeneration

Nicolas Bronsard

13.1 Introduction

Sacro Iliac Joint (SIJ) and lumbar spine degeneration are common sources of lower back pain, especially in older adults or individuals with a history of repetitive spine surgery, pelvic trauma, or multiple pregnancy. Literature related that 15–30% of lower back pain has a SIJ origin [1, 2]. This phenomenon appears to be frequent after lumbosacral arthrodesis [3–5]. This degeneration adjacent to spinal arthrodesis is widely described in the literature, particularly in deformity surgery, and appears to be linked to an increase in mechanical stresses secondary to spinal fusion [6]. Indeed, the sacroiliac joint is anatomically and mechanically intermediate between the lumbosacral spine and the coxofemoral joint, which are physiologically very mobile. The complex anatomy of the SIJ is characterized by low physiological mobility (less than 3°) and high stability linked to strong osteoarticular congruence and rich ligament reinforcement between the sacrum and the coxal bone [7–9]. In the SIJ space, a ligamentous zone and a "true" articular zone are separated [10]. The diagnosis of this joint damage is difficult and not consensual to date. The gold standard in this area remains the infiltration test with local anesthetics with improvement of more than 70% of the painful symptoms [11]. We will therefore successively look at several important points to understand the very close link between the degeneration of the lumbar spine and the appearance of pain in the sacroiliac joint.

13.2 Anatomy of Sacroiliac Joint

By definition, the sacroiliac joint is a synovial joint with very little mobility and a low joint range of approximately 2–3°. It allows the transfer of body weight from the trunk and head to the root of the limbs. In addition, walking is an alternation of monopodal support which therefore uses the spine but also the two sacroiliac joints as well as the two hips. In monopodal support, 5/6ths of the body weight passes through the sacroiliac joint on the supporting side with a significant overhang (Fig. 13.1).

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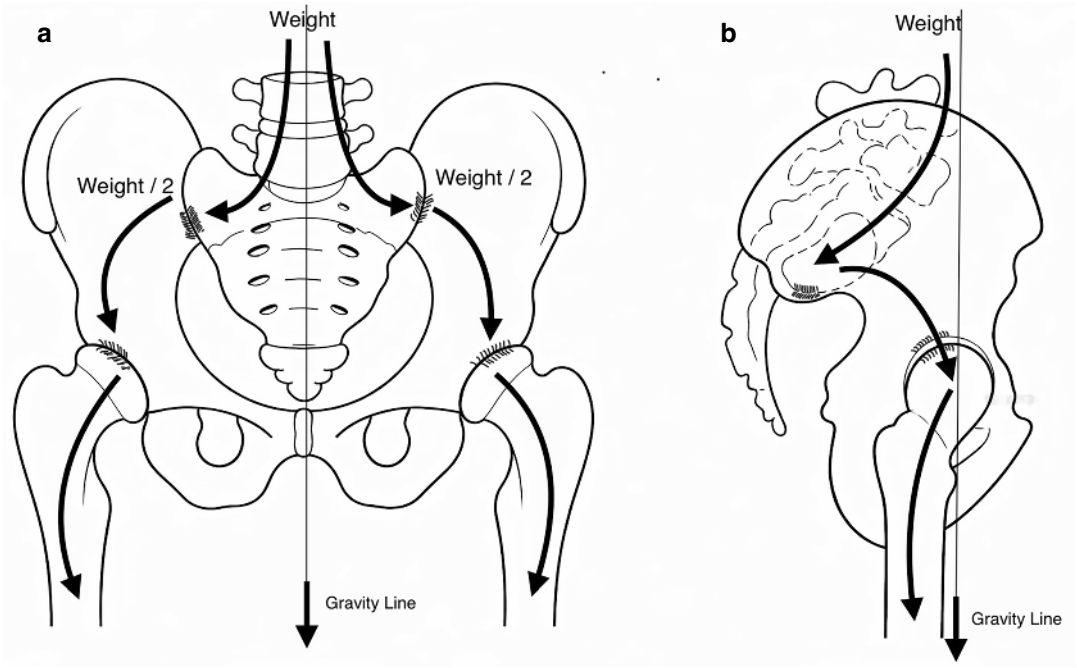

Fig. 13.1 Lumbo-pelvic-femoral complex

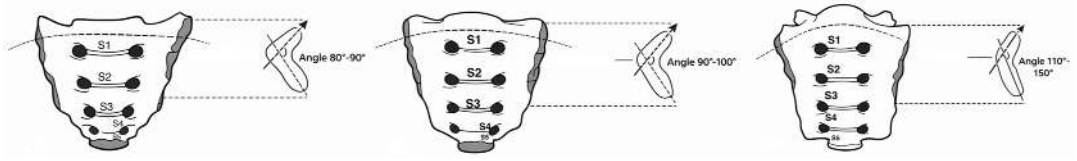

Fig. 13.2 Variability of the shape of the sacroiliac joint

A large anatomical variability of the sacral bone and the shape of the semilunar surface itself are often described, with a variable shape or angle that can be less than 90° or greater than 110° (Fig. 13.2).

In addition, the shape is correlated with the pelvic incidence. In cases of high incidence and high lumbar lordosis, sacroiliac osteoarthritis is preferentially found at the level of the foot of the sacroiliac joint. On the other hand, for cases of

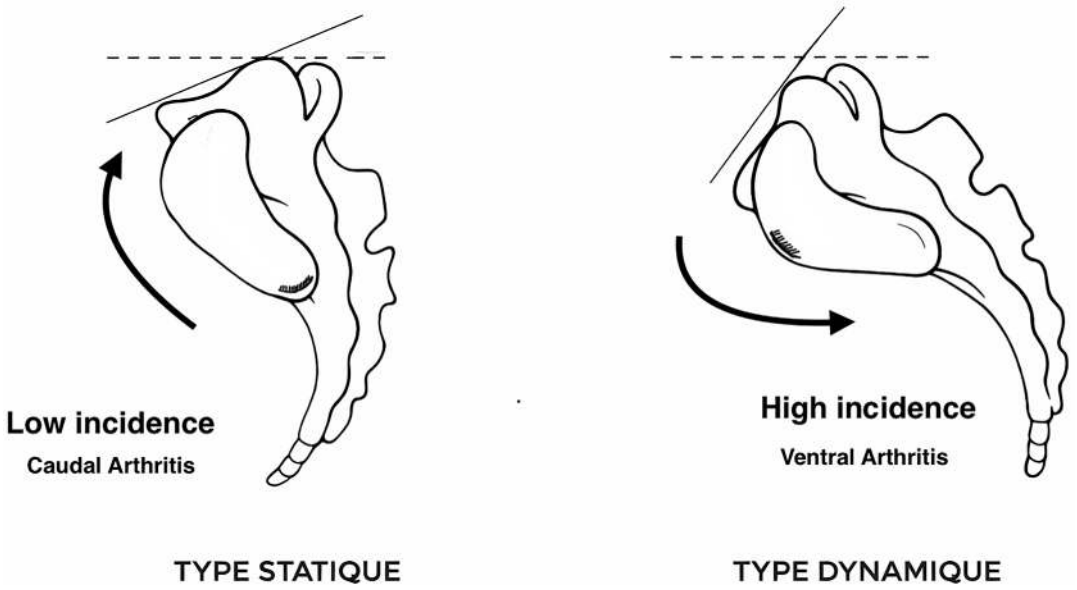

Fig. 13.3 Variability of the shape of the SIJ compared to incidence

low incidence and low lumbar lordosis, sacroiliac osteoarthritis is preferentially found at the angle of the sacroiliac joint (Fig. 13.3).

13.3 Why the SIJ Become Painful and Prevalence of SIJ Pain

Regarding the lumbopelvic-femoral osteoarticular chain, the most mobile joint is the coxofemoral joint, followed by the lumbar intervertebral complex, and thirdly, the two sacroiliac joints.

In cases of dysfunction of the lumbopelvic-femoral chain, regardless of the cause (acute, such as trauma, or chronic, following osteoarthritic phenomena or fusion surgery), stiffening of the joint chain most often leads to increased stress on the sacroiliac joints. Consequently, a thorough history must focus on identifying a cause or event at the spinal, pelvic, or coxofemoral level, or several levels among them. A simple aging mechanism will also lead to progressive stiffness of the 3 joints of the articular chain with fibrous ankylosis during aging (from 50 years old) and histologically a reduction in the thickness of the articular cartilage associated with thickening and capsular fibrosis followed by the appearance of osteophytes even if no difference in mobility was observed between symptomatic and asymptomatic patients [12].

Concerning the prevalence of degenerative pathology of the IS, it increases with age up to 91% of subjects over 90 years old. In asymptomatic patients, 65% of subjects present degeneration on imaging, including 30% severe degenerative lesions [13].

Regarding the prevalence of sacroiliac pain, it varies depending on the article and the period: Lower back pain of posterior joint origin affects 15% of young people and can reach up to 40% of older people [14]. Lower back pain of disc origin affects 40–50% of lower back pain cases [15]. Lower back pain of sacroiliac origin affects 10–38% of lower back pain cases [16].

Furthermore, when we look for degenerative changes in the sacroiliac joint 5 years after lum-

bar arthrodesis, we find radiographic signs of degeneration of the SIJ in 75% of cases, compared to 38% in a control group [17]. Similarly, the appearance or persistence of lower back pain after lumbar arthrodesis associated with permanent pain in the sacroiliac joint is found in 32% of cases [3]. Finally, after lumbosacral arthrodesis, 35% of patients are present with pain of sacroiliac origin [18].

13.4 Biomechanical Between Spine and Sacroiliac Joint

SIJ is strictly in the middle of a chain between a high lumbar spine mobility and very high mobility of the hip joint. The SIJ is a very few mobile joint but lumbar fusion increases joint mobility at the sacroiliac joint, which corresponds to the phenomenon of degeneration adjacent to fusion or neo-hinge syndrome. Lumbar fusion leads to increases in angular motion and stress across sacroiliac joint on a finite element study with52% of stress in SIJ after a L5S1 fusion and 168% after L4S1 fusion [19]. When you make a SIJ fusion it can leads to 1–3% of stress on L4L5 and 5% of stress on the hip [20] (Fig. 13.4).

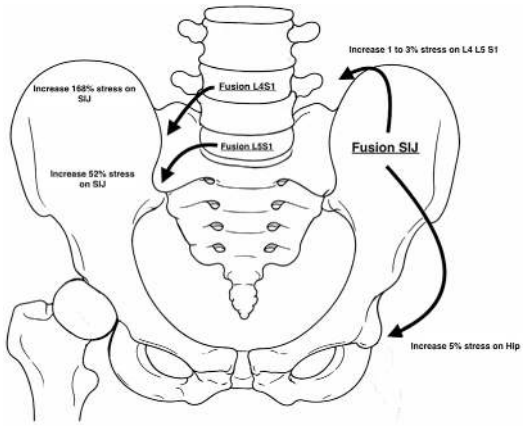

Fig. 13.4 Stress on lumbo-pelvic-femoral complex after fusion

13.5 How to Diagnose SIJ Pain and Description of a Typical Patient

Sacroiliac pain syndrome is defined by stable, disabling pain in the lumbosacral region. It has been shown that 15–30% of chronic lower back pain is actually sacroiliac pain. This syndrome also appears to be more common in patients who have already undergone lumbosacral arthrodesis, but the clinical and paraclinical diagnosis is not universally accepted.

In our study of 94 patients [21] who had undergone lumbosacral arthrodesis and presented with persistent pain more than a year after fixation, the diagnosis of sacroiliac pain was confirmed by the effectiveness of a test injection, with more than 70% pain improvement performed under CT scan by a radiologist. We excluded, using the interview and lumbar imaging, all patients with symptomatic lumbar pathology or sacroiliac involvement of inflammatory origin.

We identified four main clinical parameters and their frequency.

1. Fortin's finger test sign (Fig. 13.5a): present in 100% of cases.
2. Pseudoradiculalgia (crural or poorly systematized sciatica) not explained by lumbar imaging: present in 100% of cases.
3. Sharp pain on palpation of the trochanteric insertion of the gluteus medius not spontaneously expressed by the patient (Fig. 13.5b): present in 96% of cases.
4. Pain triggered by at least three out of five dynamic provocation maneuvers of the sacroiliac joint: 97% of cases.

We identified three imaging parameters and their frequency:

The imaging assessment was based for all patients on:

1. X-rays centered on the sacroiliac joints (inlet + outlet + right and left 3/4) with no abnormalities found in 93% of cases.

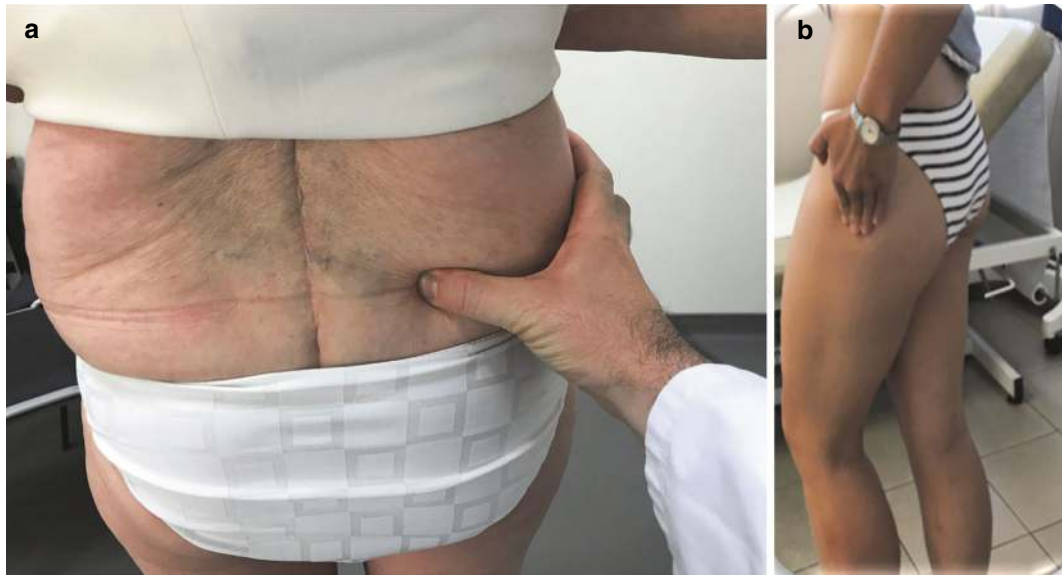

Fig. 13.5 Clinical parameters found in 100% of patient with SIJ pain after lumbosacral fusion. (**a**) Fortin test. (**b**) Pain on the trochanteric insertion of the gluteus medius

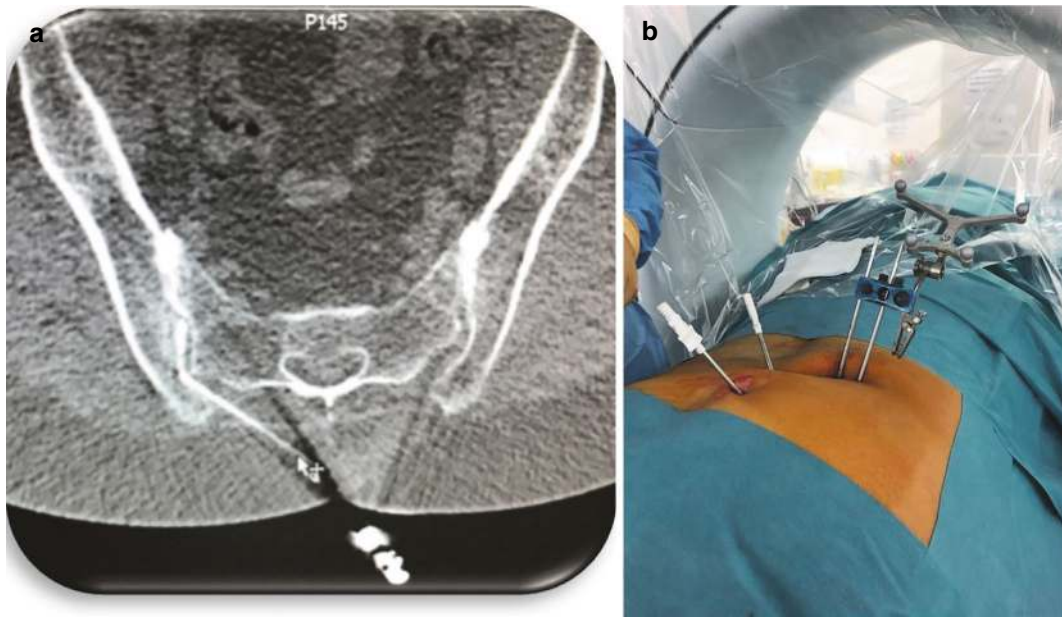

Fig. 13.6 Infiltration test: (**a**) Infiltration with CT guidance and a radiologist. (**b**) Infiltration with OARM and navigation guidance and a surgeon [22]

2. A CT scanner or MRI of the sacroiliac joints to look for osteoarthritic involvement of the sacroiliac joints and to rule out inflammatory arthritis, which revealed objective degenerative lesions in 19% of cases.
3. A bone Scintigraphy was performed to objectify SIJ involvement or to look for another cause of lower back pain, but 95% of patients had a negative Scintigraphy.

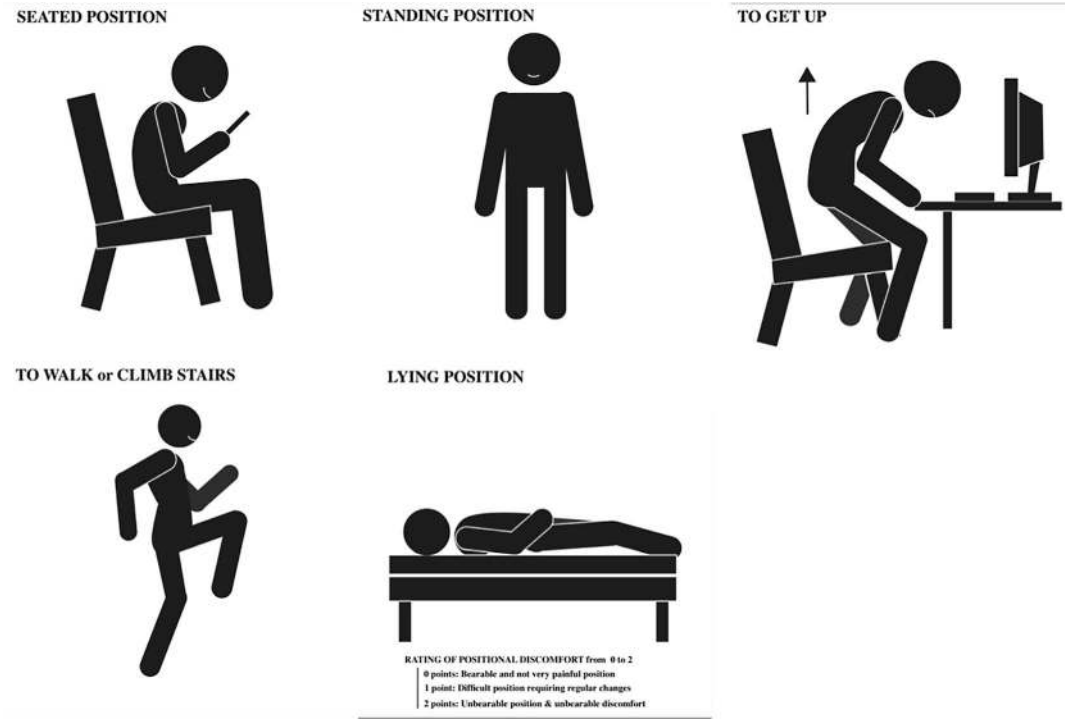

Fig. 13.7 5 Daily positions which are more painful in SIJ pain (rating from 0 to 10)

An effective infiltration test with >70% improvement was obtained in 76 patients under CT guidance by radiologist (Fig. 13.6a), and 18 required a second attempt with OARM (Fig. 13.6b) in the operating room (12 of which were effective).

If we had to describe the typical patient, it was female in 76% of cases, with a mean age of 59.2 years. The involvement was bilateral in 60% of patients and unilateral in 40%. The average ASA score was 1.90 and the average BMI was 26.6.

Patients had undergone a mean of 2.5 lumbar surgeries, and 15.4% had a hip arthroplasty.

Lumbosacral arthrodesis involved only one level (L5-S1) in 31% of cases, two levels in 34%, three levels in 15%, and four or more levels in 20%.

SIJ pain leads to uncomfortable positions in daily practice. The two most painful and uncomfortable positions in daily life were sitting position and standing position (Fig. 13.7). The two least uncomfortable positions were lying down and walking.

The average number of infiltrations required for diagnosis was 1.34 (±0.66), and they had a mean efficacy of 10 days.

Diagnostic of SIJ pain was done with 34.6 months of delay averaged.

13.6 Triggering Factor and Etiological Classification of Sacroiliac Pain

During patient history, we have to find an increase in mechanical stress which chronologically allows to identify a triggering factor or a contributing anatomical factor:

Sacroiliac pain may be found secondary to lumbosacral arthrodesis or secondary to coxo-femoral joint arthroplasty (after osteoarthritis or for fracture). This pain may also occur in the postpartum period (multiparity) or after a fall on the pelvis with or without fracture.

Furthermore, this group of patients has a high incidence of sacral dysmorphism in the form of a hinge anomaly (almost 50%), and the Castellvi classification (Fig. 13.8) helps to characterize the anomaly and also plan for potential operative difficulties.

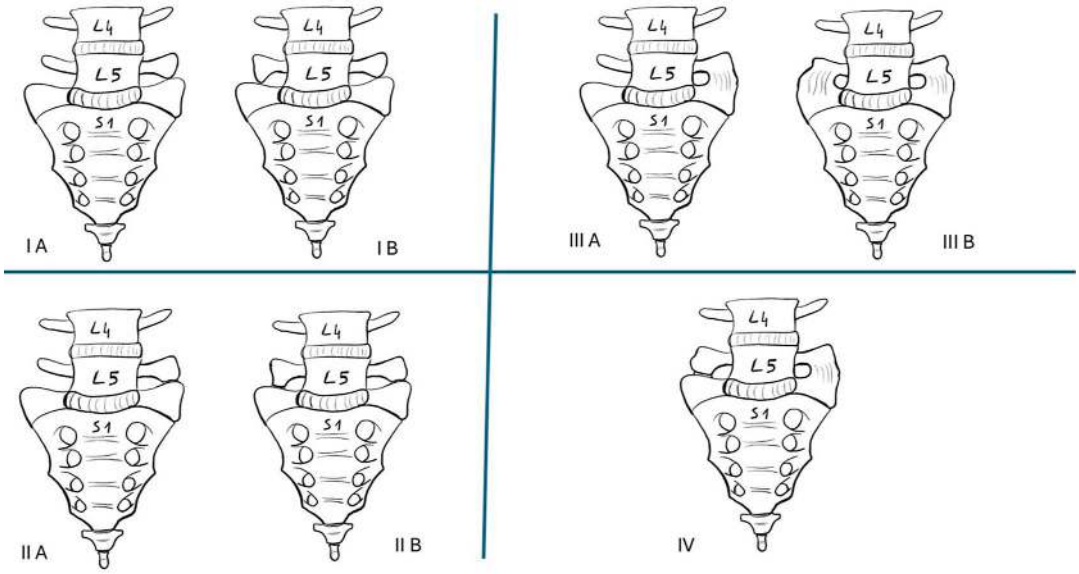

Fig. 13.8 Castellvi classification [23]

SIJ pain due to a primary Pelvic Pathology		Traumatic Multiparity +/- Dysmorphism
SIJ pain Secondary to	Spine pathology	Spine surgery - Anteriorly (ALIF or TDR) - Posteriorly (PLIF) +/- Dysmorphism
	Hip Pathology	Hip Surgery - Total hip replacement - Hip Fracture with fixation - Hip arthritis with stiffness +/- Dysmorphism
	Both	Hip and Spine events +/- Dysmorphism

Fig. 13.9 Classification of SIJ dysfunction etiologies

With experience we are able to classify groups of patients separated by the cause of sacroiliac joint pain (Fig. 13.9).

Few examples of cases classified (Fig. 13.10).

13.7 Diagnostic Algorythm for Sacro Iliac Joint Dysfunction (Fig. 13.11)

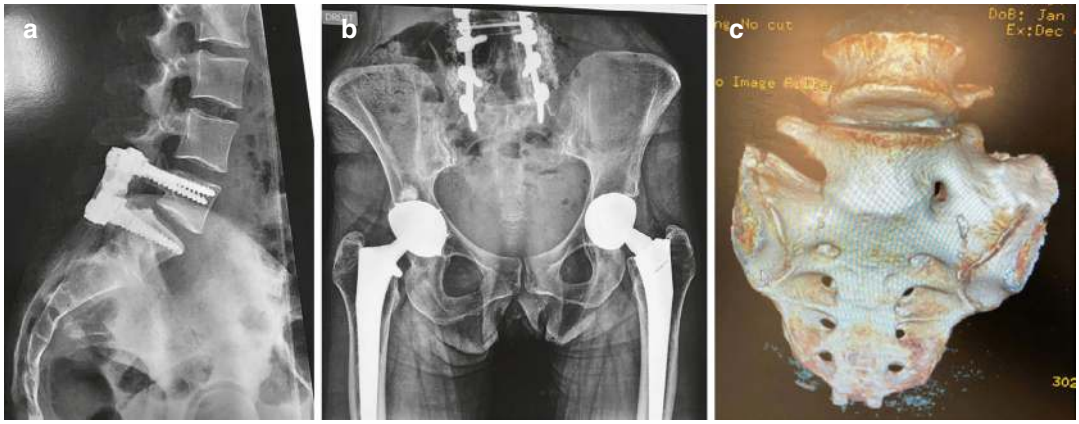

Fig. 13.10 Examples of SIJ pains: (**a**) After spine surgery + IIIb dysmorphism. (**b**) After hip surgery but both origin spine and hip. (**c**) Total L5S1 fusion + unilateral dysmorphism IIIa

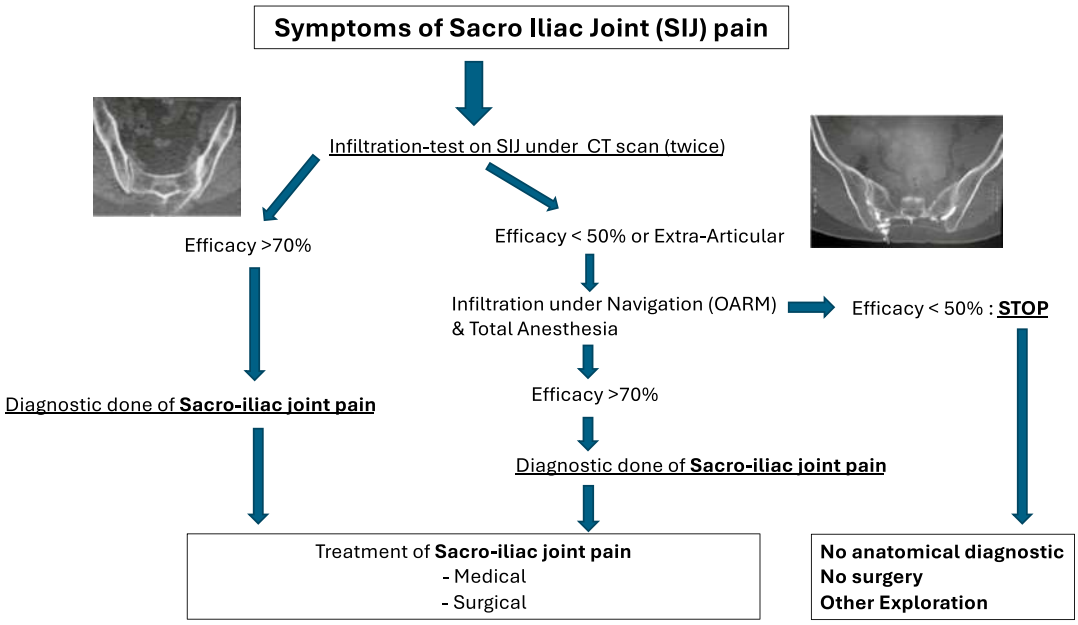

Fig. 13.11 Symptoms of Sacro Iliac Joint (SIJ) pain

13.8 Conclusion

The typical patient suspected of degenerative sacroiliac pain after lumbosacral arthrodesis is therefore a woman with bilateral involvement. She is very uncomfortable sitting, which is easily observed during consultation. She presents with pseudoradiculalgia, with no etiology found on imaging, which leads to significant diagnostic error. She also presents with pain at the tip of the greater trochanter, and the Fortin sign is positive, as are pain-triggering maneuvers. Additional examinations are primarily used to eliminate differential diagnoses and are most often negative. The diagnosis is confirmed by the infiltration test, but if it is not confirmed, it must be repeated or performed under OARM. A precise diagnosis of this condition can then lead us to treatment, particularly surgical, sacroiliac arthrodesis, which is currently undergoing rapid development with the advent of the minimally invasive technique [24–27].

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Lumbar Revision Surgery

14

Antoine Gennari and Jean Guyot

14.1 Introduction

Lumbar revision surgery represents a complex and evolving field within spinal surgery, increasingly encountered due to the growing number of index procedures performed worldwide. The reported incidence of lumbar revision surgery is approximately 15% for non-instrumented surgery and 18% for instrumented surgery [1] depending on the indication, type of index surgery, and patient-specific factors [2]. Common causes of revision include hardware failure, infection, pseudarthrosis, adjacent segment disease (ASD), and recurrent disc herniation or stenosis [3]. These conditions necessitate complex diagnostic workups and individualized surgical strategies.

Advances in technology such as intraoperative navigation, robotics, and improved imaging have contributed to safer index surgeries, potentially reducing the revision rate [4]. Nevertheless, revision surgery remains a critical component of spinal practice. High-risk groups include patients undergoing long-segment fusion, those with metabolic bone disorders (e.g., osteoporosis, diabetes) [5], and patients with severe degenerative spine disease.

In this chapter, we explore the comprehensive landscape of lumbar revision surgery, structured into early revisions (<6 months) and late revisions (>6 months) following the index procedure. The early revisions typically address issues such as malpositioned instrumentation, hardware failure, infection, and cerebrospinal fluid (CSF) leaks. Late revisions are commonly performed for ASD, pseudarthrosis, or recurrent pathology. Specific chapters will also discuss anterior lumbar procedures and minimally invasive/endoscopic approaches, highlighting their unique revision considerations.

14.2 Fundamentals of Revision Surgery

The foundation of successful lumbar revision surgery lies in a meticulous diagnostic workup and careful preoperative planning. Key steps include:

First a clinical evaluation allows an assessment of pain characteristics (mechanical vs. radicular), neurological deficits, signs of infection.

Then radiological evaluation depends on suspected and delay complication:

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- CT Scan: Crucial for assessing fusion status, hardware integrity, screw loosening, or fracture.
- MRI: Essential for evaluating neural compression, infection (epidural abscess, discitis), and soft-tissue involvement.
- Standing full-spine X-rays are used to assess sagittal balance and deformity, especially in late failures.
- Biological and Infectious Workup: In suspected infection or pseudarthrosis, blood tests (CRP, ESR), biopsy, or nuclear imaging (SPECT-CT) may be required.

This allows a careful preoperative planning which is mandatory before the redo surgery to minimize unexpected operative findings.

Surgical Planning Considerations

- *Choice of Surgical Corridor*: Avoiding the scarred posterior approach when possible can reduce operative time and complications. Virgin anterior or lateral corridors (e.g., ALIF, OLIF) are often preferred in suitable cases. The anterior redo surgery represents a very specific management that will be developed later in the chapter.
- *Navigation*: Intraoperative navigation is highly recommended, particularly in scarred areas or complex revisions [4].
- *Bacteriological Sampling*: It is imperative to obtain systematic deep samples during revision surgery, especially when hardware loosening or pseudarthrosis is present, given the high prevalence of low-virulence infections such as Cutibacterium acnes and Staphylococcus epidermidis [6].
- *Multidisciplinary Approach*: Cases with suspected or confirmed infection should involve infectious disease specialists to guide antibiotic therapy and duration. Anterior redo surgeries have to be managed with an experienced vascular or general surgeon.

Studies have shown that although revision cases are associated with longer operative times, greater blood loss, and higher complication rates compared to index procedures, they also lead to significant clinical improvements in appropriately selected patients [7].

14.3 Early Revision

14.3.1 Malposition of Hardware

Diagnostic Considerations

Pedicle screw malposition is one of the most frequent causes of early complications and revision surgery after lumbar spinal instrumentation. According to the large-scale multicenter study by Koshimizu et al., implant-related complications occurred in 4.6% of patients undergoing spinal fusion, with screw malposition representing the most common failure mode (42.8%) and the leading cause of revision within the first 30 postoperative days (72.2%) [8].

Malpositioned screws can cause a variety of symptoms depending on their trajectory. Medially or caudally directed screws can compress neural structures, resulting in radicular pain or motor deficits. Lateral or cranially malpositioned screws may not immediately provoke symptoms but can compromise construct stability or injure adjacent intervertebral discs, increasing the risk of adjacent segment degeneration.

Diagnostic workup involves detailed imaging:

- Neurological examination is essential to detect correlating deficits.
- CT scan remains the gold standard to confirm malposition and assess the breach direction and extent.

Revision Strategy

When malpositioned screws result in neurologic compromise or construct failure, prompt revision is recommended. In urgent cases with neurologic deficits, surgery should not be delayed. The use of navigated or robot-assisted insertion during both index and revision procedures dramatically reduces the risk of malposition. A meta-analysis by Shin et al. showed a 60% reduction in pedicle screw perforation with computer-assisted navigation, with a perforation rate of 6% for navigated

versus 15% for non-navigated screws [9]. Similarly, Caelers et al. demonstrated that although lateral fluoroscopy-guided techniques are widely used, 3.25% of neurological deficits postoperatively could be directly attributed to screw malposition [10].

Intraoperative Tools and Strategies

- O-arm or intraoperative CT verification should be preferred over conventional X-ray guidance. Alomari et al. demonstrated that the use of O-arm reduced the rate of reoperation for screw malposition from 0.37% to 0.02% [11].
- Navigated cannulated screws are useful in challenging trajectories or revisions. Yılar et al. reported significantly improved accuracy (malposition rate 6.6% vs. 22.6%) with the use of cannulated screws in narrow or dysplastic pedicles [12].
- Screw replacement should ideally occur during the same procedure if intraoperative imaging confirms malposition.

When revision is necessary, careful consideration must be given to trajectory adjustment. Cortical bone trajectory [13] can be used if classic pedicle screw trajectory is not "usable" and cannulated instrumentation for improved accuracy.

Expected Outcomes

When adequately addressed, revision for screw malposition offers good neurological and clinical recovery. However, a delay in diagnosis or surgical management may result in persistent neurologic deficits, especially if neural injury has occurred. In the Koshimizu study, 3 patients undergoing revision for malpositioned screws did not experience symptom relief, emphasizing the need for timely and precise correction [8].

14.3.2 Hardware Failure

Risk Factors and Preventive Measures

When planning posterior lumbar arthrodesis, numerous patient-related risk factors have been identified for pedicle screw loosening. These include advanced age, sarcopenia, hypoalbuminemia, smoking, the use of non-steroidal anti-inflammatory drugs (especially non-selective COX inhibitors), osteopenia, osteoporosis, and diabetes mellitus. All of these parameters must be evaluated preoperatively to guide the surgical strategy and potentially optimize modifiable factors [14].

The initial surgical technique plays a key role in the long-term stability of the construct. Optimal pedicle screw placement—targeting the center of the pedicle and achieving 50–75% penetration of the vertebral body—is crucial. Cortical bone trajectory screws have gained popularity, particularly in osteoporotic patients, for their improved purchase in dense cortical bone [15]. At transitional junctions or long constructs, the use of supplemental fixation (e.g., iliac or thoracic screws) is often necessary to prevent mechanical overload and early failure [16].

The use of interbody fusion is recommended to harmonize load-sharing across the construct and reduce mechanical stress on the posterior instrumentation. For high-risk patients, placing an interbody device significantly reduces screw-loosening rates [17]. Endplate preparation should be meticulous, abrading the surface without complete decortication to avoid subsidence and subsequent hardware failure [18].

Finally, restoring sagittal balance is a major principle of spine surgery. Malalignment, particularly thoracolumbar kyphosis or inadequate segmental lordosis, imposes increased stress on the construct and promotes loosening [19, 20].

Diagnostic Workup and Timing

Most cases of screw loosening occur within the first six postoperative months [17]. According to Shimizu et al., screw pullout or loosening was the most frequent cause of revision within 30–90 days [2]. Clinical suspicion arises from persistent or recurrent back or radicular pain unresponsive to medical therapy. Dynamic X-rays and multi-slice CT remain the imaging modalities of choice for diagnosis.

Although the direct correlation between screw loosening and quality of life is debated, it is a strong predictor of non-union at 1 year [17]. Therefore, early symptomatic loosening is an indication for revision surgery.

Elimination of Septic Causes

Shiban et al. found that 42% of screw loosening cases in their revision series had positive microbiological cultures, despite the absence of systemic signs and normal blood cultures [21]. Compared to other revision indications (pseudarthrosis, adjacent segment disease, and implant breakage), screw loosening is the most frequently associated with a positive bacteriological culture [22]. Routine laboratory workup is often inconclusive: WBC counts may be normal, and CRP elevation is usually modest [22, 23]. Consequently, intraoperative sampling is essential. Burkhard et al. recommend continuing preoperative antibiotic prophylaxis, as its discontinuation does not improve intraoperative culture yield [23].

Sonication of removed implants combined with in-situ samples improves diagnostic sensitivity and specificity [23, 24]. Cultures often reveal low-virulence organisms, such as Cutibacterium acnes and coagulase-negative Staphylococcus spp., which mirrors the profile of periprosthetic infections in orthopedics [25, 26].

Currently, no guidelines support systematic empiric antibiotic treatment post-revision. However, when cultures are positive, the initiation of targeted antibiotic therapy is strongly recommended, ideally in consultation with an infectious disease specialist. Treatment duration typically ranges from 6 to 12 weeks [27].

Revision Strategy

When symptomatic early screw loosening is confirmed, revision surgery should aim to restore mechanical integrity and promote fusion. If no interbody device was used initially, its placement is indicated during revision. Galbusera et al. demonstrated that adding an interbody device redistributes forces and reduces posterior screw loading [26] (Fig. 14.1). ALIF (Fig. 14.2) or OLIF (Fig. 14.3) approaches provide access to the anterior column and can be advantageous in revision settings:

- Avoid re-dissection of scarred posterior planes.
- Improve visualization for cage removal or placement.
- Restore lordosis more effectively than posterior interbody techniques [28].

Posterior screw replacement is often necessary. Strategies include:

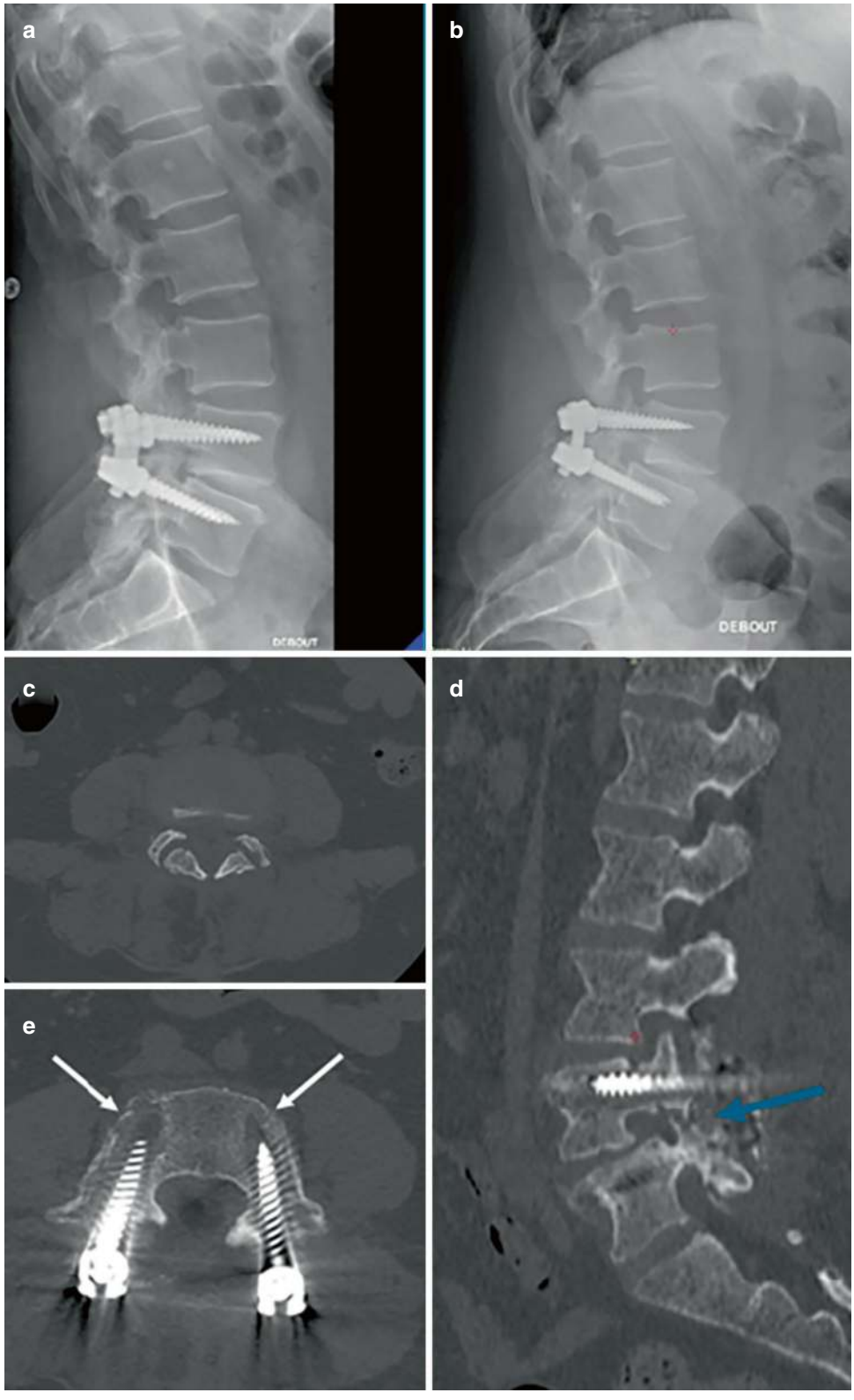
- *Larger screws*: improve insertion torque but increase the risk of pedicle fracture and canal breach.
- *Longer screws*: risk anterior wall breach and visceral or vascular injury.
  (Larger screws seem to bring a more solid construct than longer screws [29]).
- *Cemented screws*: provide stronger fixation in osteoporotic bone. Authors noted that larger screws had higher insertion torque than cemented ones, though cemented screws had better pull-out resistance [30, 31], but may cause cement leakage, nerve injury, or embolism [32].
- *Alternatives include pediculoplasty* with impacted grafts (Shen): offers improved torque with moderate pull-out resistance [33].
- *A cortical bone trajectory* revision offers also promising results. Fujibayashi et al. combined it with interbody fusion and observed favorable fusion rates at 1 year [34].

Management in Osteopenia/Osteoporosis

Patients with low bone mineral density are particularly prone to loosening [26]. Interbody support is essential in these cases and should be included in the initial procedure whenever possible [17]. If revision is needed, cemented screws remain a recommended option—even when trajectories are altered.

Emerging alternatives include demineralized bone fiber anchors, which have shown promise in elderly patients by reducing recurrent loosening rates [31].

Fig. 14.1 Illustration case of early mechanical failure of posterior lateral fusion (PLF). (**a**) Patient underwent PLF for segmental instability. (**b**) 3 weeks after, patient experienced pain. X-ray shows progressive listhesis at L4L5. (**c**) Axial CT scan reveals articular diastasis at the level above (L3L4). (**d**) Axial CT scan reveals severe L5 screw loosening. (**e**) Sag CT scan reveals L3L4 retrolisthesis and L4 pedicle fracture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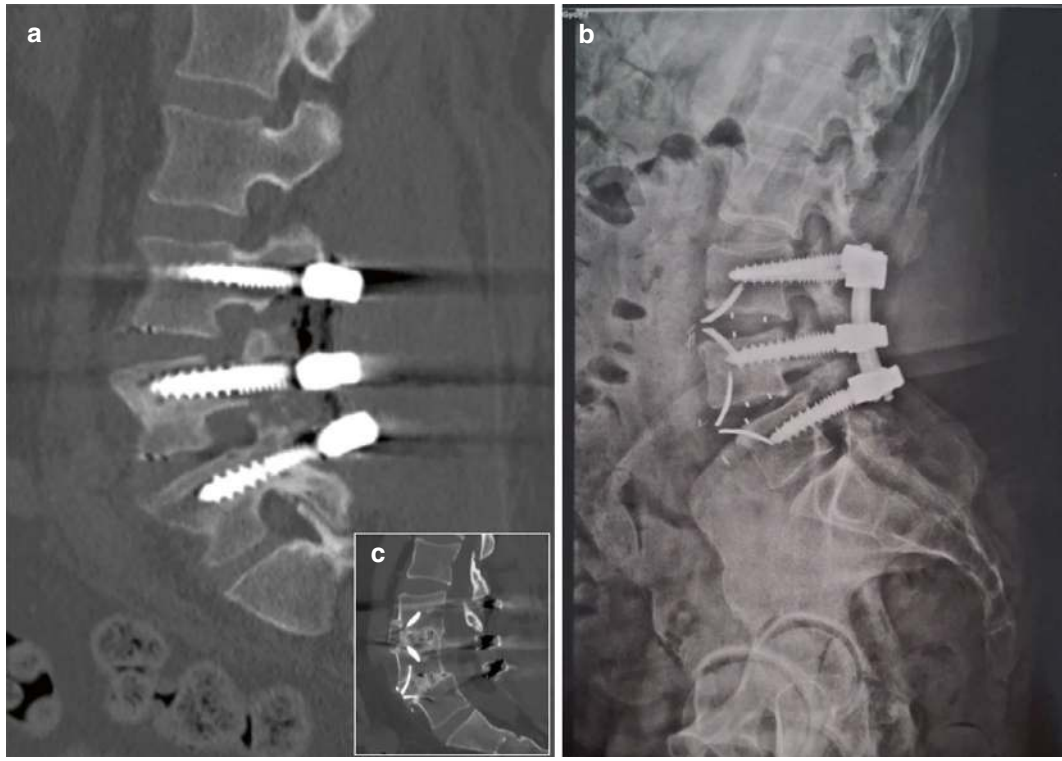

Fig. 14.2 Post-operative result of successful revision using ALIF and posterior revision with larger screws (9.0 mm diameter). (**a**) Post-operative CT scan. (**b**) 1-year CT scan showing bony fusion. (**c**) Post-operative standard X-ray

Bone Grafting

Autologous iliac crest graft remains the gold standard, although limited in quantity and associated with donor-site morbidity [35]. Bone Morphogenetic Protein-2 (BMP-2) is equally effective in achieving fusion and may even accelerate it [36]. In revision or infected cases, off-label BMP-2 use has yielded favorable outcomes [37]. Vascularized bone grafts, although still investigational, offer enhanced osteogenic potential [38].

Clinical Outcomes

The need for revision should be clinically driven. Long-term outcomes for asymptomatic patients with screw loosening are generally comparable to those without mechanical failure [20, 39]. However, early symptomatic loosening strongly correlates with pseudarthrosis [17]. When clinical signs are present, especially back or radicular pain with radiographic evidence of screw loosening, revision surgery should be pursued to improve fusion and patient quality of life [40].

Author's Preferred Treatment

In the light of these results, we propose a summary algorithm (Fig. 14.4), outlining the steps to be followed when early mechanical failure is suspected. In the event of abnormal lumbar or radicular pain, dynamic radiographs, a CT scan with fine bone sections and a routine biological work-up should be performed systematically. If screw loosening is detected, revision surgery may be necessary. Here, there are two possibilities, depending on the first operation:

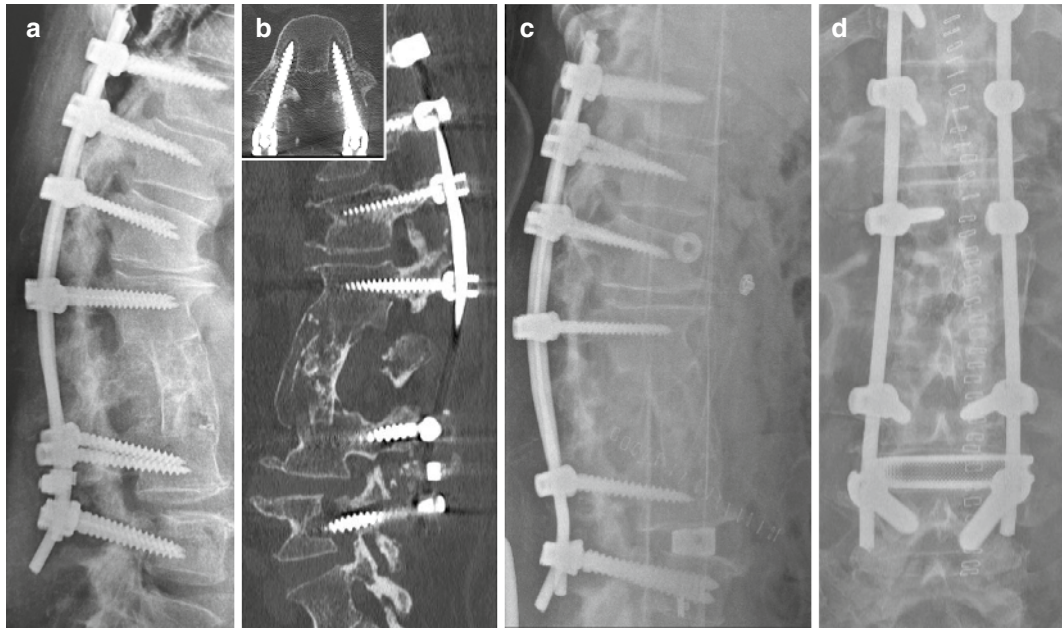

Fig. 14.3 Illustration case or early mechanical failure addressed with OLIF. (**a**) Early post-operative X-ray of a fusion extension in L4 due to ASD. We can guess the screw loosening around L4 screws. (**b**) CT scan confirms L4 screw loosening. (**c**, **d**) Hardware failure was addressed using OLIF cage and posterior revision with larger and longer screws

- If an interbody device was inserted during the initial surgery, simple posterior revision surgery may suffice, using larger screws, possibly cemented or with an alternative trajectory, depending on the quality of the pedicle bone. If the interbody device appears unstable, revision is warranted, using an anterior or lateral approach.
- If there was no interbody device at the time of the reference surgery, one needs to be added. Ideally, an anterior approach is used, respecting the segmental lumbar lordosis. A posterior revision should then take place, with the same considerations for widening, potential cementing or changing screw trajectory.

A bone graft must be added in both cases. Iliac crest autografting remains the gold standard, although in the event of harvesting limitations or insufficient quantity, the off-label use of BMP as a complement seems legitimate.

In both cases, given the high rates of septic etiology in mechanical failures reported in the literature, bacteriological samples and sonication of the explanted equipment should be systematically taken.

14.3.3 Infection

Surgical site infection (SSI) is the most frequent cause of 30 days reoperation (37% of reoperation cases within 30 days) [2]. It occurs generally around 16 days after index surgery. Risks factors of SSI in spinal procedures can be related to the patient: steroid use, diabetes, tobacco use, or related to the surgery: posterior approach, long construct, fusion to the sacrum [22].

Microorganisms commonly implicated are Staphylococcus aureus, coagulase-negative staphylococci in acute SSI, and Cutibacterium acnes, particularly in delayed or low-grade infections [41].

In those early SSI, the mechanism of contamination is a direct inoculation usually by fast-growing germs such as Staph aureus and Bacille

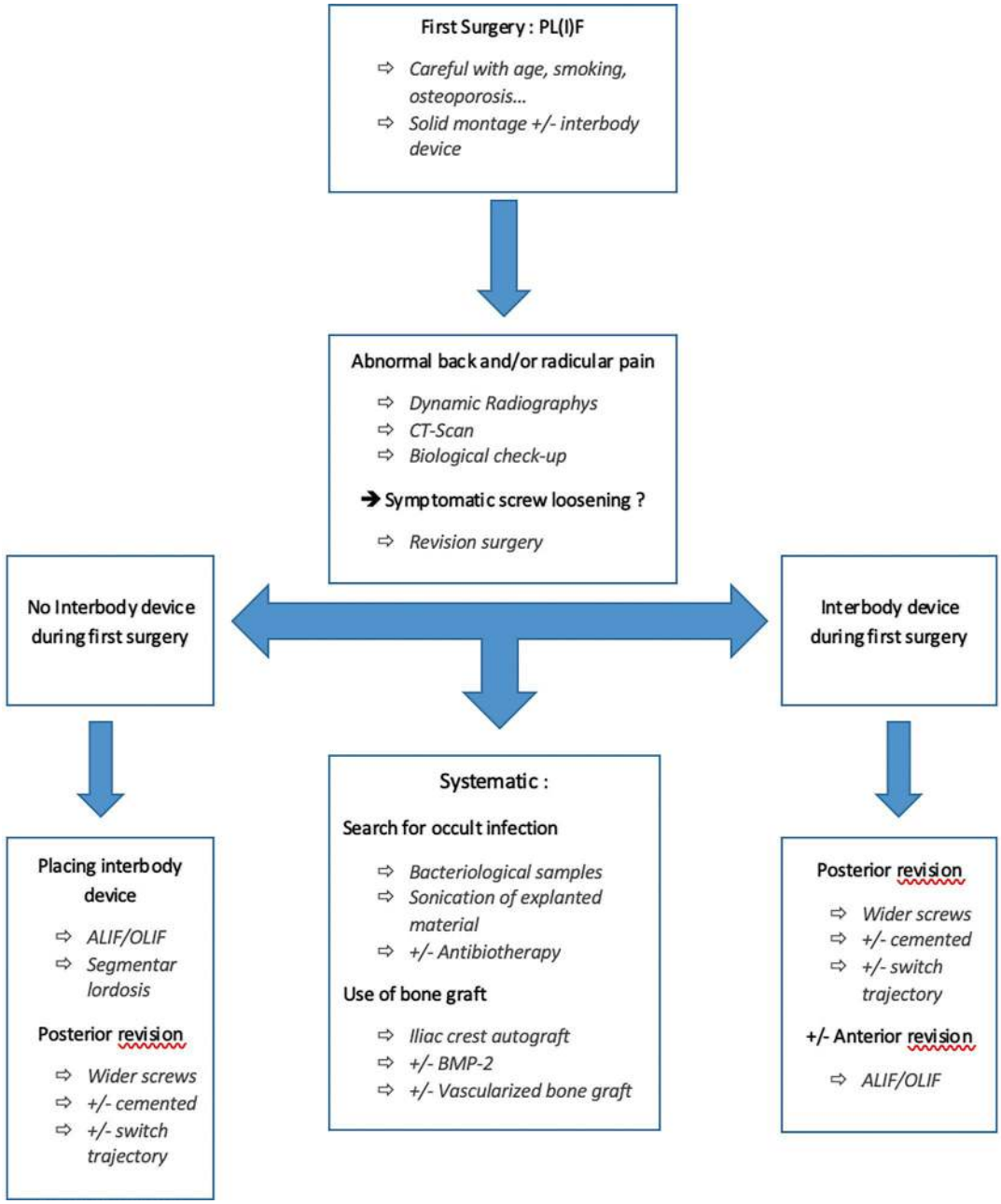

Fig. 14.4 Hardware failure revision algorithm

Gram Neg. Most of the time, the diagnosis is clinical with a wound discharge. Imaging assessment isn't always mandatory at the early phase. If needed (neurological symptoms, diagnostic doubt, fistula suspicion) MRI is the imaging modality of choice, particularly with contrast, to assess for phlegmon, abscess, or discitis. A CT scan can be useful if a hardware failure is suspected of in delayed infection cases. Superficial wound samples are not recommended [42].

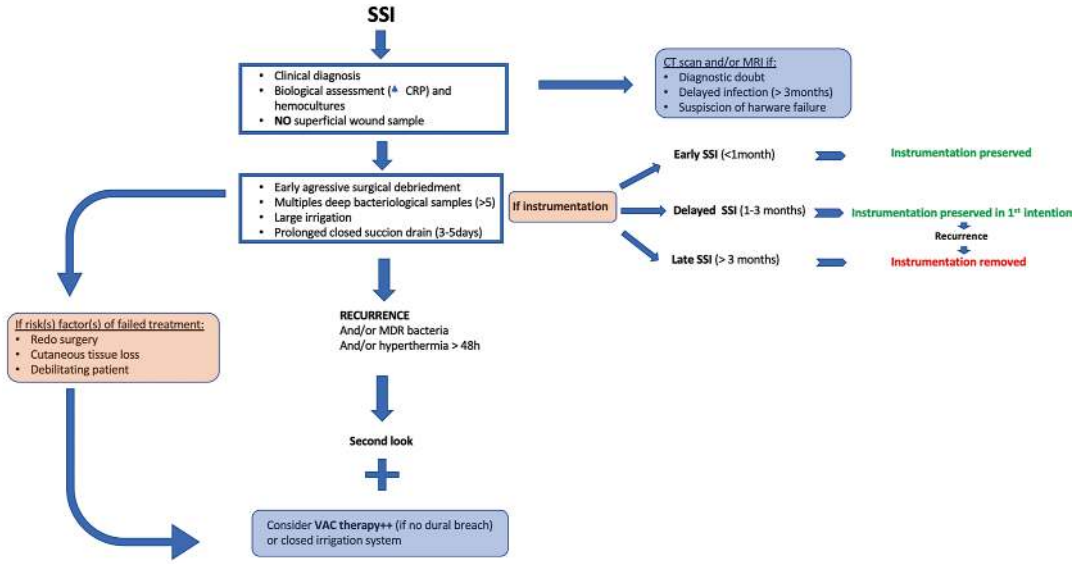

Fig. 14.5 Surgical site infection (SSI) revision algorithm

Revision Strategy

The revision surgery strategy must be early and aggressive as soon as the SSI is suspected. It involves an aggressive debridement and irrigation. Multiple deep bacteriological samples (>5) have to be performed [41, 43].

During the first revision surgery, if simple (no cutaneous tissue loss, not redo surgery, healthy patient), the surgical incision is thoroughly irrigated and then sutured with a Redon suction drain left in place for an extended period (3–5 days). If there is a recurrence of the SSI, a second-look surgery can be needed. In those recurrent SSI cases and/or in complex cases (cutaneous tissue loss, redo surgery, debilitated patient) a negative pressure wound therapy is a valuable option [44]. Obviously, a dural breach must have been ruled out before VAC installation. A closed-suction irrigation system (using one inflow tube and two outflows tubes) [45] is an alternative to VAC therapy. Both therapies have showed to be efficient in the management of deep SSI after lumbar instrumented spine surgeries.

If the SSI occurred on instrumented surgery, instrumentation should be preserved if it's an early infection (<1 month). In this case, a careful debridement and irrigation of the implants is recommended [24]. Contrarily, if it's a late infection (>3 months), instrumentation has to be removed because the biofilm has probably contaminated the hardware [27]. Surgeons should be aware in deformity patients even if solid fusion is observed, removal of instrumentation is associated with significant loss of correction. There is no consensus about delayed SSI (1–3 months). Author preference goes to try to preserve the instrumentation in first intention regarding the potential morbidity of the material ablation.

Finally, a probabilist intravenous antibiotherapy is introduced: for non-instrumented surgeries, an association of Cefazoline (Daptomycine if allergy) and 3-day Gentamycine and for instrumented surgery an association of Tazocilline (Aztreonam if allergy) and Gentamycine are introduced waiting antibiogram. This treatment has to be prolonged (>6 weeks) and discussed with a multidisciplinary team.

Author's preferred treatment is detailed in the following algorithm (Fig. 14.5).

14.3.4 Cerebrospinal Fluid (CSF) Leaks

Cerebrospinal fluid fistula (CSF) leaks represent a significant and not uncommon complication

following lumbar spine surgery. Incidental durotomy occurs in approximately 1–20% of cases [46], depending on patient factors and surgical technique. Prompt diagnosis and appropriate management are critical to avoid persistent leakage, pseudomeningocele, infection, or neurological deterioration. The most frequent cause is an unintentional dural tear during decompression or instrumentation. Risk factors include revision surgery, older age, degenerative changes, ossification of the ligamentum flavum, and prior irradiation. Some intraoperative CSF leaks are directly visualized, while others may be occult and only suspected postoperatively due to positional headaches, clear drainage, or imaging findings.

Postoperative diagnosis relies on clinical observation of wound leakage, symptoms of intracranial hypotension, or imaging evidence of CSF collection. MRI is the modality of choice to detect pseudomeningocele or persistent leaks.

Revision Strategy

Intraoperative identification should be followed by immediate primary closure if feasible. A study showed twice the revision rate in absence of direct repair [47]. When direct closure is not feasible, sealants such as fibrin glue or polyethylene glycol-based products may be used as adjuncts, though they should not replace suture repair. However, the use of fibrin glue did not decrease the rate of persistent CSF leaks or improve clinical outcomes when compared to primary dural repair [48]. The use of bio-adhesive patch was reviewed in the Miscusi et al. article, highlighting their effectiveness in reducing postoperative leaks when used appropriately [49]. Our preference goes to those bio-adhesive non-suturable sealant patch like Tachosyl®. The classic surgical technique recommends applying the yellow face on the dural tear and then applying a humid compress for few minutes to ensure the adhesion of the patch (Fig. 14.6). After direct repair is complete, the surgeon can request anesthesia to elicit a Valsalva maneuver to test the integrity of the repair.

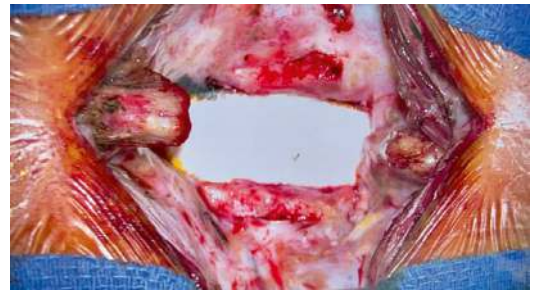

Fig. 14.6 Illustration of Tachosyl® patch. Yellow face is applied against the dura

Some authors recommend systematic use of subfascial drain with a mild pressure in order to avoid dead space and believe that the drain can promote wound healing by redirecting leaking CSF until the pressure difference normalizes. The drain is removed when the total output is less than 30 mL in a 24-hour period, which is typically around 5–7 days postoperatively. They did not find any correlation with postoperative complications and patients did not have different rates of persistent CSF leak after drain removal [46, 50]. We do not use it routinely because we believe it could major the CSF fistula.

Even if bed rest remains controversial and does not seem to reduce reoperation rate [51], we still recommend 24-hour bed rest as described by Albayar et al. [46].

For persistent leaks or in case of non-suturable tear, a paraspinal muscle flap using U-shaped stitches (Fig. 14.7) is a very effective option to achieve a dry wound [52, 53]. In cases of pseudomeningocele, careful dissection around the pseudomeningocele should be done to preserve the external capsule, which can be used as an extra layer of tissue to repair the durotomy. If non-effective, CSF diversion via lumbar drain may be considered. Drains should be maintained for 3–5 days (drainage of 10 cc/h) with bed rest to facilitate healing [46]. In cases of refractory fistulas despite those measures, a continuous CSF diversion via lumbo-peritoneal shunt can be considered [54].

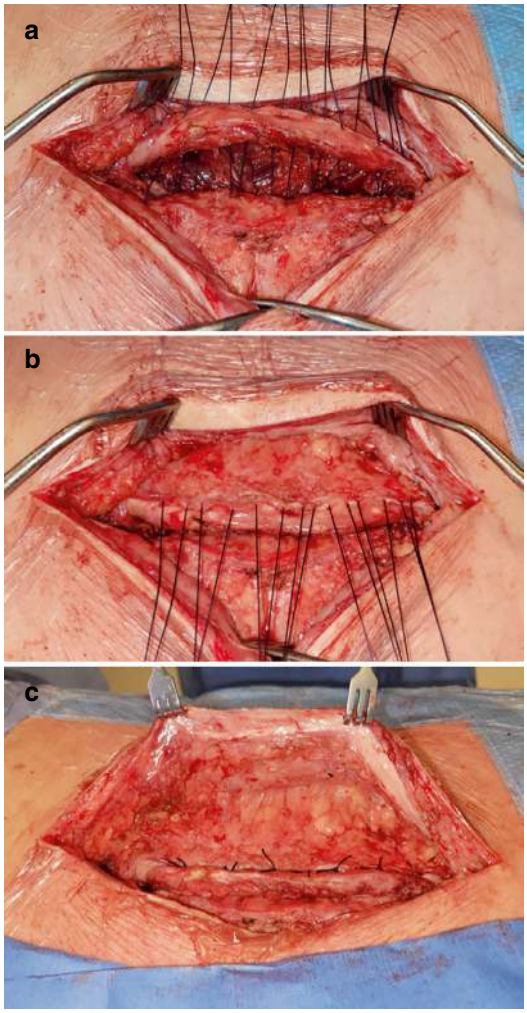

Fig. 14.7 Paraspinal muscle flap for persistent CSF leaks. (**a**) A cautious subcutaneous dissection is done to individualize the paraspinal flap. U-shaped stitches are done. (**b**) The flap is progressively closed by overlapping the two flaps. (**c**) Final closure of the flap ensuring a watertight closure. (Illustration from Dr. Ghassan Boubez (CHUM, Montreal))

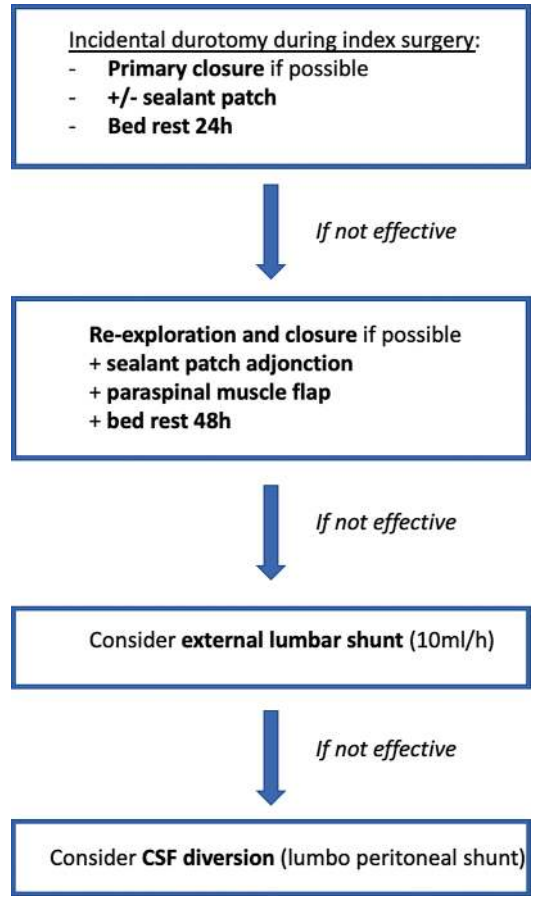

Fig. 14.8 CSF leaks revision algorithm

Based on Albayar review [46] and our institutional experience, we purposed an original treatment algorithm for CSF leaks (Fig. 14.8).

In summary, management of CSF leaks must be individualized. Prompt intraoperative repair is ideal. Sealants are useful adjuncts. Delayed cases may require more complex repair strategies such as paraspinal muscle flap repair. Multimodal postoperative management including positioning, drain placement, and infection prevention is essential. When appropriately performed, revision surgery for lumbar pseudo meningoceles achieves success rates exceeding 85% [46].

14.4 Late Revision

14.4.1 Adjacent Segment Disease (ASD)

Adjacent segment disease (ASD) refers to new degenerative changes at a spinal level adjacent to a previous fusion site that become symptomatic over time. It represents one of the most common

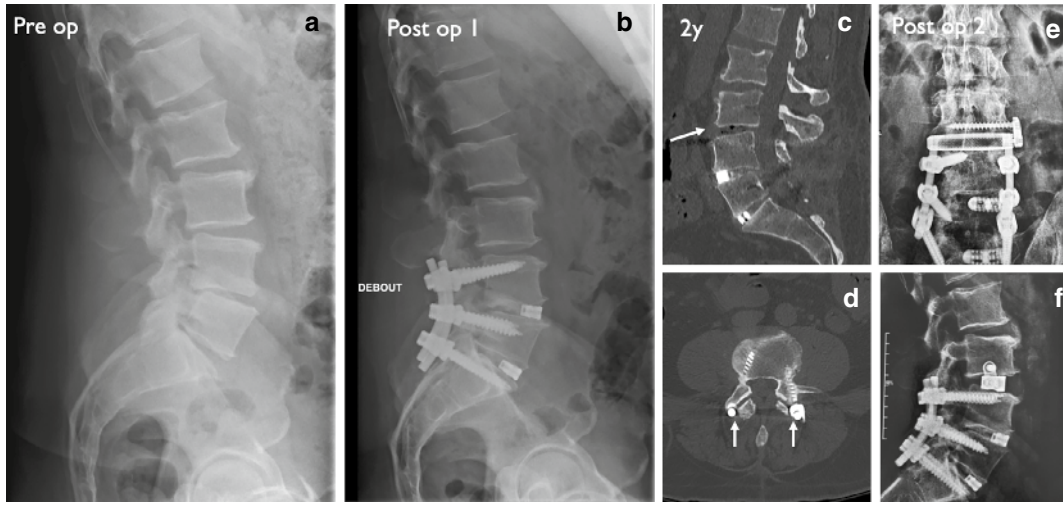

Fig. 14.9 Illustration case of stand-alone OLIF to treat lumbar ASD. (**a**) Pre-operative X-ray showing L4L5S1 degenerative disc disease and instability. (**b**) Post op 1 after 2 levels TLIF. (**c**) 2 years later, CT scan reveals severe L3L4 discopathy with retrolisthesis confirming ASD. (**d**) Axial CT scan showed a conflict between cranial screws and adjacent articular process, which can have led to ASD. (**e**) Post-operative AP X-ray showing L3L4 OLIF cage. We recommend long and large cage to ensure stability of the stand-alone construct. (**f**) Post-operative lateral X-ray showing a good lordosis distribution

long-term complications of spinal fusion, with reported incidence rates ranging from 5% to 18% after 5–10 years [55–57].

ASD results from a complex interplay of biomechanical and anatomical factors. Fusion alters load distribution across the spine, increasing stress on the adjacent levels, especially in the presence of sagittal imbalance or inadequate lordosis restoration [58]. Other contributing factors include age-related degeneration, genetics, and the extent of fusion [59]. Facet violation at cranial level during index surgery is also a risk factor of future ASD [59].

Clinically, ASD may manifest as recurrent radiculopathy, neurogenic claudication, or axial low back pain. Diagnostic workup includes standing radiographs (to assess sagittal and coronal alignment), MRI (for neural compression), and CT (for bony anatomy). It is essential to differentiate ASD from adjacent segment degeneration (ASDeg), which refers to radiographic changes without clinical symptoms.

Revision Strategy

Surgical treatment is reserved for symptomatic patients with failure of conservative management. Revision strategies depend on the type and location of the pathology:

- *Decompression alone* may be considered for isolated stenosis without instability. Minimally invasive or endoscopic procedures are favored [56].
- *Extension of fusion* is the most common approach, especially in cases of instability, listhesis, or recurrent disc herniation.
- *The choice of approach*—posterior, anterior (ALIF), or lateral (LLIF/OLIF)—depends on anatomical factors, number of levels, prior instrumentation, and sagittal alignment needs. Lateral approach has shown good clinical and radiological outcomes in ASD revisions (Fig. 14.9) with lower complication rates in selected patients [57]. In this regard, biomechanical studies showed a significant reduction of ROM of LLIF construct as a treatment of ASD [60]. Anterior approaches also have the advantage to avoid scar tissues of posterior redo surgery which one leads to a significant higher complication rate such as dural tear and surgical site infection [55].

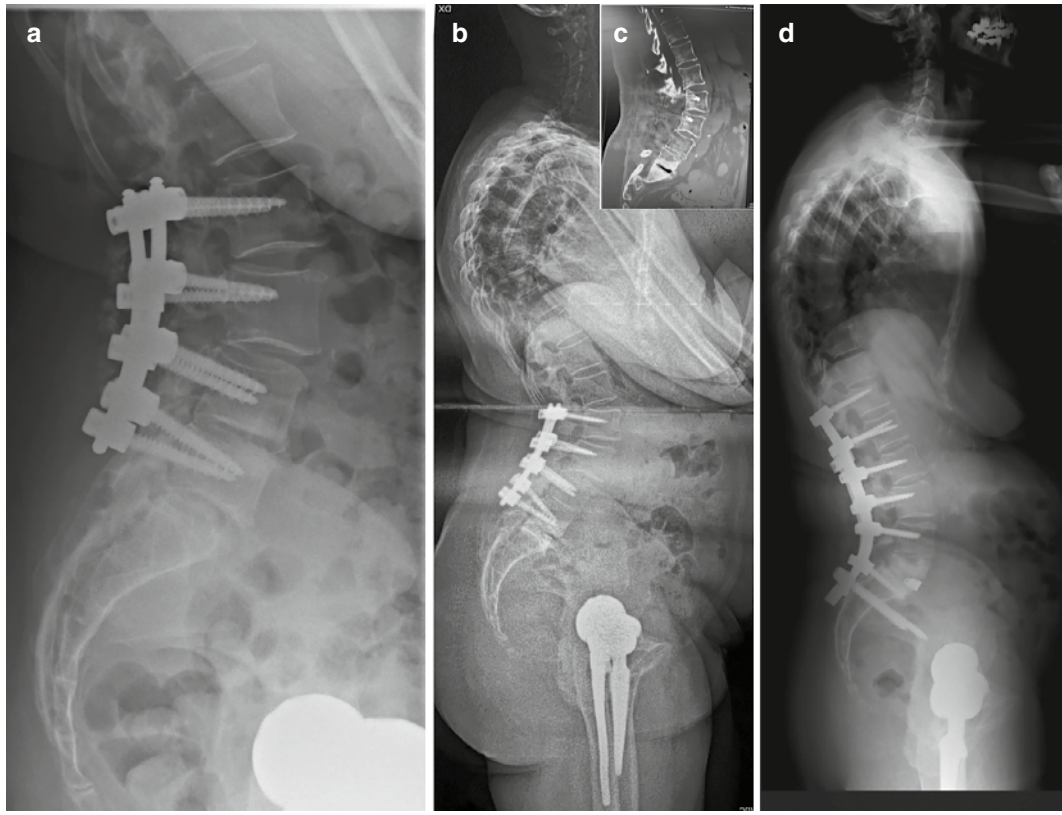

Fig. 14.10 Illustration case of lumbar ASD with sagittal imbalance treated with PSO. (**a**) Post-operative standard X-ray of L2L5 PLF. (**b**, **c**) 2 years post op imaging showing both cranial and caudal ASD with severe imbalance (L5S1 kyphosis and thoracolumbar hyperlordosis). (**d**) Patients were treated with L5 PSO, L5S1 TLIF cage and fusion extension

- *Restoration of global and segmental lordosis* is a key goal to prevent further adjacent degeneration [58]. Sagittal imbalance cases may require more aggressive approach with posterior osteotomies (Fig. 14.10).

Outcomes

ASD revision surgeries are generally effective in improving symptoms and quality of life. However, complication rates are higher than primary procedures [55]. Adogawa et al. reported significant improvements in ODI and VAS scores postoperatively, although the risk of further adjacent degeneration persists [61].

The decision-making process for symptomatic adjacent segment disease (ASD) can be guided by an evidence-based algorithm that incorporates patient-specific and anatomical criteria. The figure below illustrates a structured approach to surgical decision-making in ASD cases (Fig. 14.11).

Expanded Explanation of Algorithm

The proposed algorithm for symptomatic adjacent segment disease (ASD) emphasizes the critical role of sagittal alignment in surgical decision-making. If sagittal imbalance is present, it reflects a more global spinal malalignment that requires correction. In such cases, a posterior revision with pedicle subtraction osteotomy (PSO) is recommended. This complex osteotomy procedure provides powerful sagittal plane correction and is particularly indicated in fixed sagittal imbalance or flat-back syndrome resulting from prior instrumentation (Fig. 14.10).

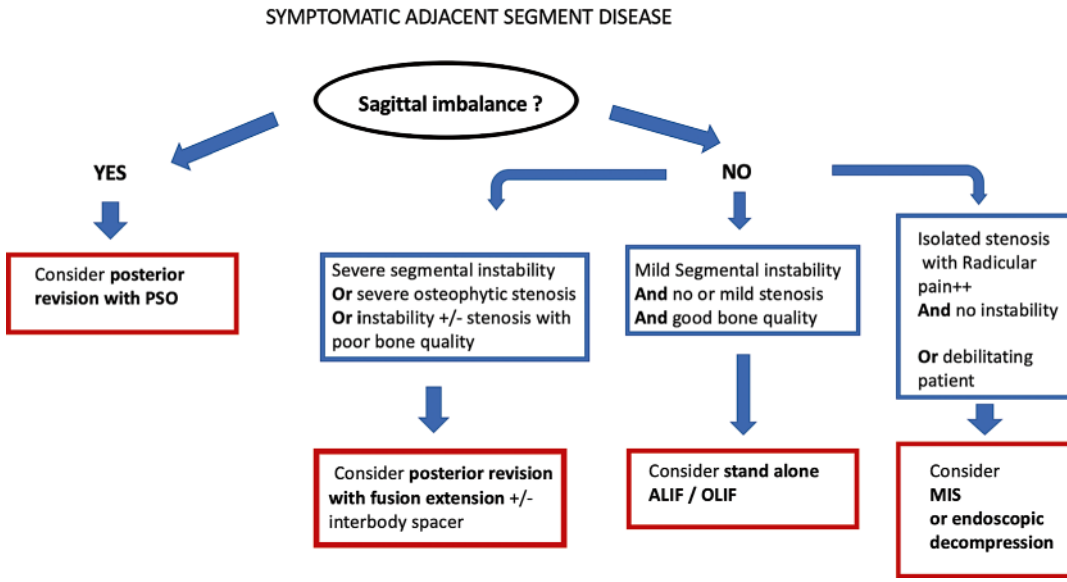

Fig. 14.11 ASD revision algorithm

In patients without sagittal imbalance, the approach is guided by the severity of segmental instability and stenosis, as well as bone quality:

- Severe segmental instability, severe osteophytic stenosis, or instability with poor bone quality warrants a posterior revision with fusion extension. In these cases, additional interbody support may be considered to optimize biomechanical stability and enhance fusion potential.
- Mild instability with good bone quality and no or mild stenosis may be addressed through a standalone ALIF or OLIF (Fig. 14.9). These anterior or lateral approaches restore disc height, indirectly decompress neural elements, and allow for lordosis restoration without posterior muscle trauma.
- In cases with isolated stenosis and predominant radicular pain without instability, or in elderly/debilitated patients with limited surgical tolerance, a minimally invasive decompression or full endoscopic decompression is a valuable option. These techniques minimize blood loss, tissue injury, and recovery time.

14.4.2 Pseudarthrosis

Pseudarthrosis, or non-union, is defined as the failure of bony fusion across a spinal segment intended for arthrodesis, generally evaluated after 6–12 months. It is one of the leading causes of late revision surgery following lumbar spine fusion and one of the most challenging revision surgeries due to technical aspect of revision and poor associate's clinical outcomes.

Multiple factors contribute to pseudarthrosis including patient-specific comorbidities (smoking, diabetes, obesity, osteoporosis), surgical technique, insufficient mechanical stability, and poor bone grafting. Long fusions, especially across the thoracolumbar junction or lumbosacral junction, are associated with a higher incidence [62]. Biological factors such as malnutrition, vitamin D deficiency, or immunosuppressive therapy may also impair osteogenesis [63, 64].

Diagnosis is based on clinical symptoms (persistent low back pain, recurrent radiculopathy, mechanical instability) and radiological findings. CT scanning remains the gold standard to evaluate the integrity of bony fusion [65]. Dynamic

X-rays may demonstrate motion at the fusion level, and SPECT-CT [66] or 18F-NaF PET-CT can offer increased sensitivity in selected cases.

Revision Strategy

When pseudarthrosis is symptomatic and confirmed radiologically, revision surgery is indicated. Key components of the revision strategy include accurate assessment of failure mode (mechanical vs. biological), mechanical optimization: reinforcement or replacement of instrumentation, extension to stable segments, increased rod stiffness or diameter [67], and biological enhancement: use of autograft (iliac crest remains the gold standard), bone morphogenetic proteins (e.g., rhBMP-2) [36], and osteoconductive substitutes.

Surgical Approach

- *Posterior-only approach*: allows for instrumentation revision, decortication, and new grafting. Ideal in cases with acceptable sagittal balance.
- *Anterior approaches (ALIF/OLIF)* are a preferred approach to address a posterior fusion pseudarthrosis (Fig. 14.12). It allows a safe corridor to remove posterior cages and to practice a meticulous bone preparation. The larger surface of anterior cage also provides better anterior column support and allows a greater quantity of bone grafting. For example, failed TLIF cages may be removed via anterior or lateral approach and replaced with larger ALIF or LLIF devices [14, 68].
- *Combined anterior-posterior approaches (e.g., ALIF + posterior fixation)* are indicated when anterior support is deficient, in complex deformity cases and when there is a failure of the posterior instrumentation.
- *Surgical planning should also consider sagittal balance*, especially in long-segment fusions. Techniques such as pedicle subtraction osteotomies and anterior column support (e.g., interbody grafts) can correct sagittal imbalance, which is a risk factor for construct failure. When pseudarthrosis is associated with sagittal malalignment, revision should address both the nonunion and the deformity [67].

In any case, host site optimization is essential: meticulous decortication, preparation of the endplates, and removal of all fibrous tissue are essential to promote fusion. Systematic bacteriological sample is mandatory due to the high rate of nonvirulent germ (C Acnes and Staph coagulase negative) found in pseudarthrosis revision cases. In a recent article, occult infections were found in 10% of patients undergoing pseudarthrosis revision after spinal fusion, even without preoperative clinical suspicion [23]. Finally, the choice of bone grafting is crucial: iliac crest bone remains the gold standard whereas Rh-BMP2 provides better fusion rates despite its higher cost. A recent systematic review noted a 92% fusion rate using Rh-BMP2 used specifically for revision surgery secondary to pseudarthrosis without increasing the complication rate [36].

Outcomes

In 2011, Adogawa et al. found that the mean duration time between index surgery and symptomatic pseudarthrosis was almost 2.5 years. A significant improvement of VAS lumbar pain (7 vs 5) and ODI (29 vs 25) was observed after revision for symptomatic nonunion whereas mental scores (SF12) were not. In the same study, all patients experienced fusion 2 years after revision surgery [40]. However, this clinical improvement is less significant in pseudarthrosis revision than in ASD or recurrent stenosis revision [61]. Derman et al. revealed that persistent pseudarthrosis after revision of posterolateral fusion can occur at rates of 35 to 51%. ALIF revision provides good fusion rates but no significant difference has been demonstrated in rates of successful fusion ALIF versus ALIF with revision posterolateral fusion for pseudarthroses after failed TLIF procedures (81% versus 88%) [14].

Although revision surgery for pseudarthrosis is technically demanding and associated with higher complication rates, satisfactory outcomes can be achieved. Fusion rates after revision can exceed 80–90% with optimized mechanical and biological strategies.

Ultimately, individualized surgical planning incorporating biological, mechanical, and technical considerations remain the cornerstone of successful pseudarthrosis revision.

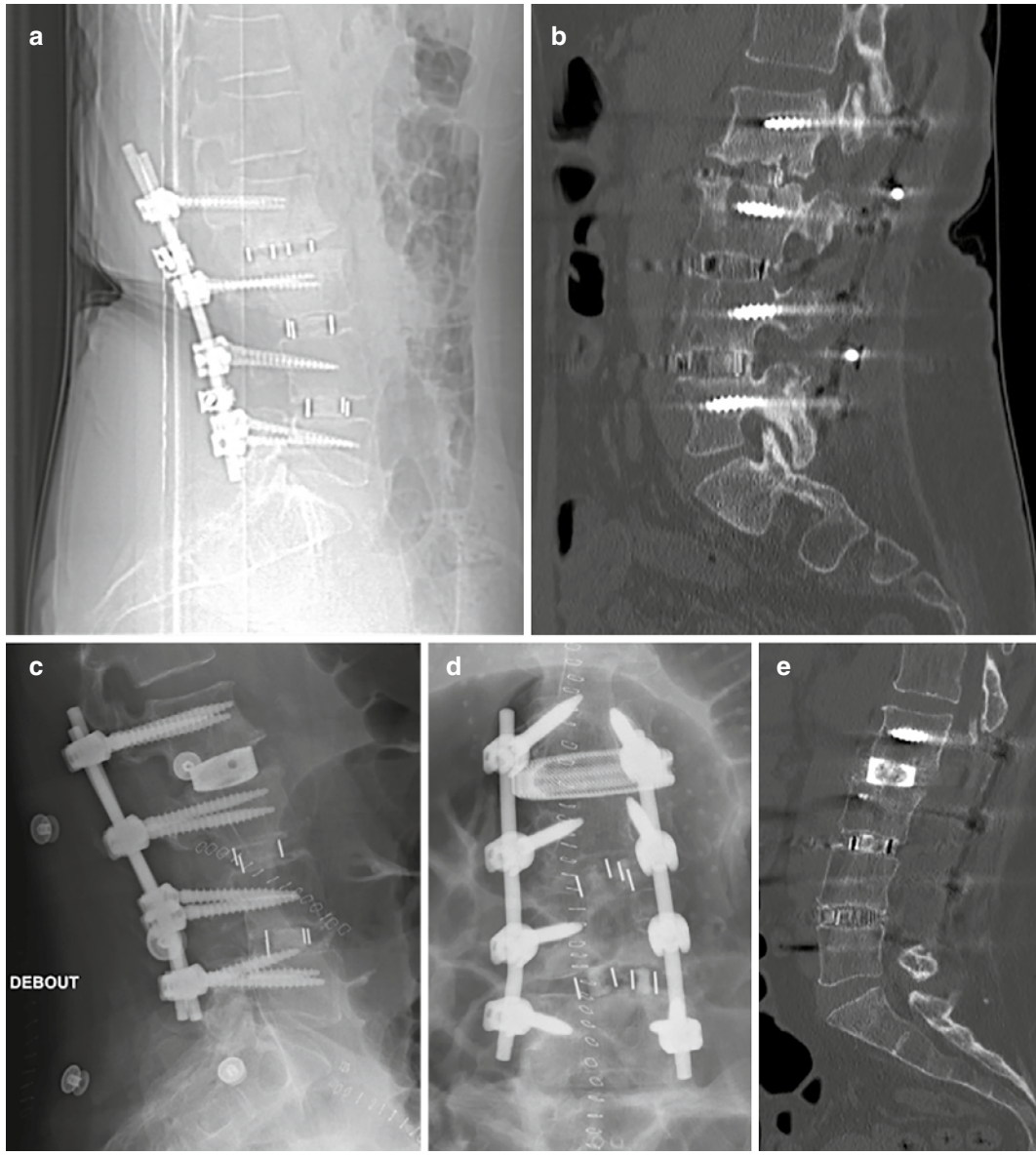

Fig. 14.12 Illustration case of lumbar pseudarthrosis treated with OLIF. (**a**, **b**) Imaging revealed the lack of bony bridges at L2L3 confirming the pseudarthrosis. (**c**, **d**) Post-operative standard X-ray. Lateral approach allowed to remove PLIF cage, excise the fibrosis tissue and place a large OLIF cage filled with rh-BMP2. This case also required a posterior revision. (**e**) 1-year post-operative CT scan confirmed bony fusion

14.4.3 Recurrent Lumbar Disc Herniation and Recurrent Stenosis

Recurrent lumbar disc herniation (rLDH) and recurrent lumbar spinal stenosis (rLSS) remain significant causes of morbidity after initial decompressive surgery. With reoperation rates reaching over 10%, it is imperative for spine surgeons to understand the pathophysiology and surgical options for these challenging conditions.

(i) Recurrent lumbar disc herniation

Large cohort studies report reoperation rates after single-level discectomy ranging from 3.95% at 3 months to 12.2% at 4 years [69]. Lumbar fusion is required in up to 5.9% of these cases, and 38.4% of patients re-operated for rLDH progress to fusion within 4 years. Leven et al. observed a reoperation rate of 15% over 8 years, primarily due to recurrent herniation (10%) [70].

General risk factors include smoking, obesity, and heavy labor. Specific anatomical factors such as disc protrusion (vs. sequestration), Bertolotti's syndrome (lumbosacral congenital fusion), and poor annular competence also contribute. Older age and asymmetric motor weakness at baseline are associated with a lower risk of recurrence [70]. Meta-analyses [71, 72] show that aggressive discectomy (AD) reduces recurrence rates (mean 3.5%) compared to limited discectomy (LD) (mean 7%), albeit with more postoperative back pain.

MRI with gadolinium contrast remains the gold standard, helping distinguish recurrent herniation from epidural fibrosis. Additional investigations like discography and CT scan may be used in ambiguous cases.

Revision Strategy

Effective revision strategies must be tailored based on clinical presentation, radiological findings, patient comorbidities, and previous surgical technique:

- *Repeat discectomy* is appropriate in cases of localized re-herniation without instability. Minimally invasive tubular microdiscectomy offers comparable efficacy to open techniques with fewer complications [73]. Repeat discectomy shows satisfactory results in 75–90% of cases, especially if the recurrence occurs after a long pain-free interval [74]. In a recent multicenter French study [75], 150 patients undergoing either repeat discectomy (RD) or instrumented surgery (IS) were analyzed. Patient satisfaction and quality of life at 12 months were similar between groups. Decision-making integrates objective criteria (instability, sagittal imbalance) with patient preferences and surgeon expertise [75].
- *Posterior instrumented fusion* remains indicated when recurrent herniation is associated with mechanical instability, Modic 1 discopathy, or multiple recurrences. Effectively, repeat discectomy could be a viable option in case of first recurrence but a fusion is recommended since the second recurrence episode. Dower et al. [72] and Guan et al. [76] confirm similar clinical outcomes between discectomy and fusion, but fusion leads to lower re-recurrence rates at the cost of longer hospitalization and higher procedural expense.
- *Anterior approaches (ALIF/TDR)* can also be effective to treat recurrent disc herniation with mechanical instability, Modic 1 discopathy, or multiple recurrences. It takes advantage of virgin anterior corridor and provides excellent outcomes [77]. Total disc replacement (TDR) is also a valuable option [78] in selected patients (young patient, no instability, intact posterior articular process) and can lead to good outcomes even in recurrent disc herniation [79].

Emerging techniques such as endoscopic approaches are under evaluation. These offer reduced tissue disruption, faster recovery, and potentially lower recurrence, although high-level comparative trials are still lacking [73]

(ii) Recurrent stenosis

Reoperation for rLSS at the same level occurs in approximately 10–20% of cases within 5–8 years post-decompression [80]. Revision surgery is evenly distributed across early (<1 year), mid (1–3 years), and late (3–5 years) phases. Bone regrowth (laminar or facet hypertrophy) is the main pathophysiological mechanism. According to Postacchini [81] and Chen [82], regrowth is classified into:

- Group 0: <10%
- Group 1: 11–40%
- Group 2: 41–70%
- Group 3: >70%

X-rays tend to overestimate regrowth compared to CT [83]. Most regrowth is located at the facet joints and correlates with recurrence and clinical deterioration. Le Huec et al. [4] emphasize the importance of global balance analysis and dynamic imaging to identify junctional issues and instability.

Risks factors of bone regrowth are listed below [82]:

- Extensive decompression (e.g., recalibration)
- Instability
- Involvement of >3 levels
- Age >60 years
- Junctional degeneration or misalignment

Noted that minimally invasive decompressions are associated with lower recurrence rates (1.6% vs. 5.8%; [84]).

Revision Strategy

- *Repeat decompression alone* is indicated in selected patients without instability. Shabat et al. [80] showed significant improvement in EVA and Barthel Index among elderly patients.
- *Decompression with fusion*: Parker et al. [85] have shown that neural decompression with instrumented fusion provides sustained symptom relief, particularly when instability or sagittal misalignment is present. Le Huec et al. [4] emphasized the need to assess global spinal alignment, especially in patients previously operated with multilevel constructs.

Finally, revision surgery for recurrent stenosis provides a clinical benefit either with or without fusion but fusion allows larger decompression and less additional surgeries. Adogawa also found that clinical benefit is greater for recurrent stenosis than revision surgery for pseudarthrosis [61].

Table 14.1 Comparaison between rLDH and rLSS

Feature	Recurrent disc herniation (rLDH)	Recurrent lumbar stenosis (rLSS)
Incidence	3.95–12.2% after primary discectomy	~10–20% at same level within 5–8 years post-decompression
Timing of recurrence	Often within 4 years, variable depending on initial technique	Evenly distributed: early (<1 y), mid (1–3 y), late (3–5 y)
Risk factors	Smoking, obesity, disc protrusion, Bertolotti syndrome	Instability, multilevel decompression, age >60, junctional issues
Diagnostic tools	MRI with gadolinium, discography	CT scan, MRI, dynamic imaging, sagittal balance assessment
Pathophysiology	Reherniation through annular defect or unaddressed fragment	Bone regrowth (facet or laminar hypertrophy), instability
Preferred surgical strategies	Repeat discectomy (micro-invasive), fusion in selected cases	Repeat decompression, fusion when instability or malalignment is present
Fusion indications	Instability, Modic changes, multiple recurrences	Instability, sagittal imbalance, recurrent compression post-decompression
Minimally invasive role	Tubular microdiscectomy, endoscopic discectomy [73]	Unilateral laminotomy for bilateral decompression [84]
Clinical outcomes	Good with tailored strategy; fusion decreases re-recurrence risk	Favorable with appropriate decompression; fusion enhances durability
Key references	Heindel et al. [69], Leven et al. [70], Guan et al. [76], Côme et al. [75]	Postacchini et al. [81], Chen et al. [82], Le Huec et al. [4], Parker et al. [85]

Recurrent disc herniation and stenosis are common causes of failed back surgery. Proper patient selection, radiological assessment, and personalized surgical strategy are crucial. Micro-invasive re-discectomy and rehabilitation are recommended for isolated recurrences without instability. Instrumented fusion is preferred in cases with biomechanical compromise, multiple recurrences, or junctional failure. Comparison between rLDH and rLSS is summarized in Table 14.1.

14.5 Revision of Anterior Lumbar Surgery (ALIF/TDR)

Anterior lumbar approaches such as anterior lumbar interbody fusion (ALIF) and total disc replacement (TDR) have gained in popularity due to their ability to restore disc height, preserve motion (in the case of TDR), and achieve solid fusion (in the case of ALIF) while preserving posterior musculature. Their rise in popularity has been paralleled by an increase in complex revision cases. However, these procedures carry distinct risks and are associated with specific complications that may necessitate revision surgery. These are not mere repetitions of a primary gesture; they unfold within a profoundly altered anatomical landscape, shaped by retroperitoneal fibrosis, vascular adhesions, and the mechanical legacy of a first implant [86–88].

Failures following anterior lumbar procedures emerge from a variation of mechanical, infectious, or iatrogenic causes, each demanding its own management:

- *Pseudarthrosis*: In the context of ALIF, non-union may result from inadequate osteointegration or subtle cage migration, often compounded by host bone quality or suboptimal load distribution.
- *Implant malposition or migration* (Fig. 14.13): These insidious complications may culminate in radicular pain or biomechanical failure, undermining the primary surgical objectives [86, 88, 89].
- *Prosthetic wear or failure*: Debris-induced synovitis, polyethylene extrusion, or metallosis can engender a cascade of inflammatory reactions, often difficult to disentangle from mechanical sources of pain [86, 87]. Poor patient selection, improper implantation, and wrong sizing are the most common examples of surgical errors causing a higher risk of failure.
- *Persistent or recurrent pain*: A specter that haunts spinal surgery, it may stem from unrecognized facet degeneration, poor patient selection, or adjacent level pathology [90, 91].
- *Delayed infection*: Though rare, such infections pose a formidable challenge, requiring explantation, bacteriological samples and prolonged antimicrobial therapy [92].

Revision Strategy

Prevention measures to avoid or facilitate an anterior revision include the choice of approach side for the index surgery: It might be to recommend that index surgeries at the L5–S1 level be done from the right side so the left-sided approach remains available for more proximal levels if they break down in the future.

Some authors also advocate the use of anti-adhesion barriers during the index procedure to facilitate future revisions—an ounce of prevention against a difficult reoperation [87].

Concerning surgical revision approach, there are two main strategies:

- *Posterior stabilization alone*: In select cases, where the anterior implant is well positioned but posterior elements have degenerated, a posterior fusion may suffice. This hybrid approach mitigates surgical trauma while addressing pain-generating structures [14, 17]. This is the safest approach.
- *Explantation of the anterior device and ALIF*: Reserved for cases of frank implant failure, infection, or mechanical instability, this

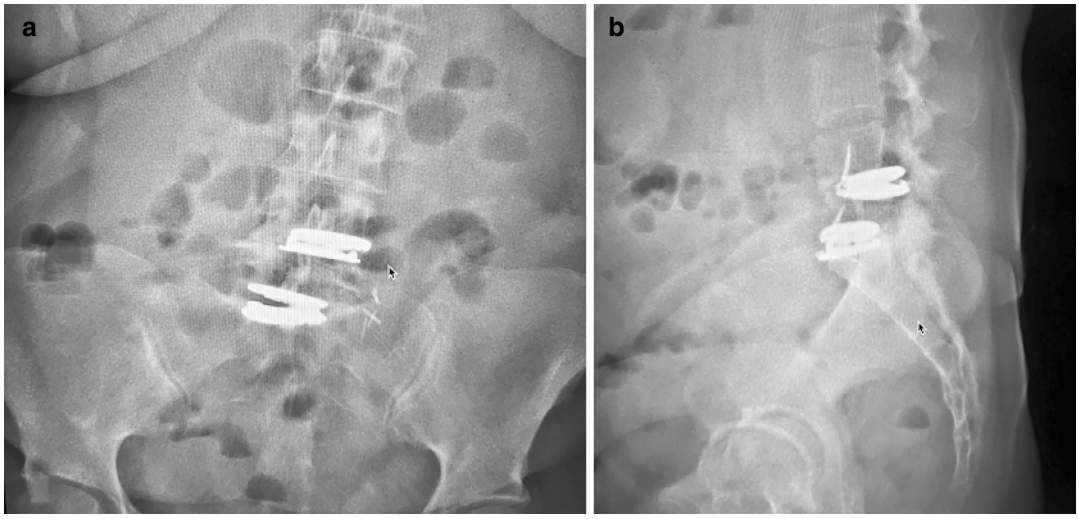

Fig. 14.13 Severe dislocation of multilevel TDR occurred 8 years after index surgery. Anterior revision surgery was the most valuable option in this case. (**a**) AP X-ray. (**b**) Lat X-ray

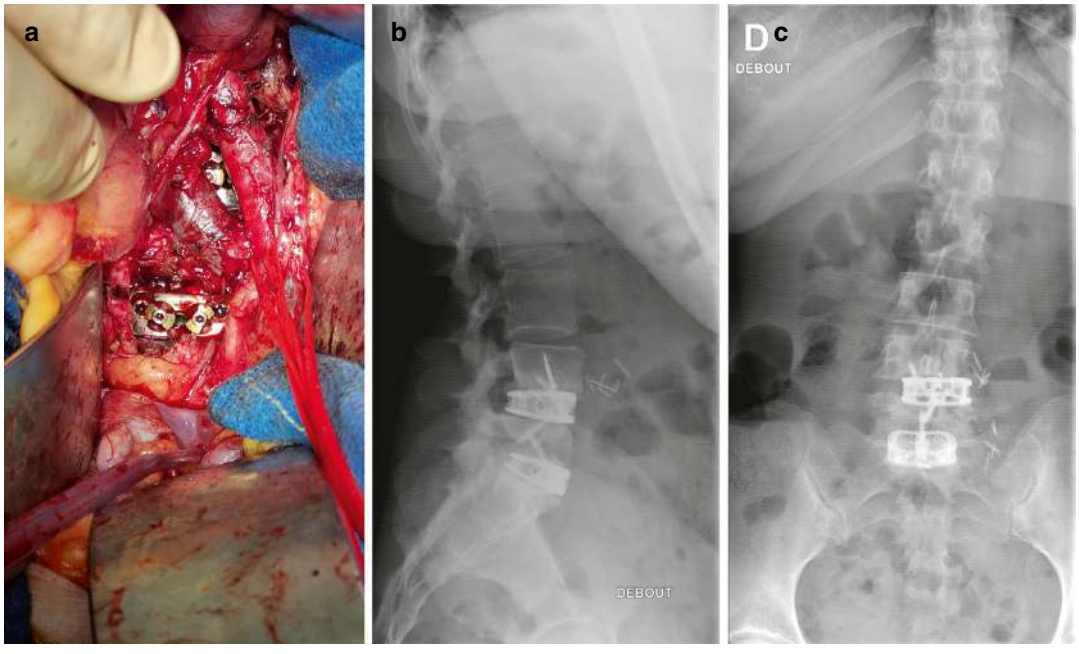

Fig. 14.14 From the previous illustrated case: TDR mobile-core design required cautious disassembly

approach restores anterior column integrity but is fraught with technical hazards [88, 89, 92]. Concerning TDR, mobile-core design may migrate anteriorly and explantation requires cautious disassembly (Fig. 14.14) whereas keel anchorage necessitates vertebral cuts with high removal morbidity [88].

Anterior revision has several specific potential complications including vascular adhesions (the iliac vessels may be adherent to the prosthesis, rendering their mobilization hazardous [87, 92]) which can lead to catastrophic bleeding or other specific complications such as ureteral injury, retrograde ejaculation, or bowel perforation—each

a dire possibility when dissection proceeds without anatomical clarity [87–89].

To mitigate these hazards, several precautionary measures should be taken. First of all, a careful planning is mandatory using CT angiography, helping to visualize the potential difficulties of great vessels dissection. Then, the intraoperative presence of a vascular surgeon is a necessity in complex cases. Preoperative ureteral stenting also helps to identify and protect the ureters during dissection [87]. The choice of surgical corridor is critical and must consider the timing since the index procedure and the level being addressed. If revision is performed within 2 weeks of the primary surgery, re-entry via the same retroperitoneal approach may be possible, particularly at L5–S1. However, beyond this window, scar formation and vascular fixation necessitate alternative strategies. For late revisions at L5–S1, a contralateral retroperitoneal approach is preferred. At levels L4–L5 or higher, a lateral transpsoas approach provides safer access, minimizing manipulation of tethered vascular structures [86]. The transperitoneal route, while feasible, is generally discouraged due to increased risk of visceral complications and retrograde ejaculation [88]. It has been estimated that the risk of retrograde ejaculation after anterior lumbar fusion is 1.7% with a retroperitoneal approach and as high as 17.5% with a transperitoneal approach [93]. In complex revision cases where anterior corridor is needed (L4–L5 revision, multilevel revision), transperitoneal route remains a good option, often preferred by vascular surgeons to control great vessels (Fig. 14.15).

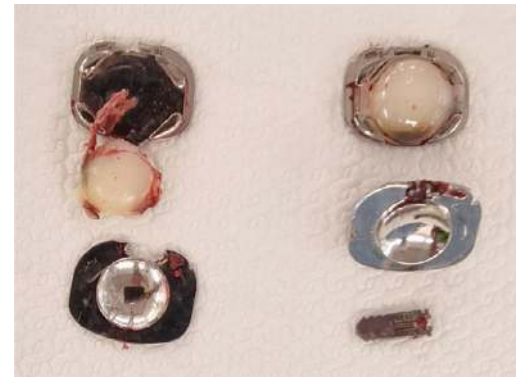

Fig. 14.15 Illustration of revision treatment for this severe TDR dislocation. (**a**) Transperitoneal approach with great vessels control performed by vascular surgeon. (**b**) Lateral X-ray showing satisfying correction with 2-level ALIF fitted with rh-BMP2. (**c**) AP X Ray showing satisfying correction of coronal malalignment

Outcomes of Anterior Lumbar Revision Surgery

Despite the strict selection of patients in the CHARITE study, 7.1% of TDR-implanted patients experienced a revision surgery. For Geisler et al., the revision surgery group did not show any clinical improvement after the secondary surgery [91]. Contrarily, in Kitzen et al.'s study, revision of a failed TDR either with posterior fusion or anterior revision was clinically beneficial in about half of the patients. Removal of the TDR was associated with a substantial intraoperative complication (63%) such as major vessel bleeding (12%) and ureteral lesion (4%), whereas complications were less significant in the posterior revision group (36%) [89].

Obviously, clinical outcomes of anterior revision surgery are strongly decreased compared to primary surgery. Posterior revision is often preferred because anterior redo carries a high intraoperative major complications, but in some complex cases such as migration, subsidence or infection, anterior revision is unfortunately mandatory. Those difficult cases are demanding a careful pre-op planning, ureteral stenting, and assistance of a vascular surgeon.

Based on literature review and institutional experience, we provide an algorithm proposition for anterior revision surgeries (Fig. 14.16).

14.6 Revision of Minimally and Endoscopic Lumbar Procedures

Minimally invasive spine surgery (MIS) and full endoscopic techniques have transformed the landscape of spinal surgery by offering less invasive alternatives to traditional open procedures. The benefits of these techniques—reduced tissue disruption, decreased blood loss, shorter hospital stays, and faster recovery—have led to their widespread adoption for lumbar discectomy and fusion. However, revision surgery in this context

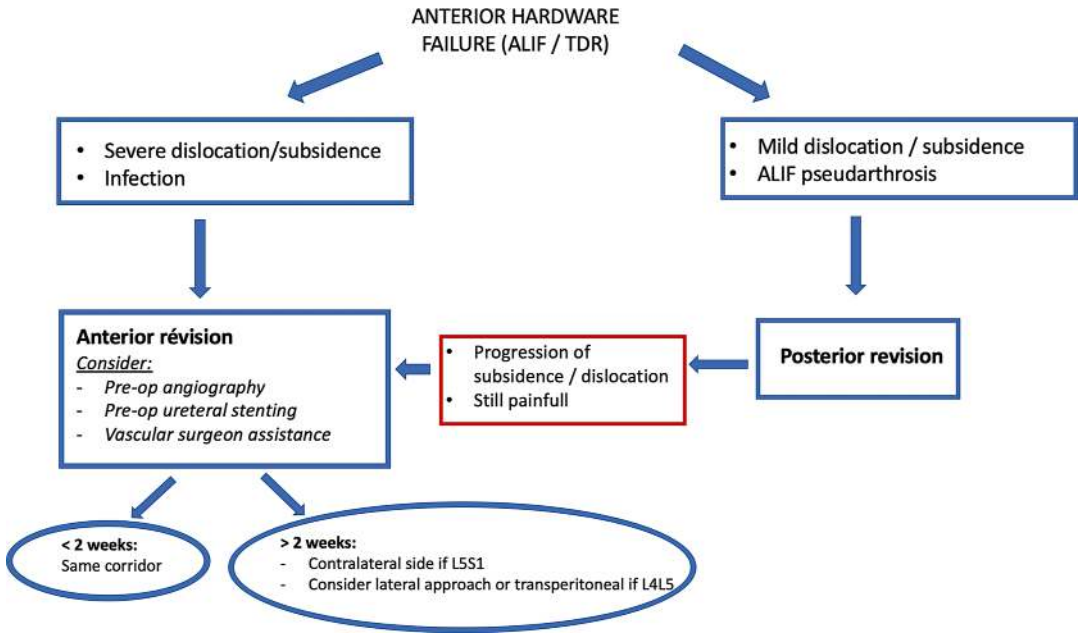

Fig. 14.16 Anterior revision surgery algorithm

presents unique challenges, given the limited operative corridors, altered tissue planes, and the presence of postoperative fibrosis. As in open surgery, MIS or endoscopic redo surgeries need a careful fibrosis dissection with the aim of recovering bony landmarks.

Reoperations following MIS or endoscopic procedures typically arise from:

- Recurrent disc herniation (at the same level and side).
- Residual or recurrent foraminal stenosis.
- Hardware-related complications (in the case of MIS-TLIF or instrumentation).
- Retropulsion of interbody cages.
- Pseudarthrosis or adjacent segment disease.

Revision Strategy in MIS-TLIF

The minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) approach, while highly effective in selected cases, may occasionally necessitate revision due to hematoma, fusion failure, cage migration, or neural compression.

Studying MIS TLIF revision, Hardy et al. found that revision surgery carried out by the same approach presented no significant technical difficulties requiring conversion to open surgery in almost all revision cases and gave satisfactory clinical results, with the disappearance of symptoms. Conversely, for cases of extensive epidural hematoma, particularly those extending beyond the initial limits of laminectomy, they recommend open surgery for complete evacuation. The key to the management of hematoma in MIS lumbar surgery is the access to MRI in an emergency. They also underlined the use of intraoperative navigation and CT guidance to significantly enhance safety in these revision procedures, particularly for re-implantation of malpositioned screws [94].

Similarly, Khechen et al. demonstrated that patients who undergo a primary decompression followed by a revision MIS TLIF do not experience differences in surgical or clinical outcomes as compared to patients undergoing primary MIS TLIF [95].

Revision Strategy in Endoscopy

Kang et al. [96] demonstrated that biportal endoscopic revision lumbar discectomy (BE-RLD)

yields comparable results to primary discectomy, with similar VAS and ODI score improvements and no increased complication rate. The technique allows for targeted decompression while preserving surrounding structures, an advantage especially important in patients with extensive epidural scarring.

Endoscopic can also be useful as a revision technique after fusion cases: McGrath et al. [97] offered a compelling case series of patients undergoing endoscopic foraminal decompression post-arthrodesis. Their indications included:

- Adjacent-level stenosis.
- Foraminal stenosis at the fused level.
- Displacement of interbody devices.

The study emphasized that endoscopic decompression in these cases led to substantial improvement in radicular symptoms without major complications. However, decompression of adjacent segments remains more technically demanding and may not prevent further degeneration.

14.7 Conclusion

Lumbar revision surgeries remain a main issue for spinal surgeons. They represent a technical challenge with a high complication rate. A carefully pre-op planning is highly recommended in order to reduce potentials intra or post-operative complications. On the other hand, patients should be aware that those revision surgeries provide less significant clinical outcomes than primary ones. Recent studies highlight the remarkable progress of artificial intelligence in advancing spinal patient care particularly in surgical planning and supporting clinical decision making [98]. Thus, in the aim to reduce post-operative complication and thereby reduce surgical revisions and their associate's morbidity.

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15 Complications in Lumbar Spine Surgery

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15.1 Introduction

Lumbar spinal surgery is responsible for a significant number of complications whose consequences, especially functional and painful may be the beginning of a long way to cross for the patient and his surgeon. Knowing these complications is essential to prevent them and inform the patient prior to the procedure. As usual in surgery, two factors emerge: intrinsic to patients, corresponding to comorbidities, and extrinsic, corresponding to types of lumbar surgeries. Unsurprisingly, many comorbidities (diabetes mellitus, obesity…) and/or complex surgeries (number of levels fused…) and their consequences (operative time, intraoperative blood loss…) are the providers of high incidence rates of complications [1–4]. Comparisons between different surgical options [5–11] are often of little value due to methodological weaknesses, but they do provide trends that should be the starting point for prospective studies with representative studied samples.

In this chapter, we will limit ourselves to perioperative and early postoperative complications. A systematic review was performed by using the PubMed database from inception to 2024. Overall, while there is a wealth of literature, there are few prospective articles with a high level of evidence. Furthermore, there is no consensus for management of many subjects. The following points will be developed: infection, dural tears, postoperative spinal epidural hematoma, neurologic complications, vascular complications, venous thromboembolism events, urinary complications, and four focused risk factors (obesity, diabetes mellitus, smoking, octogenarians).

15.2 Infection

The incidence rates of surgical site infection (SSI) after an open lumbar surgery are between 0.65% and 11.9% [12–22], whereas it is less than 1% after MIS [23–25]. In a retrospective review of a prospectively collected database, Mueller et al. [24] found a significative difference between MIS and open surgery (0.5% vs 3.3%, $p = 0.0003$), and more particularly after decompression isolated. Moreover, Ogihara et al. [25] demonstrated that endoscopic tubular surgery was a significant protective factor in a prospective multicenter study. The risk factors usually identified are obesity, diabetes mellitus, ASA ≥3, prolonged operative time ≥3 hours, and multiple fusion segments, but many others were described inconsistently [12, 16, 17, 19–21, 25–28]. In addition, malnutrition with decreased pre- and post-operative serum albumin is an underestimated risk factor [29, 30]. In this sense, He et al.

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[30] proved that a preoperative serum albumin <3.5 g/dl was significantly correlated to surgical wound dehiscence and SSI. Logically, SSI after lumbar surgery is associated with longer lengths of stay, higher mortality rates, and higher complication rates [14, 17, 21, 30].

The diagnosis of SSI after lumbar spine surgery must be suspected in two situations. The first occurs 1–4 weeks after surgery. The clinical signs and symptoms combine irregularly pain, fever, with local signs such as erythema, warmth, swelling, and wound drainage. The second is harder to diagnose, and occurs several months or even years after surgery, corresponding to a "low-noise" infection. In this delayed infection, the diagnosis is evoked by persistent pain. The dichotomy between superficial and deep infections is highly relative. True superficial infections are uncommon.

Biological markers are generally increased. In a retrospective cohort analysis, Pull ter Gunne et al. [31] observed an elevated c-reactive protein level in 98.0% but an elevated white blood cell count in only 48.6%. Moreover, the c-reactive protein level has a real interest to monitor the treatment of SSI.

MRI can help with diagnosis especially in delayed infections, but it is not absolutely necessary, particularly in acute infections, to look for epidural or paravertebral collection. CT scan is useful to assess the bone fusion after lumbar arthrodesis.

In SSI after spine surgery, Staphylococcus aureus and coagulase negative are the most common isolated organism in around 60–70% of cases. Less frequently, Gram negative bacteria and polymicrobial associations are found [13, 18, 31, 32]. Low virulence organism may be involved such as Cutibacterium acnes, more particularly in delayed infection after instrumented lumbar fusion [13].

The surgical treatment and antibiotic therapy are the mainstays of SSI after spine surgery, but there is no consensual strategy. We therefore recommend consulting an infectious disease specialist throughout the management process. This management complies with the guidelines of the French Society of Infectious Diseases (SPILF, Société de Pathologie Infectieuse de Langue Française) [33], and the steps are as follows:

- Five deep bacteriological samples with aero-anaerobic cultures for 14 days to guide antibiotic therapy.
- Intravenous probabilistic curative broad-spectrum antibiotic therapy active against Gram-positive cocci and Gram-negative bacilli.
- Surgical debridement of all necrotic tissue.
- Removal or not of instrumentation in accordance with the pre-operative strategy.
- Abundant serum irrigation of the surgical site.
- Replacement or not of instrumentation in accordance with the pre-operative strategy.
- Primary closure over one or two drains that are maintained for 2 days.
- According to the results of the pathogenic culture and bactericidal titers, intravenous antibiotics followed by oral antibiotics are administered for 6 weeks [34]. There is no consensus on how to administer antibiotics.

Retain or remove the instrumentation is controversial [13, 35–37]. But, as in orthopedic surgery, we recommend to retain the instrumentation before 1 month, and to remove or replace it after this delay, in view of the bacterial biofilm adhesion and to decrease loss of correction [38], and so whenever possible.

If there are clinical and biological signs of uncontrolled infection, further debridement and irrigation with new deep surgical samples are necessary. Delayed treatment, severe malnutrition and multiple comorbidities were the causes of ineffective treatment of the infection [32].

Delayed infection after interbody fusion is a complicated situation because of the need to remove the interbody cage due to the bacterial biofilm adhesion in a context of epidural and/or foraminal fibrosis. In a retrospective study dedicated to the management of delayed TLIF infection, Chang et al. [22] recommended a combined anterior and posterior, or a transforaminal approaches to remove the cage and obtain fusion in order to achieve better clinical outcomes. Finally, some authors [39, 40] preconized

continuous irrigation of the wound. In our experience, this is not always essential.

15.3 Dural Tears

In the literature, the lack of prospective and cohort matched controlled studies makes the data and results very heterogeneous. So, a rate of dural tears between 2% and 20% is usually retained! In a systematic literature review, Ghobrial et al. [41] reported a dural tear of 8.11%, with a higher rate in prospective versus retrospective studies (9.57% vs 4.32%, $p = 0.05$). Data on MIS and endoscopic surgery are just as heterogeneous, with the incidence of dural tears ranging from 0% to 8.6% [41–44]. Although significative lower rates seem to exist in MIS versus open surgery, this has not been demonstrated with studies showing contradictory results [41, 42].

The occurrence of an unintended durotomy is not a trivial event, and may lead to severe complications such as pseudomeningocele, cerebrospinal fluid leak, cerebral hemorrhage, wound disruption, SSI with meningitis, severe radiculopathy, sensory and motor deficits. Thus, in an observational cohort study employed American College of Surgeons National Surgical Quality Improvement Program dataset, Durand et al. [45] observed 0.2% of patients with late-presenting dural tear, which required one or more unplanned reoperations in 97.7%. Older age, lumbar posterior approach, bilateral decompression procedures and synovial cysts resection are the usual risk factors described in literature [43, 45, 46]. Dural tears increase significantly length of day, hospital costs and mortality [44, 46]. Finally, it is important to note that rare cases of complications of durotomy associating cerebral hemorrhage, hydrocephalus, and intraoperative cardiovascular dysfunctions during irrigating spinal endoscopy [47]. The authors hypothesize that the irrigation fluid introduced into the spinal canal and the dural sac migrates towards the brain, and the association of irrigation-related extra- and intradural pressure equalization and high volume of irrigation should be responsible for severe intracerebral lesions.

There is no consensus on the ideal treatment of dural tear in open and endoscopic surgeries [44, 48]. Many options were described and include no repair, primary or delayed repair, with or without sealants and with or without spinal drainage. However, in a cohort study from institutional database, Woodroffe et al. [44] observed that the absence of primary repair leads to a non-negligible risk of reoperation (39.5%) in open surgery. Thus, they recommended performing primary repair of the leak, using fibrin sealant with consideration of drain, whenever possible.

15.4 Postoperative Spinal Epidural Hematoma

Symptomatic postoperative spinal epidural hematoma (PSEH) is a rare but serious complication after lumbar spine surgery, responsible for neurological disorders related to the compression of nerve structures. The incidence rates of PSEH are between 0% and 0.85% [49–53], depending on the type of open lumbar surgery. Thus, Aono et al. [52] observed incidence rates of 0%, 0.50%, and 0.67%, respectively after standard lumbar discectomy, lumbar laminectomy, and posterior lumbar interbody fusion. Regarding MIS and more particularly biportal endoscopic spine surgery, there seems to be a higher frequency of PSEH [54–56], with incidence rates four to five times higher than conventional decompression lumbar surgery. Some authors [56–58] recommended to use thrombin-containing local hemostatics to decrease the occurrence rate of PSEH after biportal endoscopic spine surgery.

The risk factors usually identified are anticoagulation, abnormal coagulation, multilevel surgery and elevated blood pressure; many others were described inconsistently [49, 51, 59, 60]. Three risk factors are more specifically found after microendoscopic decompression: the level L2L3, multilevel surgery, and intraoperative water infusion pump [55, 61–63].

However, anticoagulation is a controversial risk factor. In retrospective studies, and systematic reviews and meta-analysis, several authors [50, 64–68] showed that there was no significative

relationship between the occurrence of PSEH and perioperative anticoagulation therapy or chemopreventing therapy. Concerning the use of antiplatelet therapy, despite the lack of a well-conducted prospective trial, several studies found no significant increase in blood loss, postoperative blood transfusion and complications, and PSEH in patients undergoing spinal surgery with continued aspirin administration [69–73].

Symptomatic PSEH usually occurs between 2.7 and 24 hours postoperatively, up to 2 weeks [53, 74]. Essentially clinical, the diagnosis is based on the occurrence of a gradual symptomatology. Patients initially describe severe and unusual back and radicular pain. Then there is sensory disturbance such as paresthesias, followed by motor deficits, before possible sphincter disorders. MRI is the baseline imaging to confirm the diagnosis. However, it is not absolutely necessary for diagnosis and should not delay emergency surgical management. It is also important to note that the rate of non-symptomatic hematoma is between 23% and 86% [75–77].

The treatment of PSEH consists in emergency surgical evacuation. The long-term neurological recovery is determined by two main factors: the degree of neurological deficit at the time of surgery, and the time between the first clinical signs and the surgical evacuation. It is therefore recommended to perform a surgical evacuation of PSEH within 12 hours of the onset of symptoms in order to hope for a complete recovery [78, 79].

15.5 Neurologic Complications

After lumbar spine surgery, iatrogenic neurological complications occur infrequently but cause significant functional sequelae. These postoperative complications include radiculopathy, motor and sensitive deficits, cauda equina syndrome, and spinal cord compression. In a review of literature, Ghobrial et al. [80] reported incidence rates of postoperative neurologic deficit of 5.7% (range 0.46–17%), and neurologic complications of 9% (range 0.46–24%). These rates seem to be higher after adult spinal deformity surgery. Smith et al. [81] collected incidence rates of 9.8% respectively for radiculopathy and motor deficit after 3-column osteotomies, while the International Spine Study Group [82] found a 13.7% incidence of neurologic complications after adult spinal deformity surgery, with increased risks for revision cases and interbody fusion.

15.6 Vascular Complications

In posterior lumbar surgery, a vascular complication should be suspected in case of circulatory instability and/or shock in the operative time, and in the presence of an arteriovenous fistula or a pseudoaneurysm at a distance from the intervention. Treatment consists of suturing the injured vessel in supine position. The vascular complications are extremely rare in posterior lumbar surgery. In a literature review, Papadoulas et al. [83] established an incidence ranged from 1 to 5 in 10,000 lumbar disc surgeries.

In anterior lumbar surgery, the situation is naturally slightly different, but this complication remains relatively rare. Limiting the study of the literature to ALIF alone, the incidence rates of vascular complications are between 1.3% and 7.2% [84–94], most often between 1.9% and 2.79% if we consider the two most recent meta-analysis and systematic reviews [95, 96]. Lesions are most often venous, and mainly affect the left common iliac vein [84, 87, 89, 94, 97].

15.7 Venous Thromboembolism Events

The venous thromboembolism events (VTE) are a classic postoperative complication after lumbar spine surgery, but several questions remain unanswered due to the lack of randomized controlled trials to assess the frequency, the risks and benefits of preventive therapeutic strategy. The incidence rates of VTE are heterogenous between 0.29% and 12.5% [98–106], varying according to the kind of studies (retrospective/prospective), the method of diagnosis, surgeries and population studied. Many studies described very

variable risk factors, but only age, obesity, neurological deficits, extended and anterior lumbar surgeries are regularly reported [100–105, 107, 108].

How effective is the chemoprophylaxis in preventing VTE? In retrospective studies, several authors [98, 99, 107] observed no significant relationship between low-molecular-weight heparin (LMWH) use and the occurrence of VTE, while others [68, 109] found a significative decrease of VTE, especially for lumbar fusion [109]. Moreover, Cloney et al. [110] showed a linear increase in the cumulative incidence of VTE within the first 2 weeks after spine surgery. Other than an author [107], and as we have previously written, several studies [50, 64–68, 106] reported that chemoprophylaxis was not associated with increased rates of PSEH, blood transfusion, hemorrhage, complications, and reoperations. Finally, because of the nonsignificant protective effect of chemoprophylaxis, some authors [99] recommend using mechanical prophylaxis.

15.8 Urinary Complications

In a retrospective review of prospectively collected data [111], the incidence rate of urinary tract infection (UTI) after spine surgery was established at 0.88%. UTI was significantly associated with sepsis and correlated with longer operative time, fusion, posterior, and lumbar procedures. Moreover, using data from the American College of Surgeons National Surgical Quality Improvement Program, Yoon et al. [112] studied patients with preoperative UTI in spine surgery. The authors identified higher rates of infections and complications, return to operative room and unplanned readmissions, and recommended to delay or cancel surgery for patients with preoperative UTI to reduce adverse outcomes.

The incidence rate of postoperative urinary retention (POUR) in the literature of posterior lumbar surgery is very heterogenous, between 5.6% and 38% [113, 114]. So, in a retrospective consecutive cohort analysis of posterior lumbar decompression with or without fusion for lumbar stenosis, Golubovsky et al. [113] reported an incidence rate of POUR of 17.1%. POUR was correlated with age and benign prostatic hyperplasia, and less regularly with male sex, previous acute kidney injury and UTI, diabetes, and depression [113, 114]. POUR was associated with longer length of stay (LOS), and not systematically with UTI, sepsis, risk of readmission within 90-d after surgery [113, 114].

15.9 Risk Factors of Lumbar Spine Surgery Complications

15.9.1 Obesity

Obesity is defined by a body mass index (BMI) of $\geq$30 kg/m^2. In the obese population, many studies [27, 28, 115–122] demonstrated higher complication rates (medical and surgical like wound and SSI), higher length of stay, blood loss, longer operative time in posterior lumbar surgery and more significatively in posterior fusion. If some authors [116, 117, 119] described equivalent clinical outcome, studies issued of postoperative data from the National Swedish Quality Registry for Spine Surgery [121, 123, 124] demonstrated lower satisfaction rate in patients after decompression for central lumbar stenosis, but not after lumbar discectomy. Moreover, in comparative study from Spine Patient Outcomes Research Trial for the treatment of lumbar disc herniation [125], obese patients had less clinical benefit from both operative and nonoperative treatment of lumbar disc herniation without any benefit for surgery treatment in obese and nonobese patients.

Poorer outcomes in obese and morbidly obese (BMI of >40 kg/m^2) patients were also found after posterior lumbar MIS compared with nonobese patients [126, 127]. As in open posterior lumbar surgery, the obese and morbidly obese patients had higher operative time, length of stay, rate of complications, revision rate and readmissions after decompression with or without fusion posterior lumbar MIS [126–128]. However, in a study comparing posterior lumbar MIS versus open surgery, Caroll et al. [126]

described a reduction in blood loss, length of stay, operative time, and infections. But other authors [129] demonstrated no difference in complication rates between MIS TLIF versus open TLIF after 2-y follow up (12.50% MIS/ 11.11% open).

Given that BMI does not reflect body mass distribution, Lee et al. [130] showed that thickness of subcutaneous fat (lesser or greater than 50 mm) was a better indicator than BMI to assess the risk of SSI after lumbar spine surgery.

Should bariatric surgery be proposed before posterior lumbar fusions? In a retrospective cohort study, Jain et al. [131] observed that patients who had undergone bariatric surgery had a lower rate of medical complications and infections than morbidly obese patients. But these patients had significantly higher rates of infections, reoperations, and readmission than nonobese patients.

15.9.2 Diabetes Mellitus

Diabetes mellitus (DM) is found to be an independent and strong risk factors for SSI and other complications after lumbar surgery [17, 19–21, 26, 132–134]. In retrospective studies issued of national databases, Zhuang et al. [133] and Guzman et al. [135] demonstrated higher medical complication rates in patients with uncontrolled DM undergoing degenerative lumbar spine surgery. Several authors [134, 136, 137] found that the preoperative hemoglobin A1c (HbAIc) value was significantly higher in patients who developed SSI after posterior degenerative lumbar surgeries with or without instrumentation. These results were more significative in patients with uncontrolled DM. Thus, in a retrospective study, Hara et al. [137] observed that SSI after posterior lumbar instrumentation surgery occurred in 1.9% in non-DM patients, 2.4% in low HbA1c (<7.0%) patients, and 9.3% in high HbA1c (≥7.0%) patients. According to these findings, some authors [134, 136] recommended to obtain an HbA1c of less than 7.0% before performing spinal surgery in order to limit the risk of SSI in DM patients.

15.9.3 Smoking

Many authors demonstrated significantly higher risk of pseudarthrosis for smokers compared with nonsmokers after posterior lumbar fusion [138–146], and after ALIF or LLIF [147–149]. Moreover, smokers exhibited worse outcome measurements after lumbar fusion surgery measured by Oswestry Disability Index (ODI), Visual Analogue Scale back and leg (VAS back and VAS leg) [150–153]. In a cohort study using the Swedish Spine Register, Sanden et al. [154] found less improvement after surgical treatment for lumbar stenosis surgery in smokers versus nonsmokers: inferior quality of life (ODI, SF 36, EuroOol EQ5D), less wellbeing, and more regular use of analgesics. In view of these findings, it is advisable to stop smoking before and after lumbar spine surgery, and within varying timeframes [138, 144].

15.9.4 Octogenarians

The morbidity and mortality of degenerative lumbar spine surgery in patients 80 years of age or older was significantly higher. In a comparative retrospective cohort based on a multicenter surgical database from the American College of Surgeons National Surgical Quality Improvement Program, Prabhu et al. [155] demonstrated significantly higher postoperative complications in patients who underwent simple-level lumbar disc surgery, regarding pulmonary embolism, transfusion requirement, UIT, and 30-d mortality. Likewise, other authors in retrospective studies [156, 157] concluded that there were higher complications rates but with an acceptable incidence in selected patients. Respectively, 22.5% mild to moderate intraoperative complications and 7% postoperative medical complications occurred after decompressive lumbar surgery without instrumentation [156]. Whereas 13% major complications and 29.7% minor complications occurred after decompressive lumbar surgery with or without fusion [157]. Longer operative time, instrumentation, number of levels, blood loss, and general comorbidities increased

significantly the morbidity and the mortality [157, 158]. In these fragile patients, these factors encourage limiting surgical burden, and so instrumentation performing.

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Surgical Strategies for Persistent Spinal Pain Syndrome

16

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Abbreviations

FBSS	Failed back surgery syndrome
HAS	Haute Autorite de Sante
IASP	International Association for the Study of Pain
LRPO	Postoperative low back pain
POPS	Post-operative persistant syndrome
PSPS	Persistent spinal pain syndrome
RF	Radiofrequency

Chronic postoperative low back pain, with or without radicular pain, is a worldwide spread problem, with an incidence of around 9.4% [1]. In 1995, the IASP [2] defined *failed back surgery syndrome* (FBSS) as pain of the lumbar spine of unknown origin, persisting despite surgical intervention, or occurring after spinal surgery at the same level.

- Once a patient has undergone spinal surgery, any lumbar pain is considered to be part of a syndrome labelled "postoperative lumboradiculalgia" (PLO), corresponding to the Anglo-Saxon FBSS, although it may be linked to another cause, independently from the initial mechanical problem. It is a dysfunction or even a failure, with the pain of surgery intertwined with psycho-social imbalance. P Rigoard [4] proposed post-operative persistent syndrome (POPS). However, these names suggest a *failure*: the surgeon and the patient are face to face.
- We need to identify a dysfunction arising from the interplay of pain, functional impairment, and psychosocial imbalance, following unsuccessful spinal surgery (whether due to a technical pitfall or disillusionment related to inadequate expectations).
- The persistence or recurrence of pain after spinal surgery ranges from 20% to 40% [5–7].

The term FBSS is misleading, ambiguous, imprecise, and pejorative. The consequence of using this term is that it can be interpreted as inadequate or poorly performed surgery, which is not the original intention and may generate

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medico-legal ambiguity. A group of experts uses the Delphi method to try to define a simple and appropriate terminology [8]. The mechanisms of this pain are multiple and complex, requiring consideration of the spine, discs, joints, and related pathologies. The nervous system, muscles, fascia, and complications of surgery also play a role in the genesis of pain, as well as the psycho-social factors. All these interconnected elements contribute, at different levels, to nociceptive and/or neuropathic pain. These different labels exclude cases where pre-existing pain is not resolved by surgery, nor do they account for recurrent pain after successful initial surgery. There is a range of similar pains with similar clinical pictures, whether caused by surgery or not. This group of experts proposes *Persistent spinal pain syndrome (PSPS)*. This term covers all the clinical manifestations of this chronic pain syndrome of spinal origin. The combination of the upright posture of Homo Sapiens and the anatomy of the spine, along with its associated structures at this stage of evolution, is predisposing to the development of a chronic pain syndrome. The term "*persistent*" is preferred to "chronic", since "chronic" includes a notion of time, whereas "persistent" refers to a previous situation that continues despite treatment, surgery, and aggravating circumstances (e.g., heavy work).

In France, the Haute Autorité de Santé (HAS) published in 2014: "Relevance of surgery for chronic low back pain in adults."

The HAS concludes from this literature review that "arthrodesis (without specifying the technique) is not superior to intensive rehabilitation and functional-cognitive management of pain." The SFCR (J Allain) issued a response letter, stating as follows:

"As spine surgeons, we are well aware of the influence of some of these parameters, and we know how to judge them in our surgical indications, so as to reserve them for the best cases." Finally, we repeat the text of the HAS document literally (summary, p. 8): "the comparison between surgical and non-surgical treatments is artificial, because in clinical practice, medical and surgical management are not competing treatments". Hence our duty today to carry out prospective studies with appropriate methodology, in close collaboration with scientific units, including a precise definition of the populations, an exhaustive description of the surgical techniques and the post-operative parameters obtained, in order to objectively determine the results of arthrodesis surgery for chronic low-back pain, which we believe remains an effective solution when its indications are well defined, and the surgical technique mastered.

For J. D. Koerner [9]: The results of surgery for discogenic pain are at best equivalent to a structured therapy program, which may be due to our inability to accurately differentiate a painful from a non-painful disc. There are both short and long-term follow-up results comparing lumbar fusion with non-operative management to treat chronic back pain. PSPS is a common condition and is often attributed to disc disease when no other cause can be identified. Despite the potential of certain emerging technologies, there is currently a lack of a precise diagnostic technique for identifying PSPS on the disc. This issue complicates treatment, leading to difficulties and frustration for both the medical practitioner and the patient. Many studies comparing lumbar spinal fusion with non-operative treatment of discogenic PSPS are flawed, and none has demonstrated a clinically significant advantage of surgery. Because of the inherent risks associated with surgery, a structured physiotherapy program should be the treatment of choice for discogenic PSPS for most patients.

The SFCR also published an update [10]: "Management of chronic lumbago: the value of a new classification based on the injury mechanism."

This new classification of chronic lower back pain is based on the presumed lesion mechanism of the pain, identifying 3 categories:

- Non-degenerative lower back pain (formerly known as symptomatic lower back pain) secondary to traumatic, tumoral, infectious, or inflammatory causes;
- Degenerative low-back pain (formerly known as common low-back pain) secondary to disc,

facet, ligament or mixed pathology, associated with a regional and/or global disorder of spinal statics (measurement of balance parameters);
- Low-back pain of psychogenic or undetermined origin, unrelated to anatomical lesions (psycho-social assessment using HAD and FABQ scores).

The aforementioned points emphasize the considerable difficulty of diagnosing and managing chronic low-back pain. In the interests of the patient, it is often useful to call on the expertise of the spinal pain team and to adopt a multidisciplinary approach. We will not go into the subject of medical treatment, which is always necessary. There are many surgical solutions, as well as neurostimulation options.

16.1 Surgical Management

Surgical management of a patient with a lumbar and/or radicular pain syndrome following lumbar spinal surgery requires a precise diagnosis. The diagnosis must logically explain the symptoms in terms of well-established pathophysiological mechanisms (such as herniated disc recurrence and sciatica, or Modic 1 disc disease and low-back pain). Nevertheless, the sometimes long and tedious pre-operative investigation, involving multiple examinations and consultations with fellow spine surgeons, rheumatologists, neurologists, functional rehabilitators, and pain medicine centers, is essential to make a decision tailored to each situation [7].

16.1.1 Questioning and Clinical Examination of Painful Surgical Patients [5]

In order to fully understand the situation, it is essential to submit a comprehensive list of questions both to the surgeon and the patient:

(a) Previous surgery(s):
- Was the operative indication justified for the previous surgery(s)?
- Was the type of performed procedure(s) appropriate for the patient's pathology?
- Were the procedure(s) performed appropriately?
- Were there any intra- or post-operative complications?
- Was the goal of the procedure achieved?

(b) Concerning the patient's reported symptoms [5]:
- Does the pain and/or disability presented by the patient appear to be consistent with the clinical examination and imaging data?
- Is the consultation part of a secondary benefit-seeking process (invalidity/disability card, repeated requests for time off work, reclassification, etc.)?
- Is it part of a dispute or even proceedings against the practitioner who performed the initial procedure?

Once we have ruled out situations that are not related to surgery, but rather to medical therapy, the history of symptoms should enlighten us as to the origin of the pain:
- Should they be exactly the same as before the operation, it is logical to conclude that there has been an error of indication (such as diabetic cruralgia or pseudosciatica due to coxarthrosis) or surgical technique (level error on a herniated disc).
- If the pain disappeared post-operatively and then reappeared rapidly, it may be due to an infection of the surgical site, a recurrence of the hernia, or even hematoma.
- If it disappeared post-operatively and then reappeared late, several diagnoses are classic: recurrence of hernia or lumbar stenosis, disc disease or even deformity-instability above arthrodesis.

Once the history determined, the features of pain should clarify and orient us. Of course, we need to differentiate between low-back pain and radicular irradiation in terms of the patient's disability. It is essential to determine the DN4 score when looking for neuropathic pain with radicular radiation. If the pain is totally different from the preoperative, and appears as soon as the patient wakes up, an intraoperative radicular lesion must be considered. This is

a highly probable scenario, particularly when no sensory and/or motor neurological deficit was observed before surgery. Although often less typical than in non-operated patients, the symptoms will present with classic features, such as intense pain in herniated discs, painful claudication in lumbar stenosis, or spinal instability. This will help us to decide whether or not to prescribe appropriate imaging to confirm our diagnostic hypotheses.

16.1.2 Radiological Exploration

A multitude of situations exist, each requiring a specific investigation. It is therefore essential to carry out a clinical "pre-diagnosis," in order to avoid an endless series of examinations.

(a) Patients for whom surgical management should be avoided, because of the risk of iterative failure or even successive worsening after each surgical attempt:
   - Patients who, following surgery, have never received appropriate medical treatment, such as low-back pain after discectomy without analgesic therapy, and who have never undergone RFR (Rééducation Fonctionnelle du Rachis: Functional Spine Training).
   - Patients clearly seeking secondary benefits, in conflict with their previous surgeon, and whose symptoms profile does not match with the pathology.
   - "Nothing works" patients, even major analgesics, anti-inflammatories, neurotropics, adapted rehabilitation supervised by multidisciplinary teams, infiltrations.

   It is pointless to start radiological investigations in this case and it is not the right way to "buy time" with a few tests, as in the very end we will have to explain to the patient that there is no indication for surgery in his case and that surgery will not improve his condition, despite the hopes he may hold in it. It is better to advise them to look for other solutions. This is no easy task, especially when the patient has already been treated by the pain medicine team. However, the wide range of therapies on offer (acupuncture, meditation, hypnosis, etc.) can give them a glimmer of hope and that is why it is important to know how to close the door on surgery.

   A special case is the appearance of a sensory-motor deficit due to intraoperative radicular lesions. In this case, we must inform the patient that there is no effective spinal surgical solution to improve his handicap.

(b) Patients in whom iterative medical or surgical management seems indicated, if imaging confirms a diagnostic hypothesis.

Radiological exploration is justified in this case, as the procedure may determine the exact nature of the spinal pathology, and it should match pain's features and nature. Instability following decompression should be detected on dynamic X-rays. Recurrence of a herniated disc is better observed by MRI with Gadolinium injection, to distinguish it from hypertrophic endocanal fibrosis. A recurrence of canal stenosis is most often visible on MRI, but in case of difficulties or positional stenosis, saccoradiculography can be very useful. The appearance of an isthmic fracture after decompression is ideally demonstrated by a CT scan in the bone window on sagittal reconstructions. Inflammatory posterior joint damage with hyperfixation on scintigraphy. Disc disease adjacent to disc arthroplasty requires MRI using the multiacquisition variable-resonance image combination protocol (mavric) to limit artifacts associated with metal implants. Intense hyperfixation on bone scans or PET scans can clarify doubts about pseudarthrosis.

16.1.3 Different Surgical Management Techniques for Lumbar and/or Radicular Pain Persisting After Lumbar Spinal Surgery [1, 8]

Neurostimulation must always be discussed in relation to conventional surgery.

A. *Pain associated with actual failure of the initial procedure*.

   To avoid trapping the patient in a post-operative state of distress, it is important to avoid associating failure with error (even if this is the case).

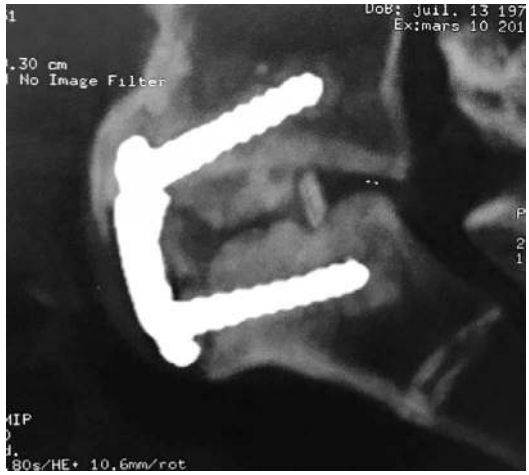

Fig. 16.1 Metal screws are shown fixed into bone, highlighting surgical hardware used to stabilize a bone fracture or fusion. The bright screws contrast with the darker surrounding bone tissue, emphasizing the placement and angle of the implants. This image helps understand how the hardware supports bone healing by holding fragments in place

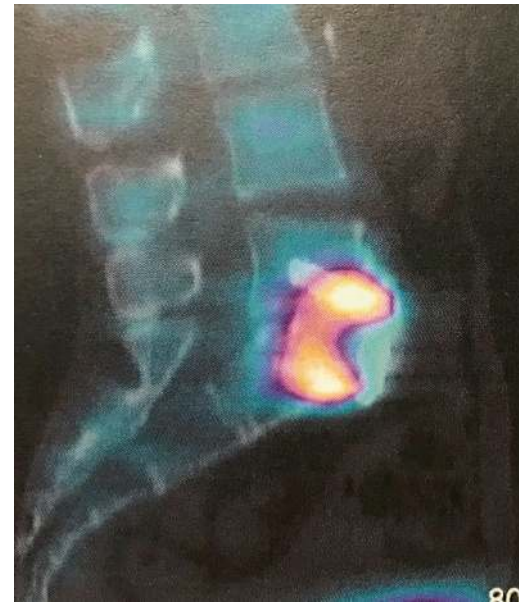

Fig. 16.2 Bright areas in yellow, orange, and red highlight a specific region within a green and blue background, indicating a focused area of activity or concentration in the sample. The surrounding colors fade to darker green and blue, showing lower levels of the measured signal. This contrast helps identify the main area of interest in the microscopy image

(a) Root conflict due to canal stenosis of disc or facet origin, not decompressed or insufficiently decompressed (as in the case of a level error).
The indication for revision surgery to relieve compression is logical and follows the same rules as for primary surgery, with a few well-known additional difficulties (frequency of breaches, etc.).

(b) Secondary mispositioning or displacement of implants used during primary surgery (neurotoxic pedicle screws, endocanal pullback of interbody cages, intracorporal impaction of cages).
In this case, revision surgery is indicated to properly replace the osteosynthesis devices.

(c) An error in the operative indication as the performed tests demonstrated.
Whatever the error (e.g., bilateral isthmic lysis or unstable spondylolisthesis undetected without CT and/or dynamic imaging), the indication for revision surgery is still reasonable and has every chance of improving the patient/s condition.

(d) Pseudarthrosis.
Pseudarthrosis may or may not be painful (of the various imaging modalities, only MRI has a positive likelihood of discogenic etiology in cases of focal disc degeneration [90] (Figs. 16.1 and 16.2). When it is, revision to achieve fusion using various techniques (circumferential arthrodesis, iliac extension, use of osteoinductors) combined with appropriate lifestyle habits (stop smoking, use of a corset, weight loss, etc.) should solve this typical mechanical problem.

(e) Spinal misalignment in arthrodesis (especially if multisegmental) leading to sagittal or frontal imbalance (scoliosis).
This situation may lead to a complex and risky surgical procedure involving either a transpedicular osteotomy or a Smith Petersen-type osteotomy, most often with circumferential arthrodesis.

B. *Pain associated with recurrence or persistence of the original pathology for which the original surgery was performed.*

(a) Recurrence of a herniated disc will logically lead to a new discectomy, although a radical discectomy followed by arthrodesis or arthroplasty may be required depending on the distribution of lumbago/radiculalgia, the size and position of the hernia (central?) and the number of recurrences.
(b) Disc disease or deformity—instability (spondylolisthesis) above a previous arthrodesis, which may have facilitated its occurrence, particularly in cases of postoperative lordosis defect, violation of the articular facets of the neo-hinge by the proximal screws of an arthrodesis, and genetic disc fragility.
(c) Genetic disc lumbago after herniated disc cure for sciatica. This is the classic indication for either radical discectomy followed by arthroplasty, or segmental arthrodesis.

C. *Neuropathic pain syndrome*

In such a situation, after ruling out the need for revision surgery, the possibility of stimulation should be considered [12–15].

Spinal cord electrical stimulation is a major therapeutic tool in the treatment of post-surgical neuropathic pain. Its basic mechanism remains the "gate" theory described by Wall and Melzack in 1968. New waveforms, new electrodes and new targets enable a wider range of indications to be covered. As already mentioned, patient selection must be rigorous and carried out by an experienced multidisciplinary team.

The principle is to implant an epidural stimulation electrode. Depending on the indication and type of electrode, implantation is either percutaneous or surgical. Surgical implantation is performed via a mini dorsal inter-spinous approach, enabling the placement of wide electrodes with 8–32 pads (multi-column electrodes) (Fig. 16.3). Percutaneous implantation is less invasive, using an epidural puncture at L2–L3 to place a wire electrode in the thoracic region. This is followed by a test phase lasting around 10 days. If there is a positive response to stimulation, a stimulator is permanently implanted subcutaneously. Depending on the level of stimulation used, a rechargeable system is installed. The patient is provided with a remote control to manage the stimulation, according to the programs set by the doctor. MRI-compatible systems (electrodes and generators) are now available.

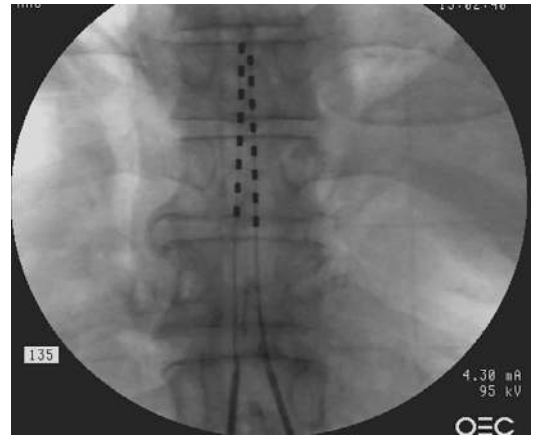

Fig. 16.3 X-ray image focused on the lower spine showing the placement of two thin, vertical medical wires or electrodes along the spinal column. The wires are marked with small black rectangular segments at regular intervals, likely for positioning or measurement purposes. The image helps visualize the exact location of these wires relative to the vertebrae, which is important for guiding medical procedures involving the spine. The surrounding bones and soft tissues appear faintly, providing context for the wire placement

An SME (medullary epidural stimulation) registry on the efficacy of spinal cord stimulation has been set up, involving 370 patients with a 2-year follow-up [16]. The results demonstrate the long-term efficacy of spinal cord stimulation, with a reduction in analgesic intake.

Spinal Cord Stimulation and Lumbar Pain

A new generation of multi-column electrodes is currently being proposed for lumbar pain. A study, "*Medico-economic evaluation of multi-column MEdullary STImulation (ESTIMET)*" is the first multicenter, prospective, randomized trial to analyze the clinical effectiveness and medico-economic impact of multi-column MHE in patients with refractory post-operative lower back pain (PLBP) with a significant lumbar component [11]. Multi-column spinal cord stimulation provides relief for these patients, who suffer from both radicular and lumbar pain.

Developments in stimulation techniques and equipment have made it possible to stimulate the

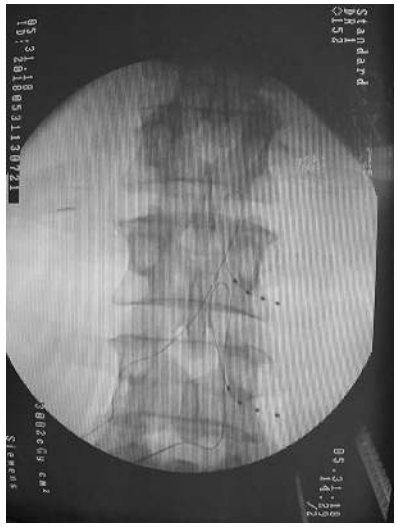

Fig. 16.4 X-ray image of the lower spine showing four vertebrae with small metal markers placed near the upper parts of the vertebrae. Thin wires or tubes are visible running across the vertebrae, likely indicating a medical procedure or monitoring. The image is in black and white with horizontal scan lines, and includes date and technical details on the edges. This image is important for assessing spinal alignment and the placement of medical devices

spinal ganglion. Huygen [17] has shown that stimulation of the L2–L3 spinal ganglion improves neuropathic back pain (Fig. 16.4). This is a new target for pain treatment, and the access is via the conventional epidural route. There is little cerebrospinal fluid at this level, so stimulation is more effective and uses less energy. Sensory and motor fibers are separated at this level, somatotopy is ideal, and the target more precise.

A meta-analysis published in November 2024 [17] finally demonstrates what we observe in everyday spinal cord stimulation practice. Randomized clinical trials compared spinal cord stimulators (SCS) therapies with placebo therapies and/or conventional medical management (CMM) or standard treatments for adults with chronic back or leg pain who had not previously used SCS.

A total of 13 studies with 1561 patients were included in the network meta-analysis comparing conventional and novel SCS therapies with CMM across the 6 outcomes of interest at 6-month follow-up. Conventional and novel SCS therapies were associated with superior efficacy versus CMM in back response rates (conventional SCS: OR, 3.00; 95% CrI, 1.49–6.72; novel SCS: OR, 8.76; 95% CrI, 3.84–22.31), back pain intensity (conventional SCS: MD, −1, 17; 95% CrI, −1, −0.70; new SCS: MD, −2.34; 95% CrI, −2.96–1.73), leg pain intensity (conventional SCS: MD, −2, −2.89; 95% CrI, −03 to −1.81; new SCSCS: MD, −4.01; 0.13–0.21). For functional disability, the conventional SCS was superior to the CMM (MD, −7.10; 95% CrI, −10.91 to −3.36). No statistically significant differences were observed for other comparisons.

D. *At the frontier between medical treatment and surgery: rhizolysis*

Rhizolysis is often used in chronic low-back pain, although its efficacy is diminished in presence of a multiple surgeries history [19]. This is the first study to develop patient-specific recommendations for the appropriate selection of patients with chronic axial and radicular lumbosacral pain for ablative radiofrequency (RFA) or pulsed radiofrequency (PRF). The recommendations were formulated by a panel of European multidisciplinary experts, using the validated RUAM (The RAND/UCLA Appropriateness Method), and integrated into an e-health educational tool (https://rftool.org), that can help improve patient selection for RF. Although the recommendations have been developed by a group of experts, their feasibility and validity need to be confirmed in daily practice to demonstrate their value for the surgeon and the referring clinician, and to determine the predictive value of the recommendations for the outcome of RF surgery [19].

16.2 Conclusion

The persistence of a lumbar and/or radicular pain syndrome after lumbar spinal surgery is a frequent situation involving a wide range of clinical pictures. They are not limited to surgical failures. Preoperative patient education is essential, so that patients understand that disc disease cannot be treated by removing a hernia (even if this is the cause of the sciatica that leads to the surgical request at the time), or that in some degenerative spondylolisthesis, we may choose to treat only a canal stenosis in order to limit the risk of surgery in fragile patients with comor-

bidities. We need to explain that the aim of surgery is not to treat all symptoms, but only the most incapacitating (sciatica rather than low back pain in the case of hernia, for example).

Lastly, this situation should not lead the surgeon to multiply the number of surgical procedures and so risk a worsening of the situation [18]. On the opposite, a careful investigation, followed by appropriate radiological examinations, can lead to a new accurate diagnosis, some of which will result in a new surgical treatment with proved effectiveness. PSPS must be approached with caution in all its aspects, and a multidisciplinary team evaluation is necessary to provide a tailored management to this complex pathology.

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