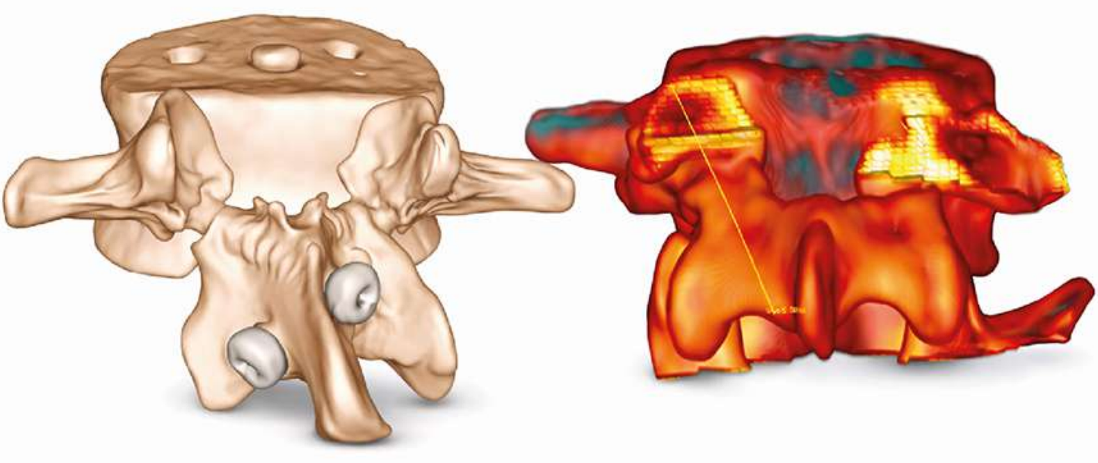
Pars Interarticularis Defect and Direct Repair: Indications and Contemporary Surgical Strategies

Asst. Prof. Burhan Oral GÜDÜ



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15 Temmuz Mah. 148136. Sk. No: 9 Şehitkamil/Gaziantep
+90.850 260 09 97
+90.532 289 82 15
www.ozguryayınlari.com
info@ozguryayinlari.com

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Preface

Among lumbar spine pathologies, spondylolysis—particularly in young, active, and athletic individuals—is not merely a radiological finding; rather, it represents a dynamic pathological process that directly affects spinal biomechanics and a patient's quality of life. Often overlooked or sometimes incorrectly regarded as a natural consequence of intense physical activity, this condition may initiate a progressive cascade of biomechanical alterations and degenerative changes if not recognized and treated appropriately.

In recent decades, our understanding of the pathophysiology, biomechanics, and clinical management of pars interarticularis defects has evolved substantially. Advances in imaging techniques, surgical instrumentation, and minimally invasive approaches have transformed the treatment philosophy from purely stabilizing procedures toward strategies that prioritize motion preservation and restoration of physiological spinal mechanics.

This book was conceived to provide a comprehensive and structured overview of spondylolysis and its surgical management, with particular emphasis on pars repair techniques. The chapters cover topics ranging from the anatomical and biomechanical foundations of the pars interarticularis to modern surgical strategies, including intralaminar screw fixation and other motion-preserving repair techniques. By integrating current literature with clinical experience, the aim is to offer both theoretical insight and practical guidance for clinicians dealing with this challenging condition.

One of the central ideas underlying this work is the concept that treatment should aim not only to eliminate pain but also to restore normal spinal biomechanics while preserving the functional integrity of the motion segment whenever possible. In this respect, direct pars repair represents an appealing surgical option for carefully selected patients, particularly young individuals with minimal disc degeneration.

During the preparation of this book, modern artificial intelligence tools were utilized as supportive research assistants for literature organization, language refinement, and structural editing. However, all scientific interpretations, clinical perspectives, and conceptual frameworks presented in this work are the result of the author's independent academic evaluation and surgical experience.

It is my hope that this book will serve as a practical reference for spine surgeons, neurosurgeons, orthopedic surgeons, and researchers interested in the diagnosis and treatment of lumbar spondylolysis. If the ideas and knowledge presented here contribute—even modestly—to improving the understanding and management of this condition, then the effort invested in preparing this work will have fulfilled its purpose.

Burhan Oral Güdü, MD

Assistant Professor of Neurosurgery

İstanbul Medipol University, Sefaköy Hospital

İstanbul, Türkiye

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CHAPTER 1

Introduction: Spondylolysis and Its Pathophysiological Foundations

1.1. Definitions and Terminology

The term *spondylolysis* is derived from the Greek words " spondylo " (spine) and " lysis " (loosening) and refers to a stress fracture or defect characterized by loss of cortical continuity in the pars interarticularis region. The pars interarticularis (isthmus) is the anatomical region located between the superior and inferior articular processes of the lumbar vertebrae, forming the weight-bearing bony bridge of the posterior column. Spondylolysis is one of the most important structural pathologies that can cause low back pain without accompanying neurological deficits, although a significant proportion of cases are detected asymptomatically (1) .

Clear terminology is critically important in clinical and surgical decision-making processes:

- Spondylolysis: A condition characterized by disruption of the integrity of the *pars interarticularis* (isthmus) due to a stress fracture or complete defect, without associated spondylolisthesis (Figure 1) (2).

Figure 1. Sagittal CT demonstration of pars interarticularis defect. Sagittal computed tomography image of the lumbar spine demonstrating a defect in the pars interarticularis at the L5 level, consistent with isthmic spondylolysis. CT imaging clearly delineates cortical disruption of the pars region and provides detailed visualization of the posterior element anatomy.

- *Spondylolisthesis* : Displacement of the vertebral body anteriorly (rarely posteriorly) relative to the caudal segment, mostly due to pars defect or degenerative processes (Figure 2) (3) .

Figure 2. Multiplanar sagittal CT images demonstrating pars interarticularis defect. Sequential sagittal computed tomography reconstructions of the lumbar spine demonstrating the pars interarticularis defect at the L4 level. The cortical discontinuity of the pars is clearly visualized across adjacent sagittal slices, confirming the presence and extent of isthmic spondylolysis. CT provides high-resolution evaluation of the posterior elements and facilitates accurate assessment of the bony defect.

Spondylolysis can occur alone without spondylolisthesis ; the key factor determining the surgical indication is the correlation of this radiological finding with the patient's pain and functional limitations (1).

1.2.Epidemiology and Risk Factors

Lumbar spondylolysis occurs in approximately 6–8% of the general adult population; recent CT-based series have reported this rate as high as 11.5%. Prevalence increases with age in childhood; it is reported at around 4% in primary school screenings, while it approaches adult levels towards adolescence. It occurs 2–3 times more frequently in males than in females is associated with both biomechanical stress and the types of sports practiced (2–4) .

Ethnic differences are striking; the prevalence of pars defects in Inuit populations reaches high rates of 20–50% in both skeletal series and living community studies, suggesting a combination of significant genetic predisposition and environmental factors. In young athletes engaged in competitive sports, the prevalence reaches the range of 15–47%, and the risk is significantly increased, especially in sports requiring repetitive hyperextension and rotation such as gymnastics, diving, weightlifting, wrestling, football, baseball and similar disciplines (5–7) .

Risk factors are multifactorial:

- Genetic predisposition and family history, including polymorphisms affecting bone mineralization and collagen structure, are important risk factors (1,8) .
- Biomechanical loading: Repetitive lumbar hyperextension , axial compression, and rotational stress. (1,5,6)
- Anatomical features: At the L5 level, the pars is thinner and more sagittally oriented, and a higher sacral slope further increases mechanical stress on the pars (2,8).
- Increased lumbar lordosis and pelvic parameters disrupt stress distribution in the pars region, increasing both the risk of lesion development and progression(2,8).

1.3. Pathophysiology and Biomechanics: A "Fatigue Fracture" Perspective

According to current approaches, spondylolysis should be considered not as a single acute trauma, but rather as a fatigue (stress) fracture of the posterior column due to repetitive loading. The pars interarticularis, connecting the superior and inferior facet joints, is a key element providing mechanical continuity and load-bearing capacity of the posterior column. Fracture of this bridge results not only in a local bone defect but also in a disruption of the segment's biomechanical stability, increased load on the intervertebral disc, and the triggering of a degenerative cascade in the long term.(1,4,8)

The pathological process progresses gradually:

1. Stress reaction (pre-lysis): Bone marrow edema around the pars is seen on MRI as a bright signal increase, especially in STIR/T2 fat-suppressed sequences(6,8–10). Figure 3

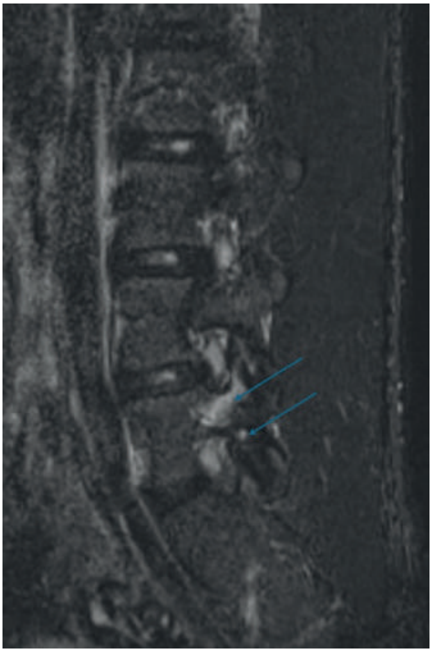

Figure 3. STIR MRI showing bone marrow edema associated with pars stress reaction. Sagittal short tau inversion recovery (STIR) magnetic resonance image of the lumbar spine demonstrating hyperintense signal within the pars interarticularis and adjacent pedicle at the L5 level (arrows), consistent with bone marrow edema related to an early stress reaction in spondylolysis. STIR sequences are highly sensitive for detecting active inflammatory changes and bone marrow edema before the development of a complete cortical defect.

2. Microfracture : The beginning of a disruption of cortical continuity at the microscopic level, which may appear as minimal irregularities or fine cracks on CT scans (Figure 4) (2,11–13).

Figure 4. Sagittal CT demonstrating a thin pars interarticularis defect in a young patient. Sagittal computed tomography image of the lumbar spine showing a narrow cortical defect in the pars interarticularis at the L5 level (arrow), consistent with early-stage isthmic spondylolysis in a young patient. CT clearly delineates the thin fracture line and cortical interruption of the pars region.

3. Complete defect and nonunion : If loading continues and the biological healing capacity becomes insufficient, a complete pars defect develops, leading to chronic pseudoarthrosis (Figure 5) (2,14) .

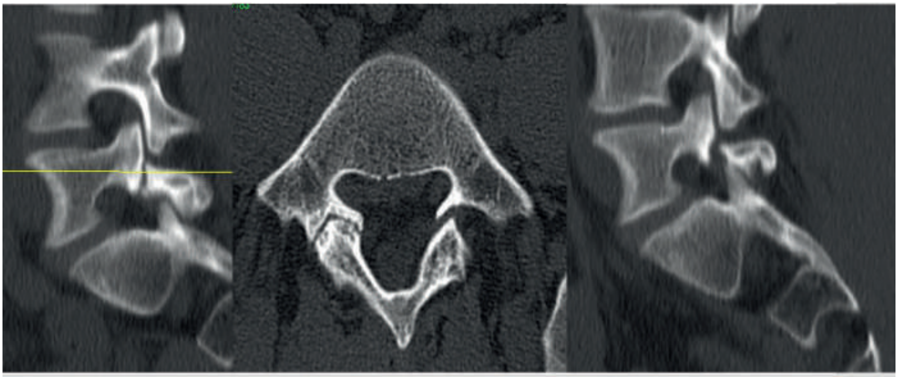

Figure 5. Bilateral pars interarticularis defects demonstrated on CT. Multiplanar computed tomography images of the lumbar spine demonstrating bilateral defects of the pars interarticularis at the L5 level. The left and right sagittal reconstructions show cortical discontinuity of the pars regions, while the axial image confirms bilateral involvement of the posterior elements. These findings are consistent with bilateral isthmic spondylolysis.

4. At the L5 level, the shear forces exerted by the inferior facets of L4 and the superior facets of S1 on the pars, particularly in cases where the sagittal pars inclination angle is greater than 30 degrees, increase the shearing effect and independently raise the risk of fracture. Increased lumbar lordosis further accentuates these shear forces, facilitating both the development of spondylolysis and the recurrence and progression of the existing defect(5,15,16).

From this perspective , spondylolysis should be considered not merely a "simple pars defect," but rather a loss of load-bearing capacity of the posterior column and the starting point of segmental instability(2,4,8).

1.4. Clinical Findings and Diagnosis

In symptomatic cases, the most common complaint is mechanical low back pain that worsens with activity and decreases with rest. The pain is most often experienced during sports or physical activity, especially hyperextension. It is aggravated by these maneuvers; radiculopathy is more common in the presence of accompanying listhesis or foraminal narrowing(6,17,18).

During the physical examination:

- Lumbar extension , paraspinal muscle spasm, and palpation tenderness at the L5 level are typical(1,6).
- Stork test (single-leg hyperextension), in which the patient stands on one leg and the spine is hyperextended , is one of the most frequently used provocative tests; however, due to its limited sensitivity and specificity, it should not be considered diagnostic on its own and must be supported by imaging studies(19–21).

The imaging approach is stepped:

- Plain radiographs: In oblique projections, the classic "Scotty dog" appearance may demonstrate a collar sign, which is indicative of a pars interarticularis defect. However, the sensitivity of plain radiographs in detecting early stress reactions remains limited (Figure 6) (8,22,23).

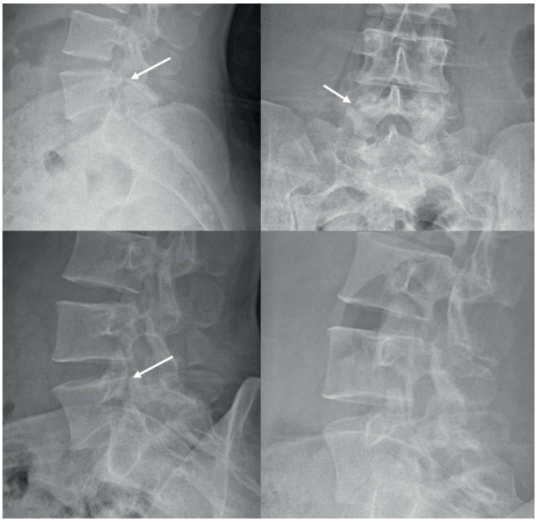

Figure 6. Oblique lumbar radiographs demonstrating the "Scotty dog" sign of pars defect. Oblique lumbar spine radiographs showing the classic "Scotty dog collar" appearance (arrows), representing a defect in the pars interarticularis. This radiographic finding is characteristic of lumbar spondylolysis and is best appreciated on oblique projections of the lumbar spine.

- Computed tomography (CT): This is the gold standard for evaluating bone cortex and pars morphology; chronic defects, pseudoarthrosis , and unilateral or bilateral fractures are best demonstrated with CT (Figure 7) (24–26).

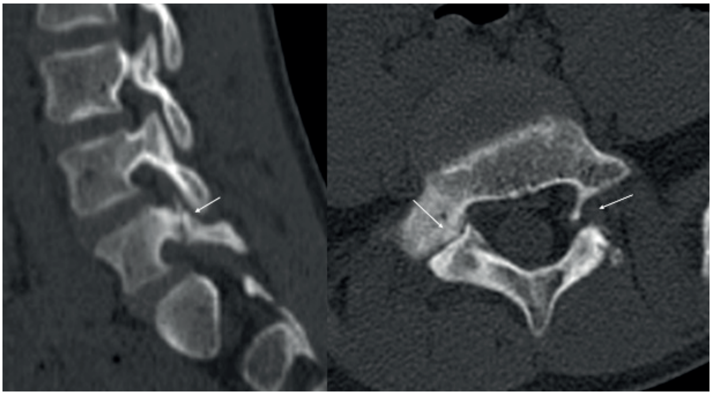

Figure 7. Bilateral pars interarticularis defects on CT in an adolescent patient. Sagittal and axial computed tomography images of the lumbar spine demonstrating bilateral defects of the pars interarticularis at the L5 level (arrows) in a 14-year-old male patient. The sagittal reconstruction shows cortical interruption of the pars region, while the axial image confirms bilateral involvement of the posterior elements, consistent with bilateral isthmic spondylolysis.

- Magnetic resonance imaging (MRI): It is indispensable, especially in child and adolescent athletes, because it reveals bone marrow edema in the early stages of stress reaction in a non-invasive and radiation-free modality (Figure 8) (8,27–29).

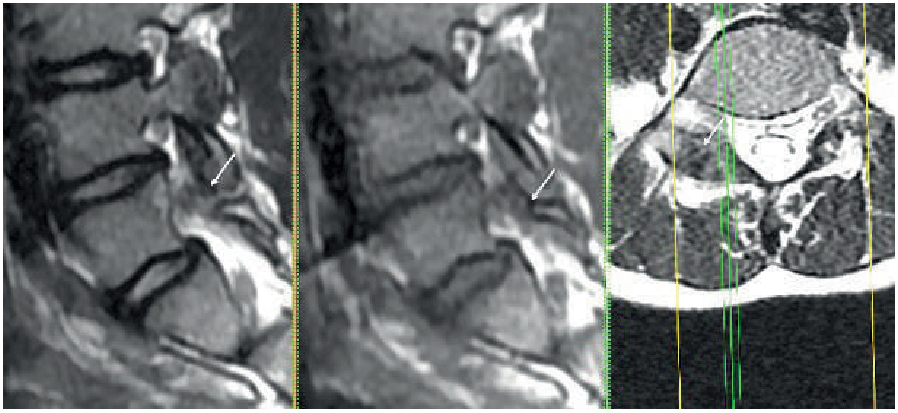

Figure 8. MRI demonstration of pars interarticularis defect.
Sagittal T1-weighted and T2-weighted magnetic resonance images, along with an axial section, demonstrating a defect in the pars interarticularis at the L5 level (arrows). The sagittal sequences reveal interruption of the cortical continuity of the pars region, while the axial image confirms the defect within the posterior elements. These findings are consistent with lumbar isthmic spondylolysis.

- SPECT/scintigraphy: This modality has historically played an important role in capturing early stress reactions; today, it is used as an auxiliary method in selected cases, especially when CT/ MRI is not clear(11,30,31).
- Lumbar Spine Bone MRI: This technique evaluates the spine using specialized 3D gradient-echo sequences designed to provide bone contrast equivalent to CT, employing a "radiation-free bone imaging" approach. Because the synthetic bone-weighted images obtained with this technique allow for the visualization of the pars interarticularis, cortical contour, and defect line in a manner very similar to classic CT, it is recommended as a radiation-free alternative for diagnosing spondylolysis, particularly in adolescents and young adults. Lumbar Spine Bone MRI offers the possibility of evaluating both soft tissue and bone components in a single session by showing both bone marrow edema due to early stress reaction (an advantage of classic MRI) and the morphology of the pars defect in synthetic bone contrast (CT-

like appearance) in the same examination. Furthermore, the ability to monitor healing, fibrosis, or progression without radiation exposure in repeated control examinations is highlighted as a significant advantage for pediatric patients(26,32).

When young athletes present with low back pain, even without radiological evidence of spondylolisthesis, pars defect should always be considered. Early diagnosis in the pre-lysis stage is critical for achieving complete recovery and preventing spondylolisthesis through conservative treatment.

1.5. The Philosophy of Treatment: Restoration of Biomechanics

Spondylolysis is a dynamic pathology, and the treatment approach is based on an integrated assessment of the biological phase of the lesion, the degree of segmental instability, disc degeneration, and the patient's clinical profile. In pediatric and adolescent athletes diagnosed during the early stress reaction phase , a high rate of bone healing and symptomatic improvement can be achieved in most cases through cessation of loading, appropriate rest, goal-oriented rehabilitation, and exercise programs that optimize spinal biomechanics(6).

Surgical indications arise in cases of mechanical low back pain resistant to conservative treatment, progressive spondylolisthesis, significant instability, and rarely, neurological deficits. The basic principles of the treatment philosophy are as follows:

- Motion- preserving (segment-preserving) approaches: In cases of pars stress fractures with biological healing potential and minimal disc degeneration, direct pars repair using intralaminar pars screw techniques from the same or opposite lamina aims to preserve the natural movement of the segment by restoring the continuity of the posterior column(33).
- Stabilization and fusion: In cases of advanced instability, significant disc degeneration, or high-grade spondylolisthesis , the primary goal is to achieve a pain-free and functional spine through safe lumbar fusion, rather than insisting on preserving segment movement(34–36).

When making surgical decisions, the presence of a radiological pars defect alone is not sufficient; it is necessary to understand that the source of pain cannot be solely attributed to muscle, ligament, or disc, to correctly position the pars defect within this clinical picture, and to shape the treatment strategy accordingly. In this context, spondylolysis should be considered by the spinal surgeon not only as a "pars defect" but also as an early indicator of biomechanical failure of the posterior column.

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CHAPTER 2

Anatomy and Biomechanics of the Pars Interarticularis

2.1. Introduction: Anatomical and Biomechanical Significance of the Pars Interarticularis

The stability and mobility of the lumbar spine are a complex balance achieved through the coordinated work of the vertebral body, intervertebral discs, facet joints, ligaments, and muscles. The pars interarticularis is a frequently underrecognized yet biomechanically critical component of this balance, acting as a short bony bridge connecting the upper and lower facet joints. A significant portion of the stress on the posterior column, particularly during flexion-extension and rotation movements, is carried through this structure(1,2).

Understanding the anatomical features of the pars and its role in segmental biomechanics is crucial for the diagnosis and treatment planning of pathologies such as pars defects, isthmic spondylolysis, and spondylolisthesis. From a surgical perspective, techniques such as direct pars repair, intralaminar or translaminar screw fixation should all be planned considering the morphology and loading characteristics of this small structure(3).

2.2. Macroanatomy of the Pars Interarticularis

The pars interarticularis refers to the segment located between the superior and inferior articular processes or facets in the vertebral arch. In lumbar vertebrae, it is adjacent to the pedicle anteriorly, the lamina posteriorly, the superior articular process cranially, and the inferior articular process caudally, and due to this location, it directly contributes to the stability of both the posterior elements and the facet joint complex(4,5).

In the lumbar region, the pars morphology varies according to level; at the L5 level, the pars is generally thinner, longer, and more oblique, and L5 is reported as the most frequently affected level. This is related to the pronounced lordotic angle of the L5–S1 segment, the sacral slope, and the coronal orientation of the lower lumbar facet joints. At the L4 level, the pars may be relatively thicker and shorter compared to L5; however, isthmic spondylolisthesis has also been reported with significant frequency at the L4 level(6).

A correct understanding of the three-dimensional structure of the pars is crucial from a surgical perspective. Visualizing the pars as a "bone bridge" between the superior and inferior facet processes allows for the identification of secure entry points during direct pars screw fixation and translaminar screw placement. Achieving safe and effective stabilization is difficult unless the spatial relationship between the lamina, spinous process, facet joint, and pars is clearly defined in the surgeon's mind as a three-dimensional model(3,7).

Anatomical variations are also clinically and surgically significant. In some individuals, the pars segment is shorter and wider, while in others it is longer and thinner; variants such as lumbarization, sacralization, and transitional vertebrae can alter the orientation of the pars and the associated joint angles. Therefore, careful morphological evaluation via CT is indispensable for each patient, both for characterizing the pars defect and for surgical planning(3,8).

2.3. Microanatomy and Bone Structure

The pars interarticularis is a structure surrounded by dense cortical bone and containing trabecular bone; the outer cortical layer is critical for load-bearing and mechanical strength. The inner trabecular structure plays a role in adaptation to microtraumas and load distribution; in stress fracture development, microcracks initially form in the trabecular structure. This is followed by thinning and irregularity in the cortical layer, and ultimately the appearance of a complete fracture line(6,8,9).

Particularly in athletes who are subjected to high levels of loading before bone maturation is complete, especially during adolescence, the adaptive capacity of the trabecular structure in the pars region may be limited, increasing susceptibility to stress damage. At the microanatomical level, the limited bone remodeling capacity in response to repetitive loads on the pars region are significant. Micro-damage occurs with loading, and the bone attempts to repair this damage during rest and adaptation phases. However, when the loading-repair balance is disrupted, the micro-damage accumulates, resulting in the clinically observed defect(10,11).

The importance of microanatomy from a surgical perspective is related to the retention capacity of screws or implants to be placed on the pars. When sclerotic bone density increases at the defect edges, screw retention may change, and proper debridement and grafting of the defect area becomes critical for both biological healing and mechanical stability. Therefore, when planning pars repair, not only the macroscopic defect but also the bone quality and sclerosis patterns at the defect edge must be considered(7,8).

2.4. The Role of the Pars in Lumbar Segment Biomechanics

The lumbar spine can be conceptualized using the three-column model: the anterior column (anterior part of the body and disc), the middle column (posterior body and posterior disc), and the posterior column (facet joints, laminae, spinous processes, and pars interarticularis). In this model, the pars is a critical element of the posterior column, determining, along with the facet joints, the segment's resistance to translational and rotational movements(12–14).

The load-bearing ratio between the disc and facet joints changes dynamically during flexion, extension, lateral flexion, and rotation movements; the anterior column of the disc carries more load during flexion, while the load on the posterior column and facet complex increases during extension and axial loading. The pars, acting as a bony bridge between the superior and inferior facet joints, is subjected to intense stress, particularly during the extension and rotation components(2,15,16).

Conceptually, the pars interarticularis acts like a locking pin that secures the movement "hinge" between the vertebral body and the posterior elements. Weakening or rupture of this lock leads to the body becoming more prone to sliding forward relative to the posterior elements, thus creating the biomechanical basis for isthmic spondylolysis and subsequent spondylolisthesis(7).

An intact pars contributes to balanced load transmission across the facet joint complex. When a defect develops, the loading pattern changes; the stress on the disc and remaining posterior structures increases, which can contribute to the acceleration of secondary pathologies such as disc degeneration and facet arthropathy in the long term. Thus, even a small bony defect may substantially alter segmental biomechanics and clinical course over time(7,9,17).

2.5. Stress Distribution in Flexion-Extension and Rotation Movements

Examining the load on the pars interarticularis during lumbar spine movements is useful for understanding the mechanism of defect development.

- Flexion: During flexion, the anterior column of the disc is compressed while tensile forces are generated in the posterior elements; although the direct compressive load on the pars is reduced, especially inadequate muscle control and repetitive flexion-extension cycles can contribute to the accumulation of microtraumatic stress(15,16,18).
- Extension: Extension is one of the most critical movements for the pars interarticularis; the facet joints move closer together, the compressive load on the posterior elements increases, and the pars, as part of the facet complex, is subjected to intense stress. Many series have highlighted the repetitive high stress placed on the pars, particularly in sports activities involving hyperextension (gymnastics, diving, figure skating, volleyball spikes, tennis serves, etc.)(19–22).
- Rotation and lateral flexion: Rotational movement, especially when combined with asymmetric loading, applies significant shear and torsional forces to the pars region; turns on one leg, rapid changes of direction, and sudden trunk rotations play a significant role in microtraumatic loading of the pars. While lateral flexion alone creates a more limited load, when combined with rotation it significantly increases pars stress(23–26).

Many of these movements form fundamental components of athletic performance, particularly in young athletes, and pars defects result not only from normal spinal movement but also from stress associated with high levels of repetitive performance. This information is important for both planning preventative approaches and designing rehabilitation programs(23,27).

2.6. Biomechanical Changes When a Pars Defect Develops

Stress fractures in the pars interarticularis, leading to disruption of cortical continuity, result in significant changes in segment biomechanics.

- Unilateral defect: In a unilateral pars fracture, the global stability of the segment is partially preserved because the contralateral pars is intact; however, loading becomes asymmetrical, and the stress on the pars and facet complex on the intact side increases. This situation can lead to overloading on the contralateral side and the development of a secondary defect over time; it can also cause lateral pain and unilateral tenderness during certain movements on the intact side due to asymmetrical loading (Figure 1)(28–31).

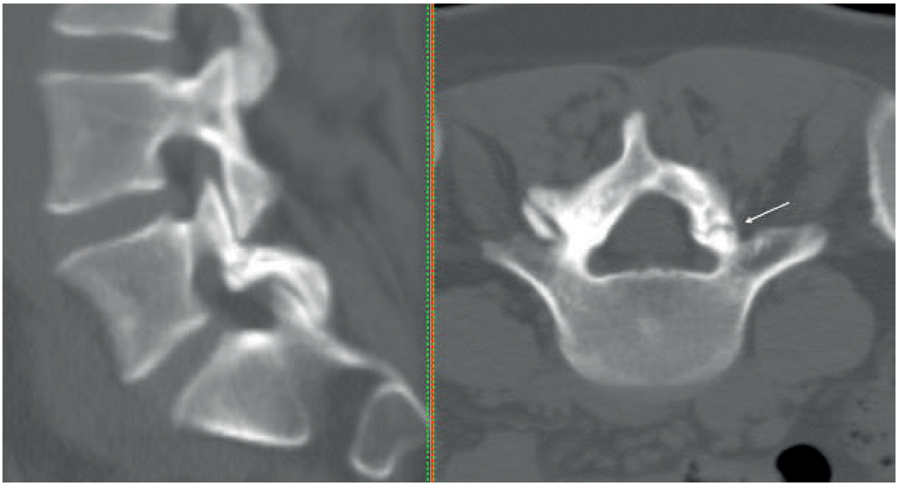

Figure 1. Unilateral pars interarticularis defect demonstrated on CT. Sagittal and axial computed tomography images of the lumbar spine demonstrating a unilateral defect in the pars interarticularis at the L5 level (arrow). The sagittal reconstruction shows cortical discontinuity of the pars region, while the axial section confirms unilateral involvement of the posterior element, consistent with unilateral isthmic spondylolysis.

- Bilateral defect: When a bilateral defect develops, the bony connection between the posterior elements and the vertebral body is lost; the body of L5, in particular, becomes more prone to anterior sliding over S1, and this process represents a transition from isthmic spondylolysis to isthmic spondylolisthesis. When segmental stability is compromised, the posterior elements can no longer act as a posterior stabilizing mechanism" for the body; the load on the disc and ligamentous structures increases, and intervertebral mobility increases both at the affected level and in adjacent segments (Figure 2) (7,32–34).

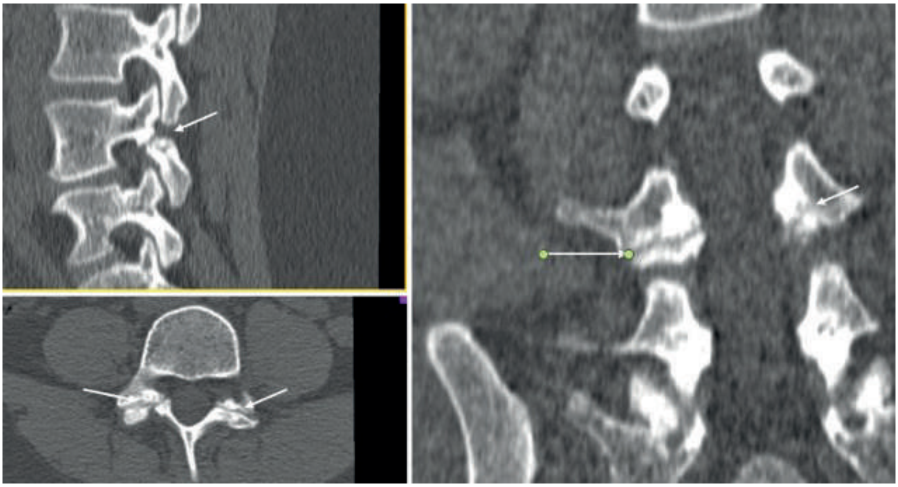

Figure 2. Bilateral pars interarticularis defects at the L4 level on CT.
Multiplanar computed tomography images of the lumbar spine demonstrating bilateral defects of the pars interarticularis at the L4 level (arrows). Sagittal, axial, and coronal reconstructions clearly show cortical discontinuity of the pars regions on both sides, confirming bilateral isthmic spondylolysis. CT imaging enables precise visualization of the posterior element anatomy and the extent of the bony defects.

These biomechanical changes are also reflected in the clinical picture. In the presence of bilateral defects and spondylolisthesis, in addition to mechanical lower back pain that increases with weight-bearing, radicular complaints due to foraminal narrowing may develop; over time, a decrease in disc height, segmental deformities, and compensatory changes in adjacent segments may be observed(8,35).

From a surgical planning perspective, these biomechanical differences directly influence treatment choice. In single-segment pars defects with minimal or no listhesis and preserved disc height, direct pars repair offers a segment-preserving option, and biomechanical studies have shown that pars fixation alone can reduce excessive mobility at both the relevant level and in the adjacent segment. In contrast, in cases with significant listhesis, deformity, and disc degeneration, segmental fusion and more extensive stabilization techniques are considered(9,36–38).

Patient-specific three-dimensional CT evaluation of the pars interarticularis has become an indispensable component of modern preoperative planning. The pars interarticularis is a small but strategic component of the lumbar spine, and a correct understanding of its anatomy and biomechanics forms the basis for accurate diagnosis and appropriate treatment strategies in patients with pars defects and isthmic spondylolysis(7,36,37,39–41).

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CHAPTER 3

Clinical Significance of Pars Defect

3.1. The Clinical Relevance of Pars Interarticularis Defect

The pars interarticularis is a small bony bridge within the posterior elements of the lumbar spine that is often overlooked but plays a critical role in maintaining segmental stability. This delicate structure, connecting the upper and low facet joints, carries a significant mechanical load, particularly at the L4–L5 and L5–S1 levels, during flexion-extension and rotation movements. While disc pathologies are the first thing that comes to mind when discussing low back pain in clinical practice, pars interarticularis defects and isthmic spondylolysis represent major underlying structural causes in the young and active population(1–5).

A pars interarticularis defect should not be regarded merely as a radiological "line" or a gap seen on a CT scan, but rather as a critical structural vulnerability within a dynamic, weight-bearing spinal segment, a factor determining the patient's quality of life and performance. For a young athlete, this defect may significantly influence athletic performance and career longevity, while for a sedentary individual, it can become a potential source of chronic mechanical low back pain over the years. From this perspective, pars interarticularis defect is not just a radiological diagnosis, but a pathology central to the clinical decision-making process, especially when planning segment-preserving surgical strategies(1,2,6,7).

3.2. Definition of Pars Interarticularis Defect

The pars interarticularis is a short bony segment located between the lamina and pedicle, connecting the superior and inferior facet processes of the lumbar vertebra. In three dimensions, it is adjacent to the pedicle anteriorly, the lamina posteriorly, the superior articular process cranially, and the inferior articular process caudally. A pars interarticularis defect is defined as a complete defect resulting from a disruption of cortical and trabecular continuity in this bony segment, in other words, a stress reaction, an incomplete fracture, or a permanent non-union. Pars defects most commonly occur at the L5 level, secondly at L4, and can be unilateral, but more often bilateral. In unilateral defects, segmental stability may be partially preserved, but the loading pattern becomes asymmetrical. In the presence of bilateral defects, the bony connection between the posterior elements and the body is lost, creating a biomechanical basis for isthmic spondylolysis–spondylolisthesis. Although a pars defect is classically described radiologically by the fracture line at the neck of the "Scottish dog" appearance on oblique lumbar radiographs, high-resolution CT and MRI are currently the most reliable diagnostic methods. CT shows the cortical edges of the defect, the degree of chronicity, the extent of the defect, and the surrounding bone structure in detail; while MRI is superior in evaluating the active stress reaction in the form of bone marrow edema, accompanying disc pathologies, and the condition of neural elements(1,7–10).

Pars defects should not be evaluated simply as "present/absent." Parameters such as whether the defect is unilateral or bilateral, whether it represents an acute stress reaction or a chronic non-union, the affected level, and any accompanying disc/facet degeneration all directly influence the treatment decision. Therefore, pars defects should not be considered merely an imaging finding, but rather the starting point and guiding principle of the treatment algorithm(2,10–13).

3.3. Pathophysiology of Spondylolysis

Spondylolysis is a pathology characterized by the formation of a stress fracture or defect in the pars interarticularis (isthmus) region, often resulting from a combination of repetitive mechanical loading, microtrauma, and developmental factors. Typically beginning in childhood and adolescence, this process can become a chronic problem extending into adulthood if not properly diagnosed and treated. At the heart of the pathophysiological process are repetitive hyperextension and rotation forces on the pars region; particularly in young athletes, technical movements that subject the lumbar spine to excessive extension-rotation combinations place a constant load on the pars. Although the muscles temporarily compensate for this load, when the biomechanical strength limit of the bone tissue is exceeded, subcortical microfractures develop, followed by cortical fractures, and ultimately, if adequate healing is not achieved, non-union occurs(2,7,14–16).

In the early stages, there is bone marrow edema in the pars region, microfractures, and local pain that increases with activity; this stage is reversible with appropriate conservative treatment. Continued weight-bearing, insufficient time for healing, or the presence of underlying anatomical weaknesses transforms this stress reaction into a permanent defect; a complete fracture line develops on the pars, and the defect gap is typically filled with fibrous tissue or fibrocartilage, resulting in chronic mechanical pain. When bilateral pars defects develop, the bony continuity between the posterior elements and the vertebral body is lost; the vertebral body becomes increasingly prone to anterior displacement, particularly at the L5–S1 level, representing the transition to isthmic spondylolisthesis. Over time, decreased disc height, secondary facet joint degeneration, foraminal narrowing, and, in some cases, radiculopathy may develop. The fundamental distinction between isthmic and degenerative spondylolisthesis lies in the underlying pathology: in isthmic spondylolisthesis, the primary lesion is a pars defect, whereas in degenerative spondylolisthesis, it originates from disc and facet degeneration.(11,17–19).

Musculoskeletal balance also plays a significant role in pathophysiology. Weak core muscles, hamstring shortening, limited range of motion in the hip, and lumbopelvic imbalance can increase stress on the pars region, contributing to the development of spondylolysis. Therefore, isthmic spondylolysis should be considered not merely a local bone fracture, but a reflection of biomechanical dissonance throughout the entire range of motion; this perspective highlights that management should not be limited to surgical intervention but should also incorporate structured rehabilitation and training modification(1,20–24).

Although pars interarticularis defects are most often associated with repetitive stress loading, the literature suggests that dysplastic or attenuated development of the pars may predispose to this process. Therefore, it is possible to position pars defects not only as an acquired "fatigue fracture" but also within a developmental spectrum where primary bone development does not occur, and pars fusion is not completed in a timely manner, either unilaterally or bilaterally, due to genetic/dysgenetic disorders of the growth plates. Similar to spina bifida subtypes, it is conceivable that pars defects may have different types that can be distinguished according to morphology and accompanying anomalies. This hypothesis holds greater potential for explaining discrepancies between radiological morphology and clinical course.

3.4. Incidence and Clinical Presentation in Young Athletes

Although pars defect and isthmic spondylolysis are seen in a limited proportion of the general population, they are reported significantly more frequently in young athletes. Sports such as gymnastics, diving, figure skating, cricket, wrestling, football, weightlifting, volleyball, and tennis, which subject the lumbar region to repetitive hyperextension and rotation, involve activities that place a high mechanical load on the pars region. In adolescents and young adults competing in these sports, pars defects can be detected by imaging in a significant proportion of those complaining of chronic low back pain. A typical complaint in young athletes is mechanical low back pain, initially mild but becoming increasingly bothersome over time; the pain usually worsens after training or competition, becomes more pronounced during intense training camps, and is partially relieved by rest. The athlete may begin to avoid certain movements requiring lumbar extension or rotation, or perform some technical maneuvers incorrectly or incompletely; as the process progresses, the pain can develop into a constant discomfort felt not only during high-performance activities but also during daily activities (1,8,20).

Clinical examination frequently reveals lumbar hyperlordosis, paravertebral muscle spasm, and local palpation tenderness; hamstring shortening and muscle imbalances around the hip and pelvis may accompany the condition. Pain provocation by extending the low back while standing on one leg (single-leg extension/Stork test) is a maneuver that may suggest pars pathology, however, it has been emphasized that its sensitivity and specificity are limited and it is not diagnostic on its own. Neurological examination is usually normal; radicular findings generally appear in the presence of advanced spondylolisthesis or concomitant disc pathology.One of the major problems in young athletes is the normalization of low back pain as a "natural part of sport"; this approach leads to delayed diagnosis and missed opportunities to detect the pars defect in the pre-lysis stage. However, a stress reaction recognized early can often be resolved without surgery with appropriate rest, load modification, and goal-oriented rehabilitation; as diagnosis is delayed, the defect becomes chronic non-union, and segment-preserving surgical options become relevant.Therefore, when evaluating low back pain in young athletes, pars interarticularis defect should always be high on the differential diagnosis list. Close communication with the coach, physiotherapist, and sports physician is critical for both early diagnosis and successful implementation of the treatment plan(25–29).

3.5. Why Direct Pars Repair?

When evaluating the clinical significance of a pars defect, the fundamental distinction in treatment strategy inevitably arises: "The fundamental treatment dilemma lies between fusion and direct pars repair?" Direct pars repair is a segment-preserving surgical approach that aims to restore the bony integrity of the pars without locking the motion segment at the defect level through fusion, and it has gained widespread acceptance in contemporary spine surgery, particularly in young, active, and athletic populations(1,30–34).

The clinical rationale for direct pars repair can be summarized as follows:

- Focusing on the source of pain: In young patients with minimal or no spondylolisthesis, the primary source of low back pain is often a pars defect; in this group, pain is associated with micromotion at the pars defect site and surrounding inflammation. A targeted intervention addressing the source of pain is achieved through debridement, grafting, and stabilization of the defect, without immobilizingthe entire motion segment through fusion (7,11,31,35,36).
- Preservation of segment movement: In unilevel isthmic spondylolysis, in cases where disc height is preserved and significant degeneration is absent, immobilizing the segment through fusion may create unnecessary restriction in the long term. Stability provided by direct pars repair allows the segment to maintain its normal or near-normal movement pattern, reducing stress on adjacent segments and potentially leading to more physiological spinal biomechanics(3,35,37,38).
- Functional advantage for young athletes: In high-performance athletes, preserving range of motion is essential for both pain-free living and a return to top-level performance. Fusion surgery may result in measurable restrictions in segmental motion, particularly in flexion-extension and axial rotation; however, following direct pars repair, it has been reported that a large proportion of young athletes with appropriate indications can return to their sports at a high level and achieve good functional results(39–41).
- Preservation of Future Surgical Options One of the important philosophical advantages of segment-sparing surgery is that it does not exhaust future treatment options. In cases of failed pars repair, segmental fusion at the same level can always be performed in the following years; however, restoring movement in a fused segment is practically impossible. Therefore, considering direct pars repair in the early stages of the treatment algorithm, especially in young patients, is a rational approach in terms of long-term strategy(3,5,13).

In light of these arguments, the clinical significance of a pars defect is not limited solely to an anatomical fracture line. The pars, both as the source of symptoms and the focus of surgical strategy, occupies a central place in spinal surgery, particularly in young and active populations; direct pars repair is the most concrete expression of this focus.

3.6. Clinical Implications of a Segment-Sparing Approach Instead of Fusion

Segment-sparing surgery is a concept that has gained increasing emphasis in spinal surgery in recent years. Its aim is to preserve the natural movement pattern of the spine and the biomechanics of adjacent segments as much as possible while treating an unstable or symptomatic segment. In the case of pars defects, the segment-sparing approach primarily involves direct pars repair and often minimally invasive stabilization techniques that do not completely eliminate movement.

Fusion surgery is an indispensable option in cases of advanced spondylolisthesis, significant deformity, or multi-level degeneration; however, in young patients with single-level isthmic spondylolysis and preserved disc height, proceeding directly to fusion may unnecessarily limit long-term functional capacity. In this group, segment-sparing surgery targeting the pars defect has the potential to both shorten the rehabilitation process and enable earlier mobilization in the short term, as well as reduce the risk of adjacent segment degeneration(1,33,42,43).

The clinical implications of a segment-preserving approach can be summarized as follows:

- Shorter rehabilitation period with earlier return to functional activity.
- Higher rates of return to daily life activities and sports.
- Potential for reduced risk of progressive degeneration in adjacent segments and adjacent segment disease requiring surgery.
- Higher psychological acceptance and motivation associated with perceiving the intervention as a restorative rather than ablative procedure.

In this context, the clinical significance of pars defect is not limited solely to its role as a source of pain; it is also a decisive factor in determining which surgical strategy will be offered to the patient, its long-term effects on spinal biomechanics and quality of life, and any future interventions that may be necessary. Accurate interpretation of pars defects is central to contemporary spinal surgical decision-making and long-term patient management(9,32,35).

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CHAPTER 4

Radiological Diagnosis

4.1. The Importance of Clinical-Radiological Correlation

The diagnosis of spondylolysis is not simply based on demonstrating a pars interarticularis defect on any imaging method; it is essential to differentiate asymptomatic radiological findings from true surgical candidates. The patient's age, activity level, and the character of the pain should be evaluated together with the radiological findings to determine the clinical significance(1–4).

Pain is usually mechanical in nature; low back pain that decreases with rest and increases with activities requiring lumbar hyperextension and rotation (sports, prolonged standing, heavy lifting) is the most common complaint. In adolescent athletes, "fatigue-type" low back pain that develops in parallel with increased training intensity should definitely be investigated. Spondylolysis alone often does not lead to radiculopathy; if there is pain, numbness, or weakness in the leg, careful evaluation should be made for accompanying disc herniation or foraminal stenosis due to spondylolisthesis(5–7).

4.2. Physical Examination

Physical examination is a fundamental step in establishing the clinical correlation of radiological findings.

- **Inspection:** Posture, lumbar lordosis, and gait should be assessed; in cases of overt spondylolisthesis, flattening of the lumbar lordosis or short-stepped, forward-leaning gait patterns may be observed(2).
- **Palpation:** Local tenderness may be detected over the spinous processes; a "step-off" deformity at the L5 level may suggest the presence of spondylolisthesis(2,8,9).

- **Provocative tests – Stork test (single-leg hyperextension):** The patient stands on one leg while extending their torso; the side on which pain is triggered may suggest ipsilateral pars pathology. However, systematic reviews have shown that the sensitivity and specificity of this test are low to moderate, and it is not reliable on its own for detecting active spondylolysis. Therefore, it should only be used as a supportive finding and must be confirmed by imaging(10–13).
- **Neurological examination:** Sensory and motor skills and reflexes must be evaluated; spondylolysis does not cause neurological loss in most cases, such findings should be considered a "red flag," and MRI should be used to rule out concomitant disc herniation, severe spondylolisthesis, or other pathologies(14–17).

A correct diagnostic approach should follow an algorithm progressing from simple to complex: history and physical examination → plain radiographs → MRI if necessary → CT for surgical planning.

4.3. Imaging and Diagnostic Algorithm

Surgical planning begins in the outpatient clinic with radiological images, not in the operating room. Since relying on a single imaging modality can lead to significant errors, a systematic algorithm combining information from each method should be preferred.

4.3.1. Direct radiographs

- **Oblique radiographs:** In the classic " Scottie dog" appearance, the "collar" mark on the dog's neck represents a pars defect; however, it has low sensitivity in capturing early stress reactions.
- **Dynamic radiographs (flexion-extension lateral radiographs):** Important for assessing segmental instability and the degree of spondylolisthesis; provide critical information when determining whether pars repair or fusion is necessary (Figure 1)(18–22).

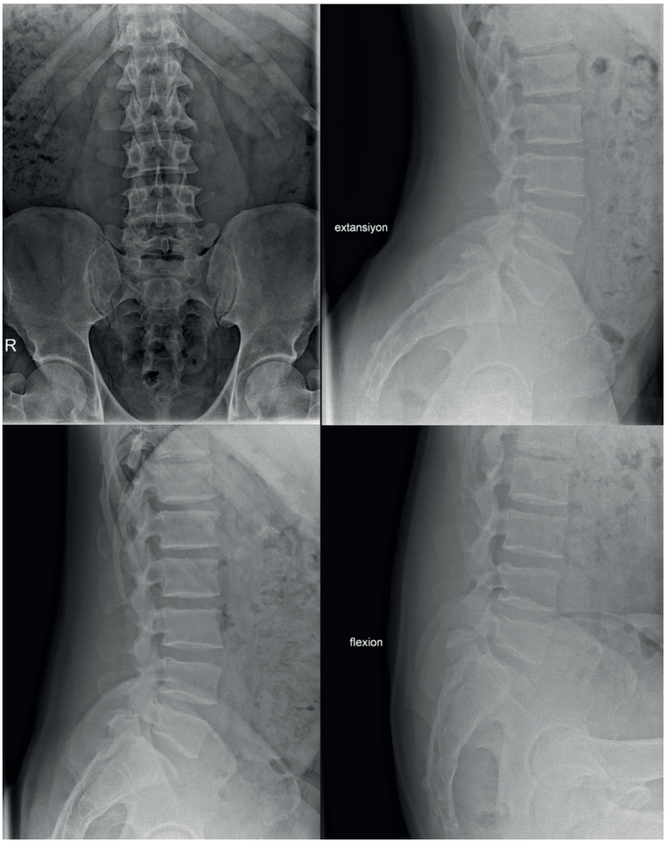

Figure 1. Dynamic lumbar radiographs demonstrating spondylolysis and segmental instability. Anteroposterior and lateral lumbar spine radiographs with flexion and extension views. The dynamic lateral images demonstrate anterior translation of the L5 vertebral body over S1, consistent with isthmic spondylolisthesis associated with pars interarticularis defects. Flexion–extension views are useful for evaluating segmental instability and dynamic vertebral slippage.

4.3.2. Computed Tomography (CT) – The Gold Standard in Bone Morphology

CT is the gold standard for demonstrating bone morphology in the pars interarticularis region and provides detailed information about the presence, configuration, and degree of chronicity of the defect.

- **Typical findings:** Loss of bone continuity in the pars region is observed as a "gap" or "slit" in axial and sagittal sections. In chronic cases, sclerosis and fragmentation at the defect edges are suggestive of pseudoarthrosis; in acute lesions, the edges are sharper and sclerosis is not prominent.

- **Assessment of spondylolisthesis:** CT scan provides detailed information on the presence and degree of concomitant spondylolisthesis, facet joint morphology, and canal/foramen configuration.
- **3D reconstruction:** In surgical plans such as pedicle and intralaminar screw fixation, 3D reconstructions offer significant advantages in terms of bone anatomy and fracture line extent(Figure 2-3)

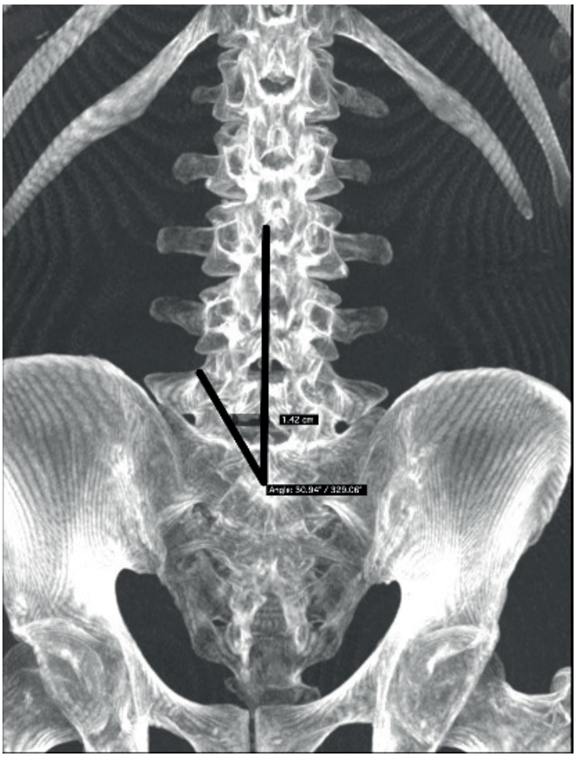

Figure 2. Three-dimensional CT reconstruction demonstrating screw trajectory planning. Three-dimensional reconstructed CT image of the lumbar spine and sacrum demonstrating the planned trajectory and angulation for laminar screw placement. The image illustrates the screw entry point relative to the midline and the measured distance from the midline, as well as the medial angulation of the intended screw trajectory used for surgical planning.

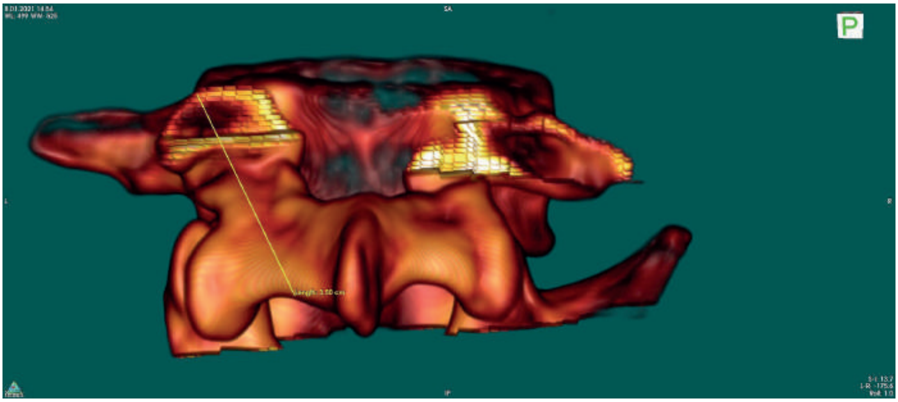

Figure 3. Three-dimensional CT reconstruction demonstrating screw length measurement. Three-dimensional reconstructed CT image of a lumbar vertebra demonstrating measurement of the planned laminar screw trajectory. The measured line indicates the estimated screw length (approximately 3.5 cm) along the intended path through the posterior elements, facilitating preoperative planning and appropriate screw selection.

The most significant limitation of CT is its use of ionizing radiation; this is particularly important in children and adolescents, the age group where spondylolysis is most common. Therefore, efforts are being made to reduce the radiation dose to conventional radiography levels using low-dose CT protocols and limited z-axis coverage(23–26).

4.3.3. Magnetic Resonance Imaging (MRI) – Key to Early Diagnosis

MRI is critical for the early diagnosis of spondylolysis due to its high sensitivity in demonstrating bone marrow edema and early-stage stress reactions. Bone marrow edema can be detected in the pars and adjacent pedicle even before cortical integrity is compromised; this phase is when conservative treatment is most effective.

The main advantages of MRI are:

- **Showing an early stress response:** Bone marrow edema (grade 1 lesion) in the pars region reveals the loading phase, which is not yet visible on CT(27).
- **Soft tissue and neural structure assessment:** Nerve roots, dural sac, disc, facet joints, epidural and foraminal soft tissues can be examined in detail on MRI(24).

- **Radiation-free examination:** This offers a significant advantage, particularly in repeated check-ups in pediatric and adolescent populations(28–30).
- **Exclusion of accompanying pathologies:** Disc degeneration, end plate fractures, transition anomalies, and tumoral or infectious processes can be evaluated in the same examination(24,28).

Proposed basic MRI protocol:

- Sagittal T1: Anatomy of the pars, pedicle, and facet, and demonstration of the fracture line as a hypointense band.
- Sagittal STIR or fat-suppressed T2: Demonstrating bone marrow edema and stress reactions.
- Axial T1/T2 (thin section): Evaluation of the lateral recess, foramen, epidural fat, and nerve roots.
- If necessary, sequences such as 3D T1-VIBE or UTE: Three-dimensional, high-resolution visualization of cortical bone and fracture line (Figure 4)(24,27,31–33).

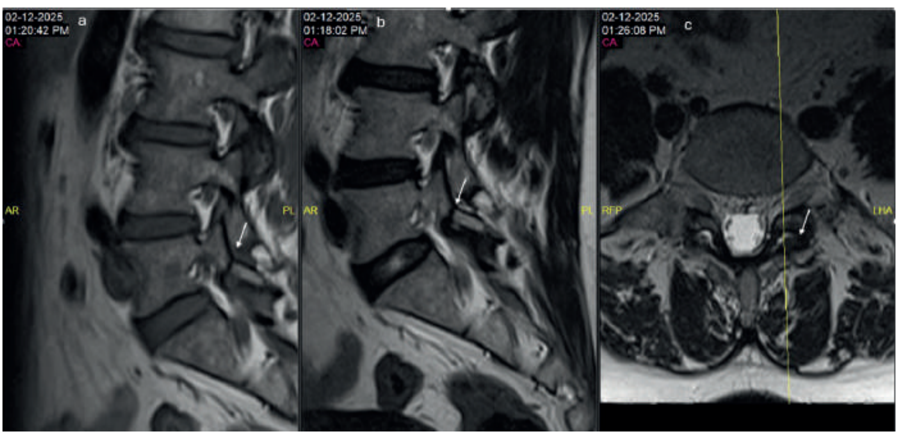

Figure 4. MRI demonstration of pars interarticularis defect on sagittal and axial images. Sagittal T1- and T2-weighted magnetic resonance images (a, b) and an axial section (c) of the lumbar spine demonstrating a defect in the pars interarticularis at the L5 level (arrows). The sagittal images show interruption of the pars continuity, while the axial image confirms the defect within the posterior elements. These findings are consistent with lumbar isthmic spondylolysis.

Posterior epidural fat interposition (EFI) is an indirect MRI finding resulting from minimal anterior displacement of the corpus and slight posterior displacement of the lamina and pars complex, causing the normally segmental epidural fat pads to coalesce as a single mass. This appearance allows for the prediction of spondylolysis with high sensitivity in midsagittal T1-weighted sections, especially at the L5 level, and its diagnostic value increases in cases where a pars defect cannot be directly demonstrated or in early-stage lesions (34). (Figure 5)

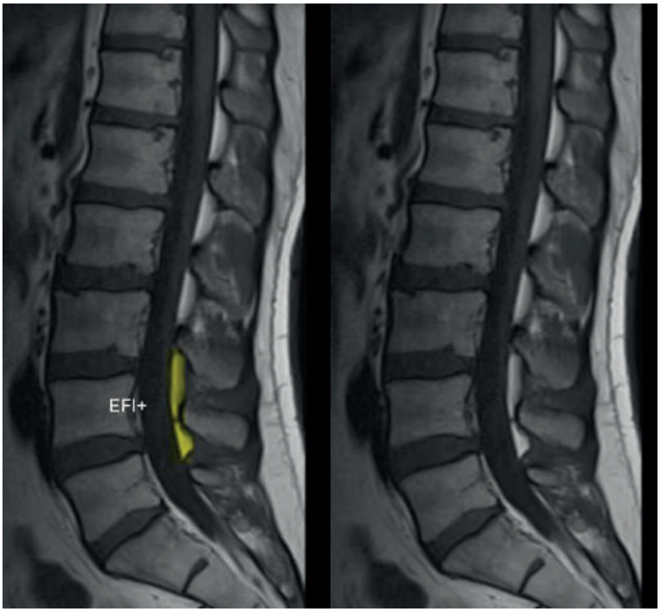

Figure 5: In mid-sagittal T1-weighted images, impaired posterior epidural fat segmentation and epidural fat interposition (EFI) are established indirect radiological markers of spondylolysis with high diagnostic reliability.

4.3.4. MRI-CT Comparison and Clinical Algorithm

Table: MRI-CT Comparison and Clinical Algorithm(24,35,36)

Feature	MRI	CT
Early stress reaction (edema)	Very good – the most sensitive method for grade 1.	Limited – bone marrow edema is not visualized.
Fracture line morphology	Good, very good with special sequences.	Gold standard
Soft tissue and neural structure	Gold standard	Limited

Repair/ fibrous tissue, pseudoarthrosis	Very good	Good correlation with sclerosis and gaps.
Radiation	None	Yes – it is significant in pediatric patients.
3D reconstruction	In development (T1-VIBE, 3D sequences)	Routine, very good.
Indirect sign (EFI sign)	Posterior epidural fat interposition sign: highly suggestive for pars defect, even when the fracture line is not clearly visible.	Not visualized; evaluation of EFI relies on MRI

Practical clinical advice:

- In adolescent and young adult patients suspected of having spondylolysis, MRI should be the first further imaging choice after plain radiography in most cases(24,28).
- If only a grade 1 stress reaction or subtle, indistinct changes are detected on MRI, conservative treatment is preferred; if progression or surgery is considered, complementary examination with CT should be performed for a detailed assessment of the morphology of the pars fracture line and bone structure(24,37).
- In cases where surgery is planned, CT scans are often indispensable for evaluating screw trajectory, lamina thickness, and pars canal(23,24,38).

4.4. Influence of Radiological Findings on Surgical Decision-Making

Not every spondylolysis patient is a candidate for surgery; imaging findings should be interpreted together with clinical findings to clarify the patient profile.

- **"Ideal" pars repair candidate:** Young, active patients with minimal or no spondylolisthesis, preserved disc height and facet joints, and MRI confirming an "active" lesion with bone marrow edema(2,37,39–41).
- **High-risk pars repair candidate:** Cases of advanced spondylolisthesis with significant sclerosis and large gaps at the pars margins, marked disc narrowing, and segmental instability; in this group, insistence on direct repair may be insufficient in the long term, and the need for segmental fusion is high(37,41,42).

The surgical strategy should be explained to the patient as follows: "The goal is to achieve stability while preserving the disc and segment as much as possible; if intraoperatively the bone quality is found to be unsuitable for repair, the plan can be changed to a safe fusion if necessary." This flexibility is critical for realistic expectation management for both surgeon and patient(2,39,43–45).

4.5. The Role of Imaging in Intralaminar Screw Planning

In intralaminar screw surgery, the entry point and trajectory angle are among the most critical factors in preventing complications.

- **CT planning:** Lamina thickness and cortical boundaries must be carefully measured in axial and sagittal CT sections; a thin lamina increases the risk of cortical breach and neural injury. **Personalization:** Each patient's anatomy is different; the ideal length and diameter of the screw, ensuring it securely grips both the superior and inferior cortex, must be calculated precisely on the CT scan . It is crucial to recognize that the pars defect bed is a narrow and delicate bony corridor, and surgery should be avoided based on "approximate" anatomical information without three-dimensional preoperative planning(38). (Figure 6)

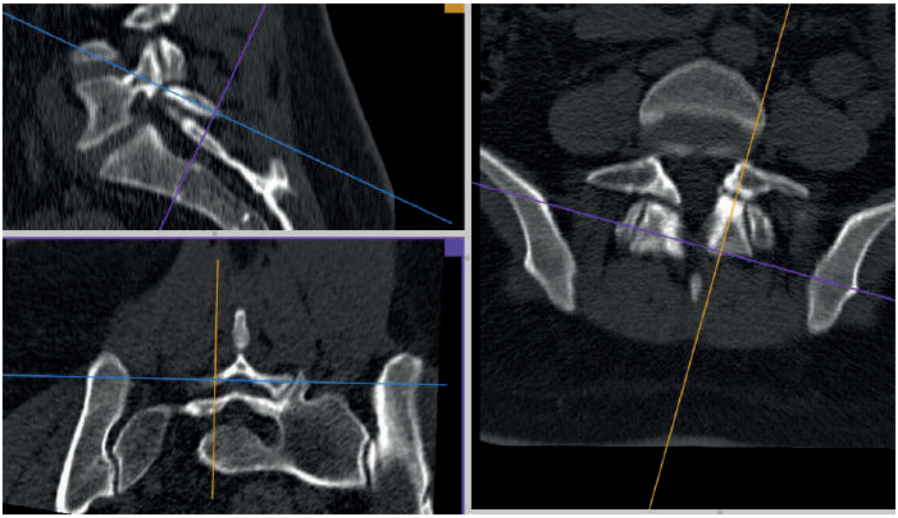

Figure 6. Multiplanar CT reconstruction demonstrating intralaminar screw trajectory. Sagittal, axial, and coronal multiplanar computed tomography reconstructions illustrating the planned trajectory for intralaminar screw placement. The colored reference lines indicate the intended screw path through the lamina toward the contralateral posterior elements, highlighting the spatial orientation and angulation used for preoperative planning of intralaminar fixation.

4.6. Staging and Hollenberg Classification in MRI

Hollenberg et al.'s MRI-based classification provides a system to guide clinical management by defining pars stress reaction and spondylolysis in five stages.

- Grade 0: Normal parity, no signal change.
- Grade 1: Only T2/STIR hyperintensity (bone marrow edema) in the pars/pedicle region, T1 normal; early stress reaction, most favorable period for conservative treatment.
- Grade 2: Thinning and irregularity of the pars with associated edema, incomplete fracture; conservative treatment is still the first choice.
- Grade 3: Complete fracture line and accompanying edema; acute/subacute fracture, conservative treatment should be attempted but surgical risk is increased.
- Grade 4: Complete fracture line, marked sclerosis, no edema; chronic pseudoarthrosis, surgical repair or stabilization is more frequently considered in cases of long-standing symptoms.

This classification clarifies the acute-chronic distinction made with CT via bone marrow edema and provides practical guidance, especially in the decision-making process between conservative treatment and direct pars repair (27).

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CHAPTER 5

The New pars listhesis grade (PLG) Classification System

5.1. Introduction and Requirements

Isthmic spondylolisthesis is a pathology characterized by anterior displacement of a vertebral body over the underlying vertebra due to a defect in the pars interarticularis. Meyerding classification is a radiographic grading system used to quantify the severity of vertebral slip in spondylolisthesis on lateral lumbar X-rays. The inferior vertebral body is divided into four equal parts, and the percentage of anterior translation of the superior vertebra over this inferior vertebra is measured. Grade I corresponds to 0–25% slip, Grade II to 25–50%, Grade III to 50–75%, and Grade IV to 75–100% slip. When the slip exceeds 100%, it is classified as Grade V, also called spondyloptosis. This system is widely used because of its simplicity and acceptable inter- and intra-observer reliability, but the numerical grade should always be interpreted together with the patient's symptoms and other radiological parameters, as clinical severity does not necessarily parallel the degree of slip(1,2). Clinical management includes conservative or surgical treatment options depending on the degree of slippage, symptom severity, and the patient's functional capacity. While the Meyerding classification is currently the most widely used system, it is limited in its ability to adequately describe the posterior column morphology and pars-level slippage, especially in low-grade (Grade 0–1) cases.

The new Pars Listhesis Grade (PLG) classification defines anterior displacement by evaluating the position of the pars neck relative to the inferior articular process (IAP) line, rather than the vertebral body. This is a CT-based, morphometric isthmic analysis focusing on the posterior column.

The PLG system was introduced as a CT-based classification for isthmic spondylolisthesis(1).

5.2. Definition and Basic Principle

The PLG classification is based on parasagittal CT scans evaluating anterior–posterior displacement of the defective pars neck relative to the IAP reference line. The evaluation is based on anatomical relationships in a neutral, static position, the system describes posterior column morphology rather than segmental instability. Its main objectives are as follows:

- The Meyerding classification aims to provide more detailed morphological staging, especially in Grade 0–1 patients.
- To present a practical evaluation algorithm with high intra- and inter-observer reliability.
- To define the clinical significance of PLG grades by revealing their relationship with pain and functional scores (VAS, ODI, SF-36).

5.3. Imaging Technique and Reference Line Definition

Reference section selection: Evaluation is performed on the parasagittal CT section where the pars neck, IAP and pedicle are most clearly visualized (Figure 1).

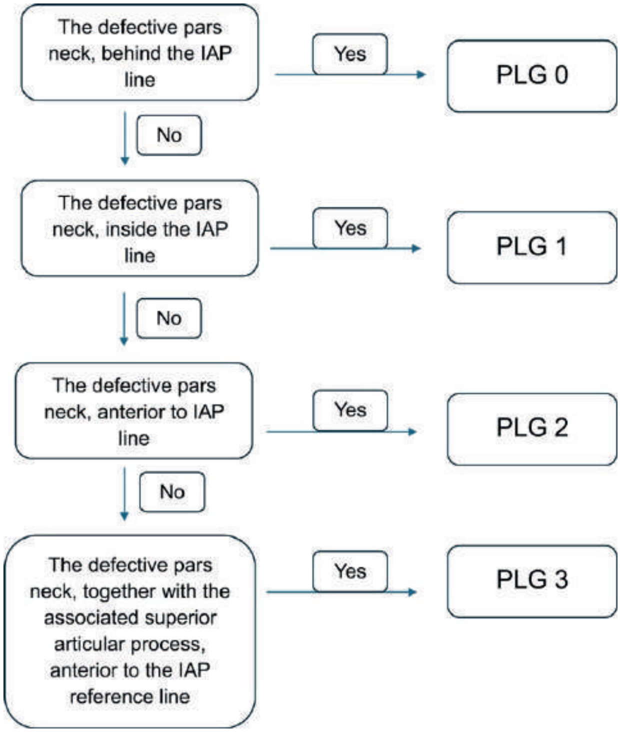

Figure 1. Pars Listhesis Grade (PLG) classification algorithm. The decision tree outlines the grading of pars listhesis based on the location of the defective pars neck relative to the inferior articular process line. PLG 0–3 corresponds to increasing degrees of anterior displacement and associated morphological changes.

Drawing of the IAP reference line:

- IAP with oblique/concave anterior surface: The cranial and caudal endpoints are connected, and this line is extended cranially to be accepted as the reference line.
- Flat-faced IAP: A line parallel to the front face of the IAP is used as a reference line.

All PLG assessments are based on the position of the pars neck relative to the IAP reference line (Figure 2).

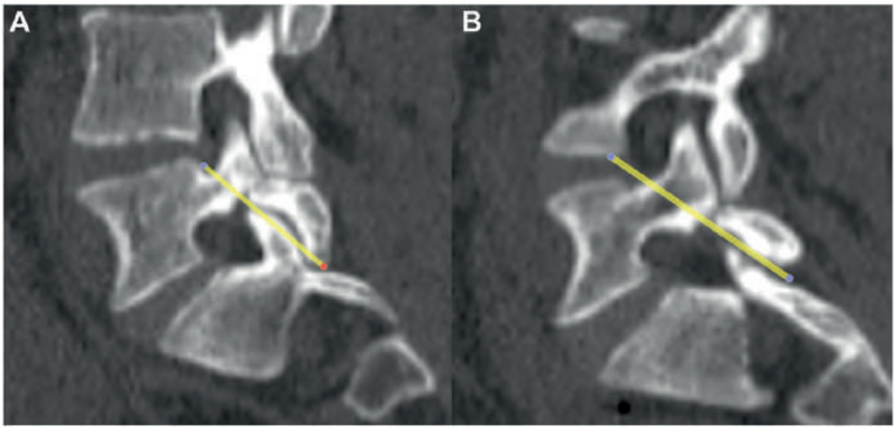

Figure 2. Parasagittal lumbar computed tomography section at the L5–S1 level of the same patient. On the right side, the reference line was established by drawing a parallel line through both ends of the inclined inferior articular process (A), whereas on the left side, the reference line was determined parallel to the anterior edge of the straight inferior articular process

5.4. PLG Staging: Definitions

PLG consists of four degrees: 0–3.

- **PLG 0 – Normal. Pars neck posterior to the IAP line.**

The entire pars neck lies posterior to the IAP reference line, regardless of whether the pars interarticularis is intact, fractured, or chronically defective. (Figure 3-4)

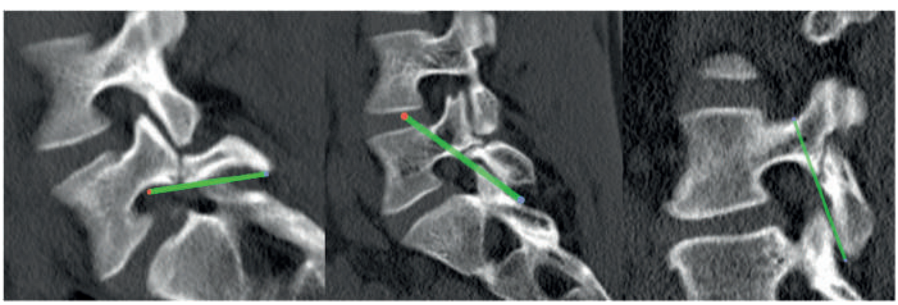

Figure 3. Parasagittal CT images of three patients in the degenerative disc group showing the intact pars interarticularis located posterior to the line drawn anterior to the inferior articular process (green line) (Pars Listhesis Grade 0).

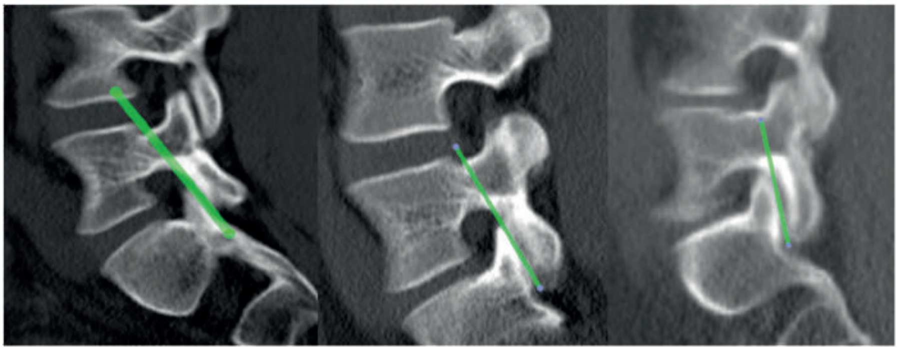

Figure 4. In the parasagittal computed tomography images of three patients within the pars defect group, the defective pars neck is located posterior to the line passing anterior to the inferior articular process (green line) (Pars Listhesis Grade 0).

- **PLG 1 – Mild listhesis**

The defective pars neck partially intersects the IAP line; a portion of the neck extends anteriorly to the line, while another portion remains posteriorly (Figure 5).

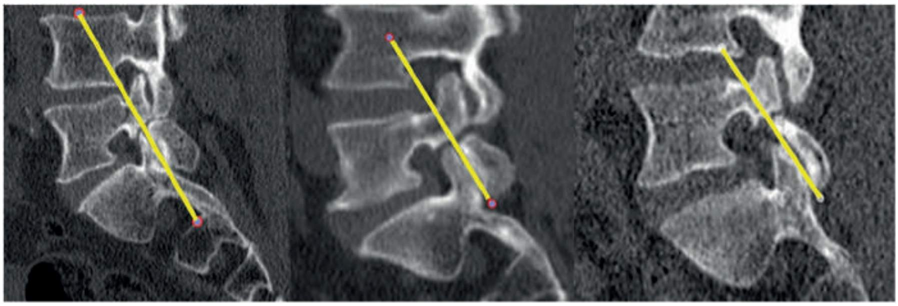

Figure 5. Parasagittal computed tomography images of three patients in the pars defect group. The defective pars neck is above the inferior articular process line (yellow line) and slightly displaced anteriorly Pars Listhesis Grade 1).

- **PLG 2 – Moderate listhesis**

Anterior displacement is moderate. The entire pars neck lies anterior to the IAP reference line (Figure 6).

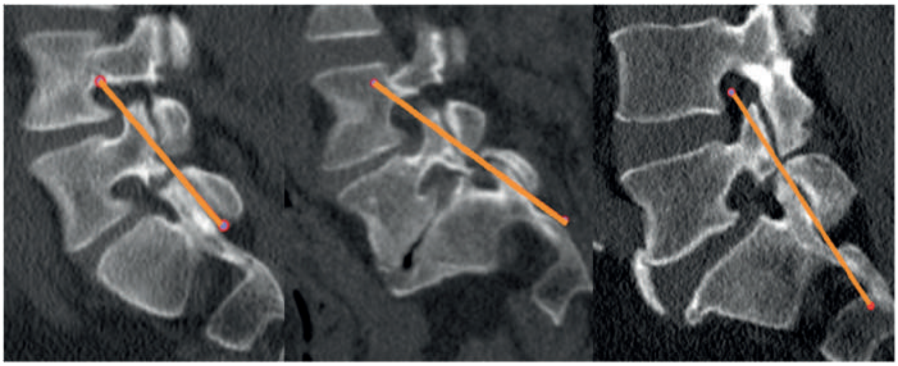

Figure 6. Parasagittal computed tomography images of three patients in the pars defect group. The defective pars neck is completely anterior to the inferior articular process line (orange line) (Pars Listhesis Grade 2).

- **PLG 3 – Severe listhesis**

The defective pars neck is entirely located anterior to the IAP reference line. The posterior column and facet complex together show a marked anterior translation (Figure 7).

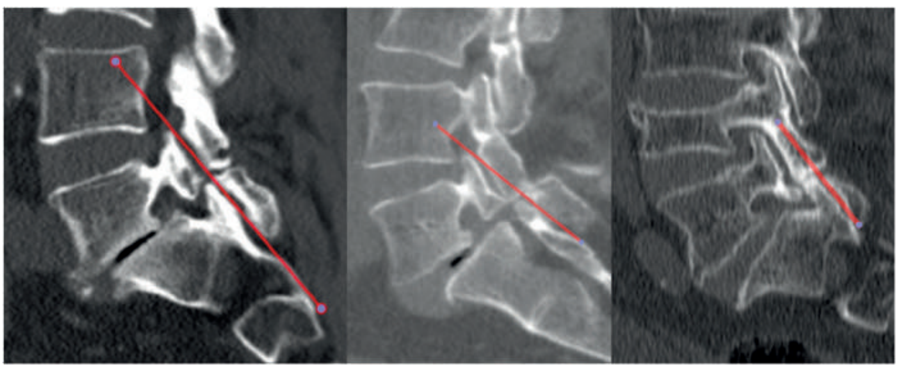

Figure 7. Parasagittal computed tomography images of three patients in the pars defect group. The defective pars neck is anterior to the inferior articular process line (red line) with the superior articular process (Pars Listhesis Grade 3).

Reporting should be done separately for the right and left sides; the “right PLG / left PLG” rating should be indicated at each level.

5.5. Relationship with Meyerding and Clinical Correlation

A moderate positive correlation (approximately $r \approx 0.46$) was shown between PLG and Meyerding grades. A strong positive correlation ($r \approx$

0.82) between right and left PLG values supports the reliability and internal consistency of the system. The detection of significant displacement at the pars level, even at low Meyerding grades, suggests additional discriminatory value of the PLG system.

In our cohort, approximately 90% of Meyerding Grade 0 cases demonstrated anterior displacement of the pars neck relative to the IAP line (PLG ≥1).

- In Grade 1 cases, this rate reaches 99%.
- Meyerding Grade 2 is only compatible with PLG 2–3, and Grade 3 is only compatible with PLG 3.

These findings suggest that the PLG system provides additional morphological discrimination, particularly in Meyerding Grade 0–1 cases. Clinically, in a series of 40 patients, it was reported that increasing PLG grade had no significant effect on pain intensity (VAS) and mental health (SF-36 MH), but decreased physical function (SF-36 PH) and significantly increased disability level (ODI). A higher PLG grade is associated with lower physical capacity and greater functional limitations.

The method's intra-observer and inter-observer kappa values were reported to be in the range of 0.80–0.97, with statistically excellent reliability. These data support that PLG is a reproducible and reliable measure in clinical practice(1).

5.6. Clinical Use and Practical Recommendations

The PLG classification should be considered in patients diagnosed with isthmic spondylolysis or spondylolisthesis, particularly in the following situations: · Meyerding Grade 0–1 patients in whom additional morphological differentiation at the posterior column level is required. Situations in which objective grading of posterior column translation is desired prior to surgical planning.

Reporting recommendation:

- For each level, the Meyerding grade and the right and left PLGs must be clearly indicated (e.g., "L5–S1: MG 1, right PLG 2, left PLG 1").

In treatment planning, PLG alone is not an indicator of instability; it should be considered as a structural parameter reflecting morphological severity. In surgical decision algorithms:

- Meyerding degree,
- PLG classification,
- Spinopelvic parameters,

- Findings of instability in dynamic radiographs,
- Clinical scores (VAS, ODI, SF-36)

should be evaluated together.

The PLG classification is a CT-based, highly reliable morphometric system focusing on posterior column morphology and serves as a complementary staging tool for isthmic spondylolisthesis. Especially in Meyerding Grade 0–1 cases, its use as a complementary tool in patient follow-up and treatment planning both enriches morphological evaluation and refines the clinical decision-making process(1,3–6).

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CHAPTER 6

Clinical Indications and Patient Selection

6.1. Introduction: Does Every Pars Defect Require Surgery?

With the widespread use of imaging techniques, pars interarticularis defects and isthmic spondylolysis are being detected more frequently than expected. However, not every radiologically observed pars defect is clinically significant and requires surgery. Therefore, establishing the correct symptom-radiological relationship is critical to avoiding unnecessary surgery and to treating patients who truly need surgery in a timely manner and with appropriate methods. A significant proportion of patients with pars defects are asymptomatic; pars defects may be detected without clinical symptoms, particularly in individuals who do not participate in sports and who undergo imaging for other reasons. In such cases, the approach is not aggressive treatment, but rather informing the patient, reviewing risk factors, and planning periodic clinical and/or radiological follow-ups if necessary(1–3).

In symptomatic pars defects, the primary complaint is mechanical low back pain; the pain is usually localized in the low lumbar region, may be unilateral or bilateral, and increases especially with weight-bearing, prolonged standing, extension, and rotation. In athletes, post-training exacerbation, decreased performance, and avoidance of certain technical movements are typical; when spondylolisthesis develops, symptoms such as pain radiating to the legs, pain in the hip and hamstring, and fatigue during long walks may also be added to the clinical picture.

The distinction between asymptomatic and symptomatic cases is a fundamental starting point for determining surgical indication; planning surgery solely on the basis of radiological findings is not consistent with current approaches. The patient's history, duration of pain, response to conservative treatment, and level of functional limitation must all be included in the decision-making process(1,3,4).

6.2. Criteria for Transition from Conservative Treatment to Surgery

In patients diagnosed with pars defect or isthmic spondylolysis, the first-line approach is usually conservative treatment. Especially in young patients with acute/subacute stress reactions, incomplete defect development, or no significant spondylolisthesis, symptom regression and functional improvement are often possible with conservative treatment.

The key components of the conservative approach are:

- Activity modification: Restricting or temporarily stopping movements that force lumbar hyperextension and rotation; reorganizing the in-season/off-season training plan for athletes.
- Analgesic/anti-inflammatory therapy: Short-term, targeted use of medication to control pain.
- Corsets and external supports: Especially in acute stress reactions, short-term brace use can support healing by reducing micromovements.
- Rehabilitation and exercise: Programs aimed at strengthening core muscles, stretching hamstrings and hip flexors, and improving lumbopelvic stability.

The effectiveness of conservative treatment is generally evaluated over a period of 3–6 months; guideline reviews report that structured conservative treatment is recommended for at least 3–6 months in most patients. At the end of this period:

- Significant reduction in pain,
- an increase in functional capacity
- return to sport for athletes

If this is the case, surgery may not be necessary.

The main criteria that warrant surgical evaluation are:

- Significant mechanical low back pain that persists despite at least 3–6 months of well-implemented conservative treatment.
- Significant limitations in activities of daily living (marked decrease in tolerance for walking, sitting, and standing)

- In athletes, repetitive and severe pain that prevents return to performance.
- Radiologically progressive spondylolisthesis or segmental instability demonstrated by dynamic radiographs.
- Although rare, persistent or progressive neurological deficits can occur despite conservative treatment.

This framework prevents the notion that "every painful area requires surgery," and directs surgery to the patient group that truly needs it(1,5–8).

6.3. Spectrum of Surgical Indications: Pars Repair and Fusion

Surgical indications for pars defects can be broadly grouped into two main categories: direct pars repair (motion-preserving) and segmental fusion. The intermediate gray area includes stabilization techniques that support pars repair with pedicle/intralaminar screw fixation(4,7,9–12).

6.3.1. Indications for direct pars repair

Direct pars repair is particularly advantageous in patients with the following profiles:

- Young (approximately 15–40 years old), active or athletic patient.
- Unilateral spondylolysis (mostly L5), minimal or no spondylolisthesis.
- A segment with preserved disc height and no significant disc degeneration.
- Mechanical low back pain that persists despite at least several months of appropriate conservative treatment.
- Absence of significant neurological deficits, only minimal or transient radicular symptoms.

In these patients, direct repair targeting the pars defect aims to stabilize the source of pain and preserve segment movement by promoting bone fusion as a segment-sparing method. Studies show that in appropriately selected young athletes, a high rate of return to sport can be achieved within 5–12 months after direct pars repair(8,12–16).

6.3.2. Indications for segmental fusion

In patients unsuitable for a segment-sparing approach or with persistent instability after failed pars repair, segmental fusion is a rational and often unavoidable option.

The main indications for fusion are:

- Advanced spondylolisthesis (especially high-grade L5–S1 displacements).
- Significant disc degeneration, loss of disc height, and instability findings on dynamic radiographs.
- Multilevel pathology or a combination of defects and degenerations at multiple levels.
- Cases with significant neurological deficits, accompanied by severe foraminal or central stenosis.
- Ongoing instability and pain following a previous failed pars repair.

In this group, repairing only the pars defect is often insufficient; stabilizing the entire segment and readjusting load sharing are necessary(3,4,17–22).

6.4. Special Groups: Young Athletes and Sedentary/Elderly Patients

6.4.1. The nuances of indications in young athlete patients

Young athletes are one of the most vulnerable groups when it comes to pars defect surgery; not only pain and radiological findings, but also return-to-sport goals, performance level, career plans, and psychological state must be considered.

Key points to consider:

- Pain intensity and duration: Not only the VAS score but also the movements the patient is unable to perform during training, their participation in competition, and training intensity should be considered.
- Adherence and response to conservative treatment: Was genuine 3–6 months of load modification and rehabilitation implemented, or was it merely a matter of "managing" with analgesics?
- Radiological stage: Is it an active stress reaction (edematous pre-lysis) on MRI, or a large, chronic defect with sclerotic edges on CT? Is listhesis present, and if so, to what degree?

In this group, segment-preserving surgery (especially direct pars repair) stands out strongly; the aim is both to relieve pain and to preserve range of motion and performance potential. However, in the presence of advanced spondylolisthesis, significant disc degeneration, or neurological deficits, fusion options should also be considered, after explaining the risk-benefit balance(1,1,5,13,23).

6.4.2. Sedentary adult and elderly patients

In sedentary adults or elderly patients, pars defect is often associated with isthmic spondylolisthesis and degenerative changes; the pain profile depends not only on the pars defect but also on disc degeneration, facet arthropathy, spinal stenosis, and adjacent segment pathologies.

Those to be considered in this group are:

- What type of pain is it: mechanical low back pain, neurogenic claudication, or radicular pain?
- Walking distance, sitting/standing tolerance, level of functional independence.
- Accompanying comorbidities and acceptability of the surgical/anesthesia risk profile.

Pars repair alone is rarely sufficient in this age group; often, combined pathologies requiring segmental fusion and decompression are involved. Nevertheless, accurate analysis of the defect and segment biomechanics guides which levels of fusion should be involved and which technique should be used(3,7,24–27).

6.5. Biomechanical and Radiological Parameters in Patient Selection

When determining surgical indications, not only clinical but also specific biomechanical and radiological parameters should be systematically evaluated:

- Degree of spondylolisthesis: Meyerding classification based on slip percentage; pars repair is a stronger option at low degrees, while fusion is preferred at high degrees.
- Disc height and Pfirrmann grade: Preserved disc height and low degeneration grades favor segment-sparing surgery.
- The shape and extent of the pars defect: A small, acute defect presents different surgical challenges and graft requirements than a large, chronic defect with sclerotic edges.
- Instability on dynamic radiographs: The presence of significant translation (e.g., ≥4–5 mm) or angulation on flexion-extension radiog-

raphs provides information about the segment's stability reserve and strengthens the indication for segmental fusion.

Systematic analysis of these parameters makes patient selection more objective and repeatable, reducing reliance on subjective surgical experience(1,9,16,28–30).

6.6. Decision-Making Algorithm and Communication with the Patient

Surgical indication and patient selection are not only a technical assessment but also part of healthy communication and expectation management with the patient. A practical decision-making process can be shaped around the following questions:

1. Are there any symptoms? If so, what is their severity, duration, and functional impact?
2. Was conservative treatment applied for a sufficient duration and with adequate content, and what was the objective response?
3. What is the radiological stage of the defect, the degree of spondylolisthesis, the disc/facet status, and the findings of instability?
4. What is the patient's age, activity level, occupation, sports goal, and general expectations?
5. Is segment-sparing surgery a realistic and safe option, or is fusion more suitable?

Once these questions are clearly answered, the potential benefits and risks of pars repair versus fusion, return-to-sport/daily life times, and long-term expectations should be explained to the patient in understandable language. Explaining why pars repair is more suitable for a young athlete and why fusion is more suitable for a sedentary elderly patient, when necessary, is an approach that improves not only radiological but also functional and psychological outcomes(1,7,31–34).

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CHAPTER 7

Percutaneous Surgical Technique – Percutaneous Intralaminar Screw Fixation and Bilateral Cross-Laminar Screw (CLS) Fixation (Modified Buck)

7.1. General Principle and Purpose

This method applies the lamina-pars-pedicle screw concept used in classic open Buck's pars repair with a minimally invasive approach, aiming to significantly reduce surgical damage to the posterior muscle tissue by directly targeting the defect. Cannulated screw systems aim to stabilize the pars defect under controlled compression and support bone grafting and biological union(1–4).

7.2. Percutaneous Intralaminar Screw Technique (Modified Buck)

Positioning: The patient is placed in a prone position on a radiolucent table with appropriate thoracic and pelvic bolsters to maintain physiological lumbar lordosis. The arrangement should allow for free movement of the C-arm fluoroscope in both AP and lateral projections.

Imaging: Entry should not be made until the C-arm is in focus at the L5 vertebra and pars interarticularis line in "true AP" and "true lateral" views; the spinous process should be midline, and the pedicle contours should be symmetrical. (Figure 1)

Figure 1. Intraoperative imaging and postoperative evaluation in L5 spondylolysis with L4 grade I spondylolisthesis. The upper panel shows the intraoperative setup with C-arm fluoroscopic guidance during posterior lumbar surgery. The lower left panel demonstrates postoperative sagittal CT reconstruction confirming intralaminar screw fixation across the pars interarticularis defect. The lower right panel shows dynamic lateral lumbar radiographs used for postoperative evaluation. The case illustrates L5 spondylolysis associated with grade I spondylolisthesis at the L4 level.

Skin incision: In the traditional technique, an incision at the level of the defect and a second incision at a lower level for the passage of the Jamshidi needle are required; however, in percutaneous application, a single 2 cm incision in the midline, usually 1-2 levels lower, is sufficient; this minimizes soft tissue trauma and blood loss. (Figure 2-3)

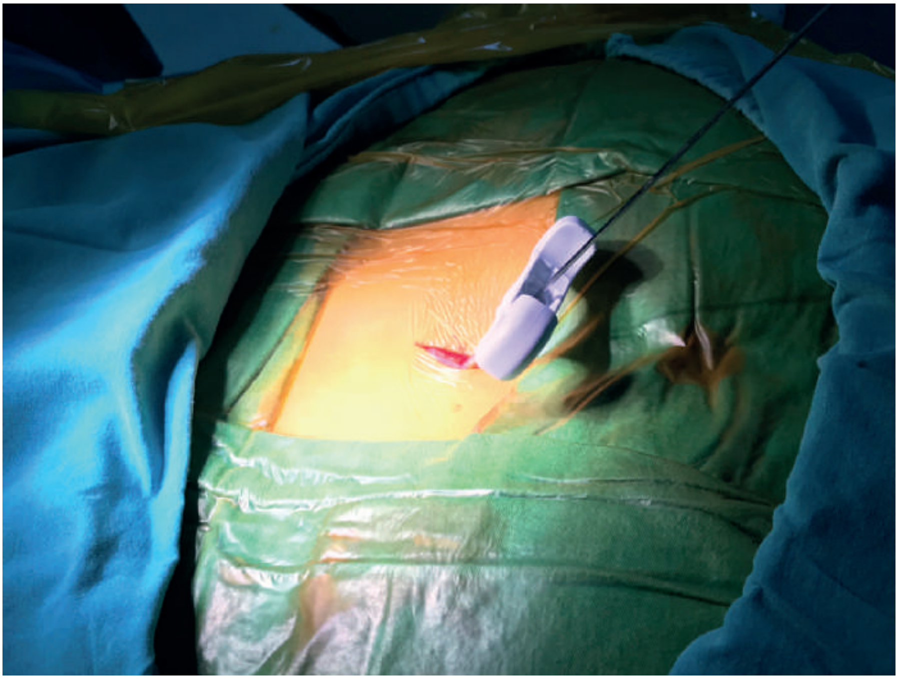

Figure 2. Intraoperative placement of a guidewire during intralaminar screw fixation. Intraoperative photograph demonstrating placement of a Kirschner wire during intralaminar screw fixation for pars repair. Following entry of the intralaminar screw guide into the lamina, the Kirschner wire is advanced toward the pedicle to guide the intended screw trajectory under fluoroscopic control.

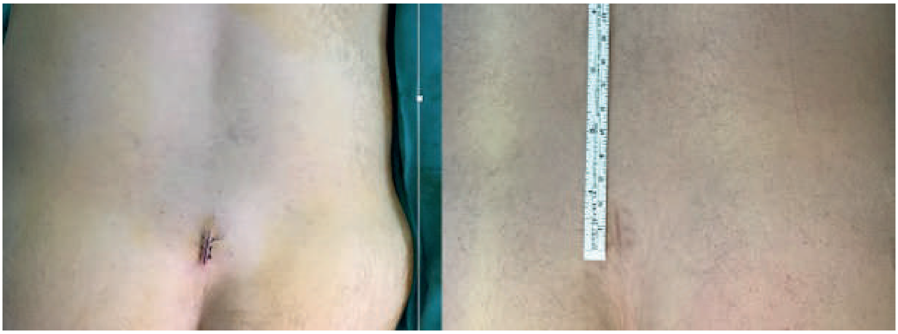

Figure 3. Intraoperative and postoperative skin incision for intralaminar screw fixation. Clinical photographs demonstrating the small skin incision used for minimally invasive intralaminar screw fixation. The left image shows the intraoperative incision immediately after the procedure, while the right image demonstrates the healed incision during follow-up examination. The incision length is approximately 2 cm, reflecting the minimally invasive nature of the technique.

Lamina entry point (Jamshidi needle placement):

- The primary entry point is the lower edge of the junction between the base of the spinous process and the lamina; this represents a relatively safe area because the lamina thickness is greater and it is distant from intracanal structures (Figure 4)

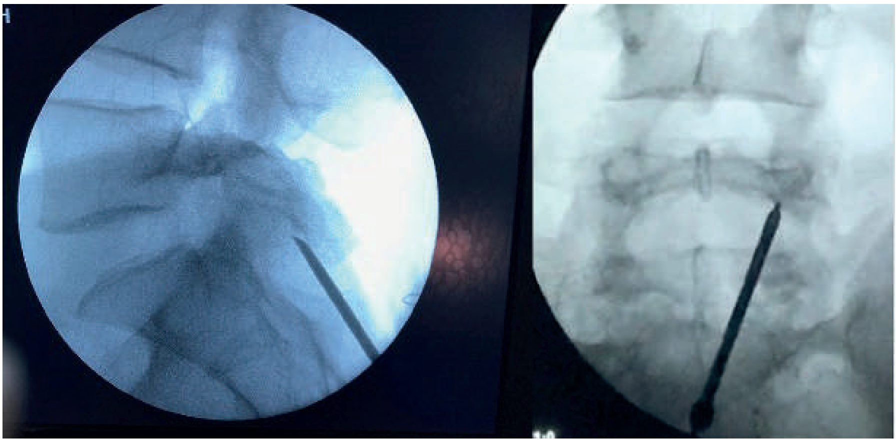

Figure 4. Fluoroscopic visualization of Jamshidi needle entry into the lamina. Intraoperative fluoroscopic images demonstrating the insertion of a Jamshidi needle into the lamina during intralaminar screw fixation. The lateral and anteroposterior fluoroscopic views confirm the correct entry point and trajectory of the needle through the laminar structure under real-time imaging guidance.

- Depending on the patient's anatomy, the entry point may sometimes be shifted to a more cranial area of the lamina or closer to the inferior articular facet; it is important that this choice be made with CT pre-planning. (Figure 5-6)

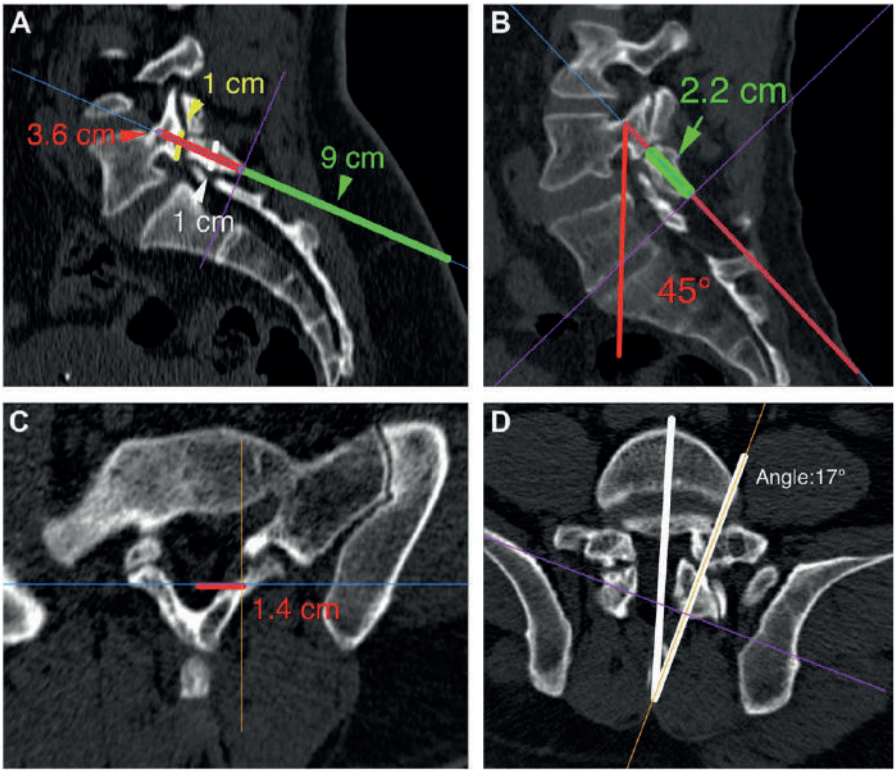

Figure 5. (A) Linear values for the ideal intralaminar screw trajectory in the lumbar 5 vertebrae (L5) lamina in the sagittal plane. Intralaminar screw length 3.6 cm, pars defect neck diameter 1 cm, midlamina thickness 1 cm, skin-to-lamina distance 9 cm (B) Sagittal angle (45°) and isthmic lamina length (2.2 cm) of the ideal screw trajectory relative to the posterior cortex of the vertebral corpus on computed tomography in the sagittal plane. (C) Distance of the screw insertion site from the line passing through the middle of the spinous process on computed tomography in the axial plane. (D) Trajectory of the coronal angle between the midspinous line and the screw trajectory line.

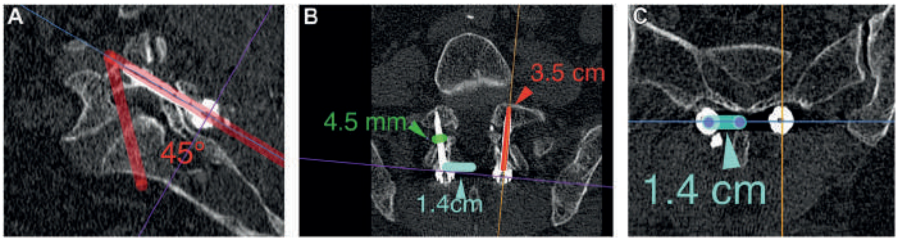

Figure 6. Ideal screw trajectory with 3-dimensional (3D) multiplanar reconstruction using a lumbar computed tomography scan of a patient in whom we performed pars fixation with a percutaneous intralaminar screw. (A) 45° sagittal screw insertion angle. (B) 3.5 cm screw length, 4.5 mm screw diameter. (C) Approximately 1.4 cm lamina lateral screw distance.

Guidewire (K-wire) advancement: After the Jamshidi needle is placed into the lamina cortex, the guidewire is aimed to cross the pars defect within the cortical boundaries of the lamina; the ideal trajectory crosses the pars neck along the laminar axis and terminates in or near the superior cortex of the pedicle. Wire position should be confirmed by both AP and lateral fluoroscopy; anterior or cranial bone breach from the cortical wall carries a serious risk of neural and visceral organ injury and must be corrected immediately. (Figure 7-8)

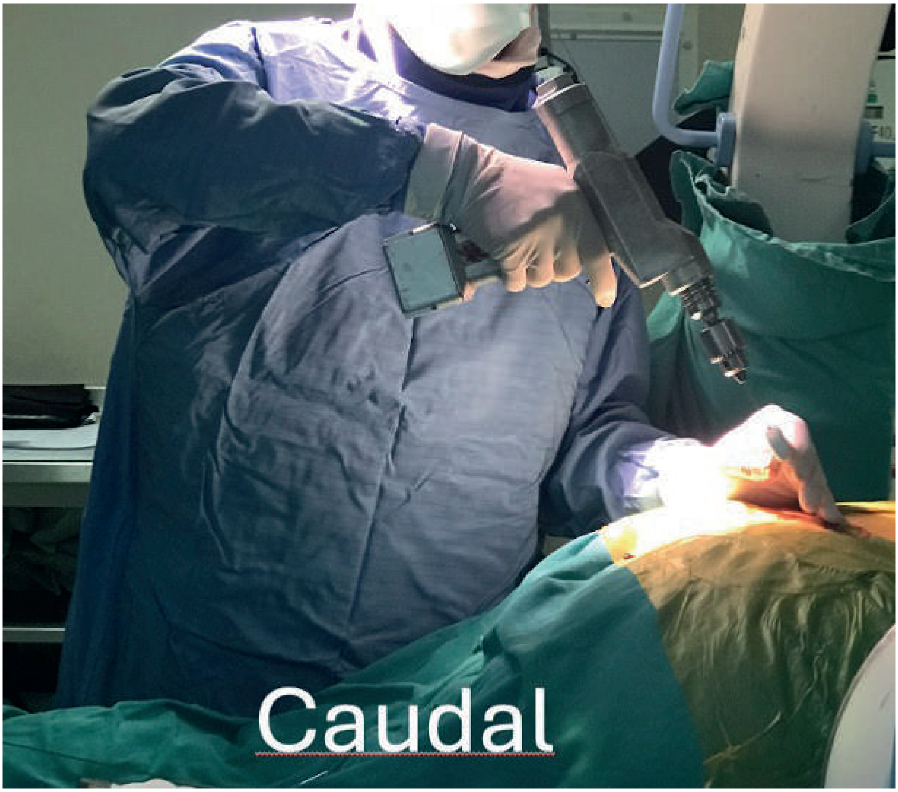

Figure 7. Intraoperative placement of a Kirschner wire using a surgical drill. Intraoperative photograph demonstrating advancement of a Kirschner wire using a powered surgical drill during intralaminar screw fixation. The wire is inserted through the laminar entry point and advanced along the planned trajectory to guide subsequent screw placement under fluoroscopic control.

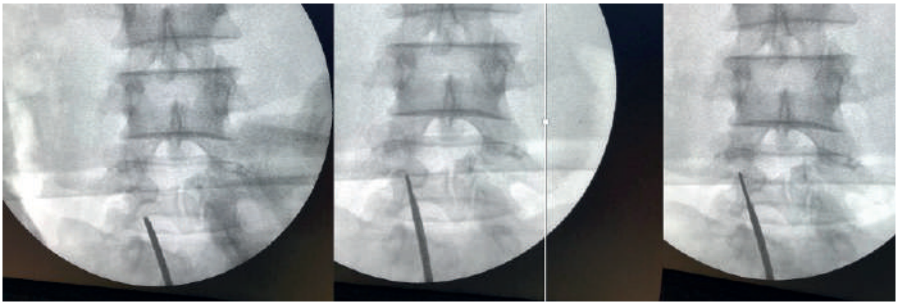

Figure 8. Intraoperative fluoroscopic visualization of Kirschner wire advancement through the Jamshidi needle. Sequential intraoperative fluoroscopic images demonstrating advancement of a Kirschner wire through the Jamshidi needle toward the pedicle during intralaminar screw fixation. The images illustrate the progressive positioning of the guidewire along the intended trajectory under real-time fluoroscopic guidance.

High-speed drill usage: A 3 mm diameter high-speed drill is advanced along the lamina over a guidewire to the pars defect; in chronic defects, drill advancement may be difficult due to sclerotic bone and pseudoarthrosis. In this case, excessive force should not be applied, and controlled and short-interval advancement should be preferred; otherwise, there is a risk of anterior perforation and retroperitoneal or abdominal organ injury due to abrupt passage (Figure 9)

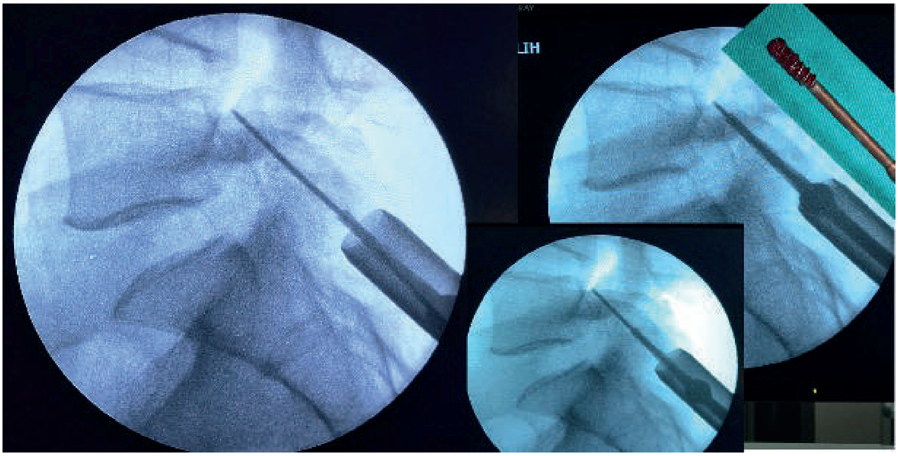

Figure 9. Lateral intraoperative fluoroscopic view during preparation of the screw tract. Intraoperative lateral fluoroscopic images demonstrating preparation of the intralaminar screw tract using a high-speed drill. The drill is advanced along the planned trajectory to open the screw pathway and debride the pars defect. The drill tip containing bone debris is also shown, illustrating removal of sclerotic bone from the defect prior to screw insertion.

Defect debridement and grafting:

- The defect neck is debrided posterolaterally through a midline incision using long-tipped angled drills (ultrasonic if necessary) curettes, and the sclerotic edges are cleaned; alternatively, access to the defect is possible through a small midline incision on one or both sides of the retracted skin, a posterolateral mini-approach, or an endoscopic portal (Figure 10)

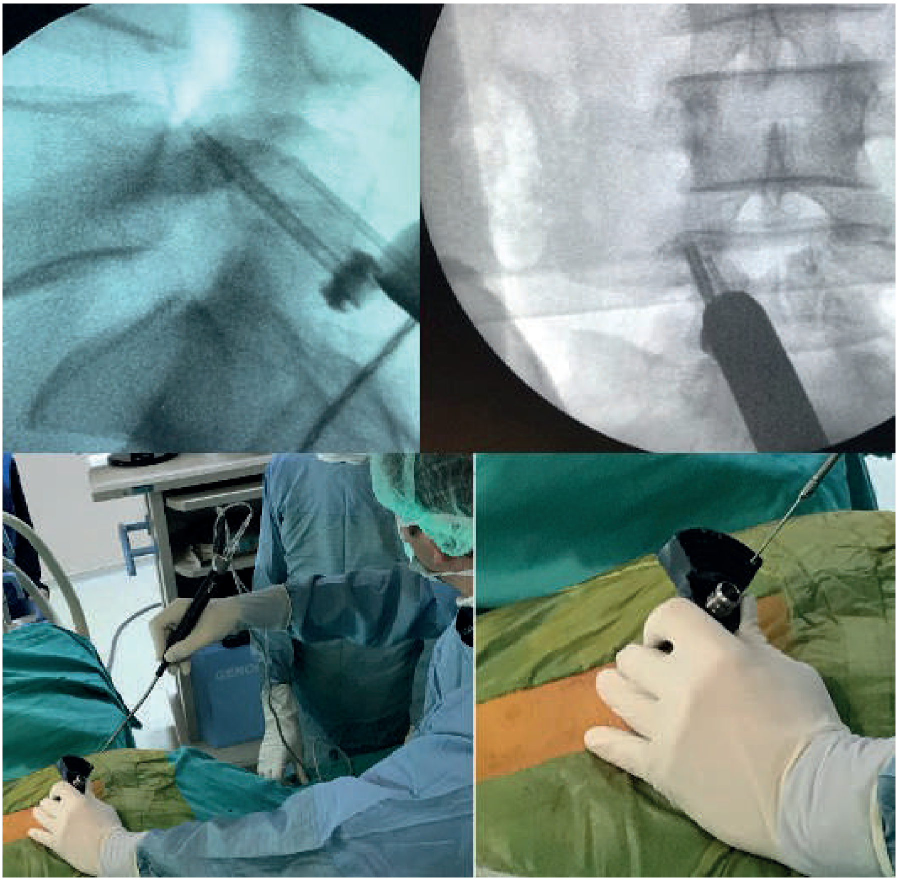

Figure 10. Pars preparation using an ultrasonic bone scalpel under fluoroscopic guidance. Intraoperative fluoroscopic images and operative photographs demonstrating preparation of the pars interarticularis using an ultrasonic bone scalpel. Under fluoroscopic guidance, the pars region is carefully contoured and the defect margins are refreshed to facilitate subsequent fixation and promote bone healing during pars repair surgery.

Placement of an autograft (e.g., iliac crest) or suitable allograft into the defect bed is critical for supporting mechanical stabilization through biological fusion. (Figure 11)

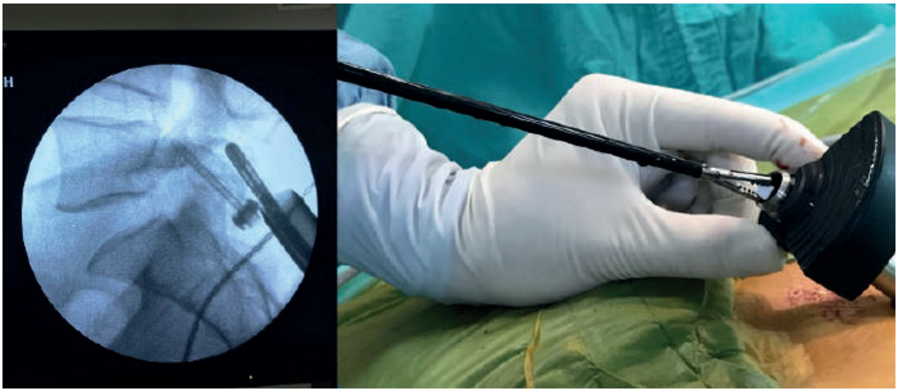

Figure 11. Bone graft placement into the pars defect under fluoroscopic guidance. Intraoperative fluoroscopic image and operative photograph demonstrating placement of bone graft into the pars interarticularis defect during pars repair surgery. The graft material is inserted into the prepared defect site to promote osseous healing before definitive screw fixation.

Screw installation:

- Based on the lamina and pars trajectory measured in preoperative CT, a cannulated cannulated titanium cortical screw, typically 35–45 mm in length and 4.0–4.5 mm in diameter, depending on the vertebral level and CT-based measurements, is selected.
- The screw is advanced along the guide wire; the screw head is positioned to sit on the lamina surface, while the tip reaches the cortical support at the base of the pedicle (Figure 12)

Figure 12. Placement of different screw systems for pars fixation. Intraoperative photographs demonstrating insertion of two different screw systems used for pars repair. The left image shows placement of a compression screw designed to achieve interfragmentary compression across the pars defect, whereas the right image demonstrates insertion of a facet fixation screw used to stabilize the posterior elements during intralaminar fixation.

- Controlled compression is applied to the pars defect with gradual tightening; the aim is to close the "gap," firmly pressing the defect in contact with the graft, and creating a rigid bridge between the pedicle and lamina (Figure 13)

Figure 13. Final screw advancement and confirmation of pedicle purchase under fluoroscopy. Intraoperative fluoroscopic images demonstrating advancement of the screw along the prepared intralaminar trajectory toward the pedicle. As the screw reaches the pedicle, increased resistance indicates firm cortical purchase and stable fixation. The lower panel shows the surgeon performing final tightening of the screw during intralaminar pars repair under operative visualization.

The same technique can be applied through the same midline incision, across the opposite lamina, to achieve bilateral pars fixation. Percutaneous intralaminar rigid screw fixation of pars defects, particularly at the L4 and L5 levels, is a preferred treatment for lumbar spondylolysis in adults. This technique represents a minimally invasive, low-profile instrumentation strategy. Anatomical analyses show that the optimal screw trajectory starts from the inferolateral edge of the lamina and requires an approximate sagittal placement angle of 45° and a coronal angle of 10°-20°. For adequate stabilization, screws typically 30-40 mm long and 4-5 mm in diameter are sufficient. Since lamina anatomy varies significantly between patients and at different vertebral levels, a one-size-fits-all approach is not appropriate. Therefore, meticulous preoperative planning using advanced imaging techniques is essential to guide screw selection, determine lamina orientation, and minimize the risk of intraoperative complications(1,5–10). (Figure 14)

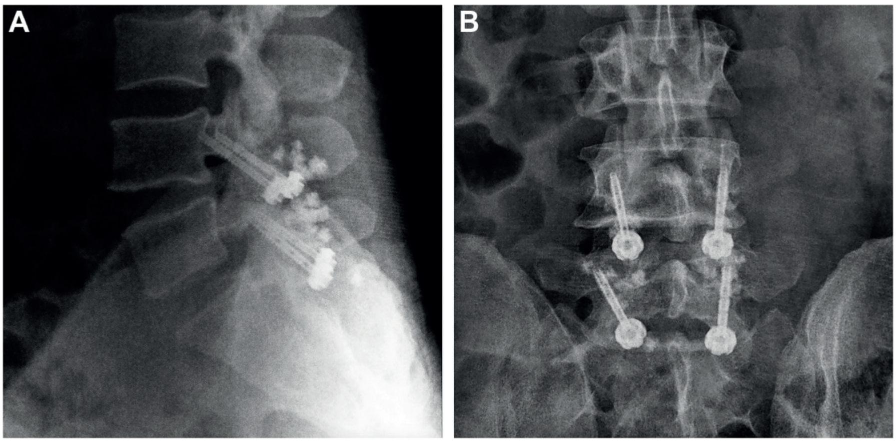

Figure 14. Long-term postoperative radiographs following bilateral percutaneous intralaminar stabilization at L4–L5. (A) Lateral and (B) anteroposterior lumbar spine radiographs obtained during long-term follow-up demonstrating bilateral percutaneous intralaminar screw fixation at the L4–L5 level. The images confirm maintained hardware position and stable posterior element fixation without evidence of implant failure or displacement.

7.3. Bilateral Cross-Laminar Screw (CLS) Technique

The traditional ipsilateral modified Buck technique may have limiting screw pull-out resistance, especially in patients with thin lamina thickness or steep lamina inclination. The bilateral crossing laminar screw (CLS) technique is a modification in which the screw crosses the lamina towards the opposite side and targets the pars defect from the contralateral spinolaminar junction. The aim is to maximize bone-screw contact surface and increase fixation resistance by extending the screw trajectory within the bone.

CT-based pre-planning:

The success of the CLS technique relies on millimeter-accurate preoperative measurements. Using multiplanar reconstruction (MPR) on thin-section CT:

- Lamina height and width,

- Spinolaminar angle and available intralaminar corridor height
- Trajectory length from the neck of the pars to the base of the pedicle.

These parameters should be carefully measured during preoperative CT-based planning. Our study showed that 4–5 cm long and 4.5 mm diameter screws were safe in most cases for fixation of L3–L5 pars defects with CLS; the lamina width at L5 being approximately 10 mm makes this level the most favorable segment for the technique (Figure 15).

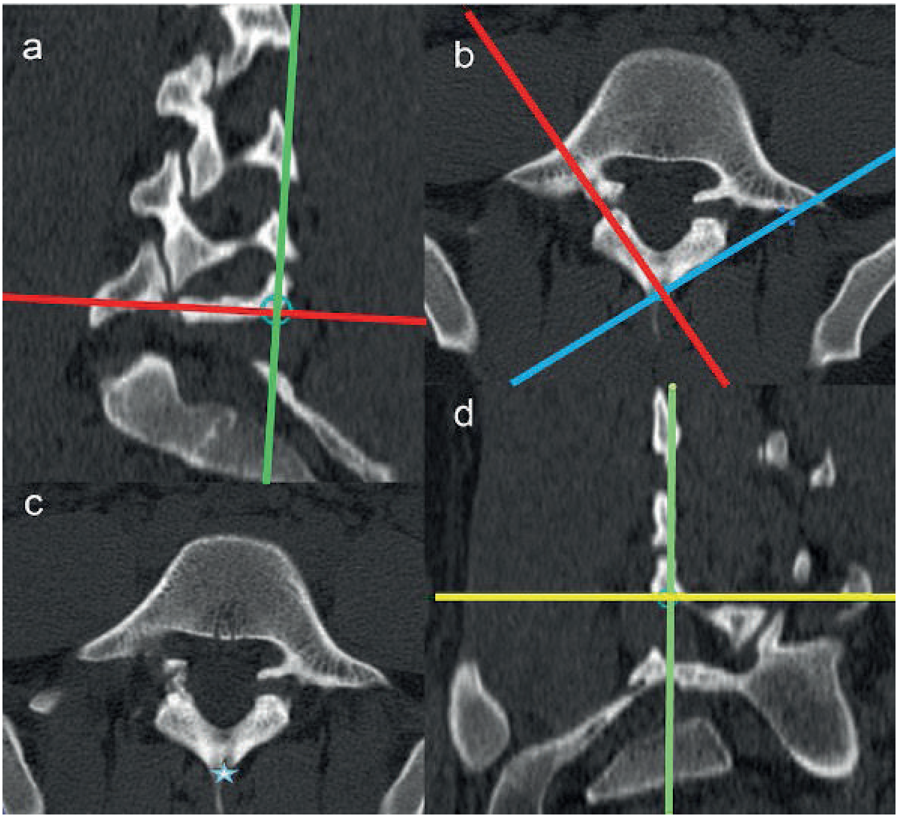

Figure 15: Three-dimensional computed tomography views in the parasagittal, axial, and coronal planes demonstrating the ideal trajectory for crossing laminar screw placement. (a) Parasagittal oblique reconstruction showing the full trajectory. (b) Axial view illustrating the screw path originating from the spinolaminar junction and passing through the laminar isthmus and pedicle. (c) Axial slice displaying the laminar entry zone. (d) Coronal plane showing the entry point of the screw

Entry point:

A characteristic feature of the CLS technique is that the entry point is the spinolaminar junction opposite the target pars defect (Figure 16).

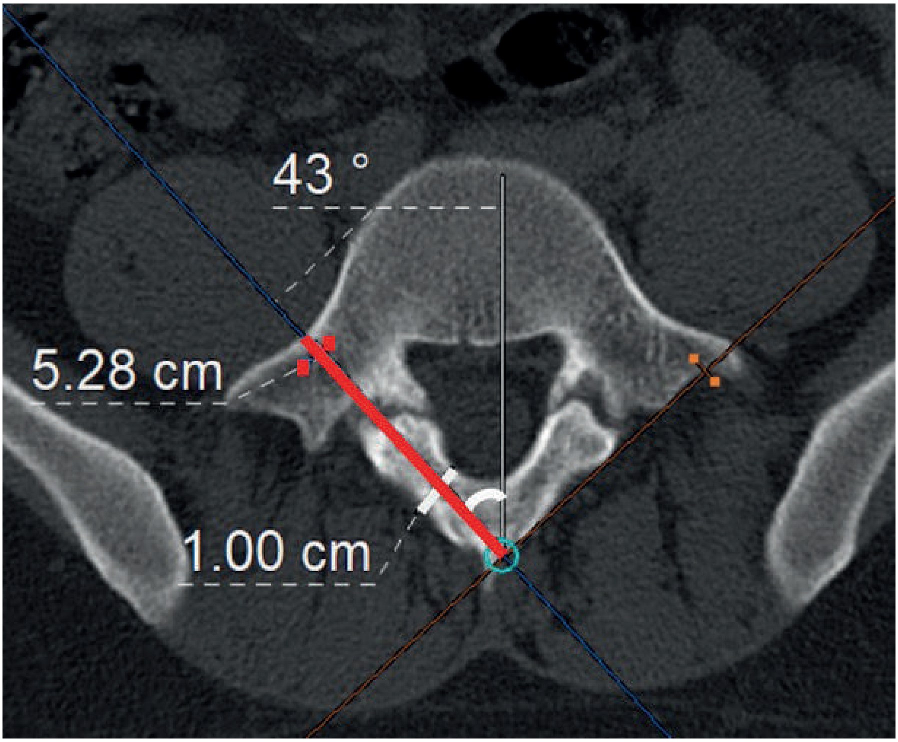

Figure16: At the L5 level in the axial plane, the ideal trajectory length for crossing laminar screw placement was measured as 5.28 cm, with a spinolaminar angle of 43° and a laminar width of 1 cm

- The **entry point** is located in the upper or lower third of the spinolaminar junction, at the point where the base of the spinous process joins the lamina.
- When applying bilateral CLS, one screw is positioned more cranial (upper 1/3) and the other more caudal (lower 1/3) to prevent the screws from colliding within the lamina (cranial–caudal offset)(11) (Figure 17).

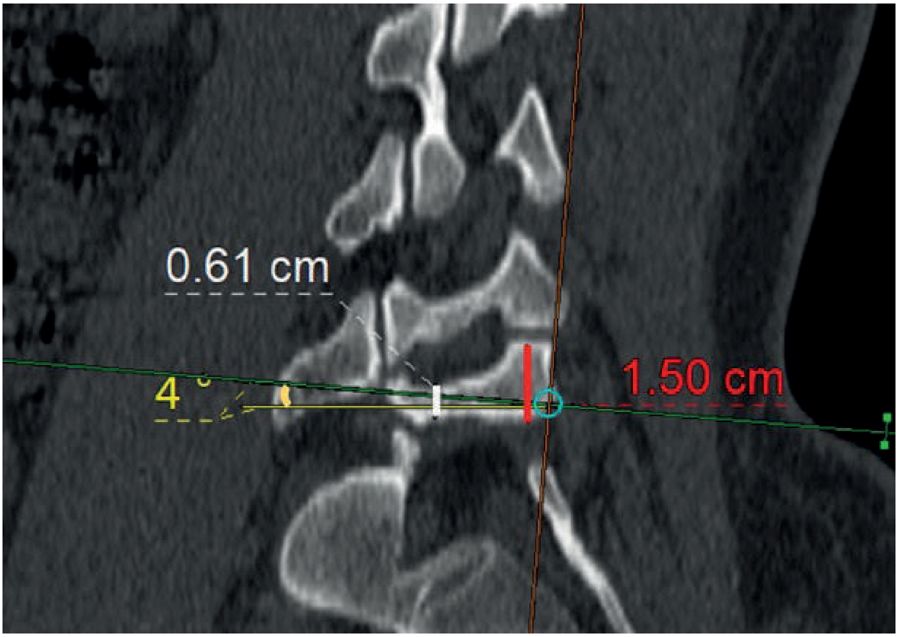

Figure17: In the parasagittal oblique plane, the crossing laminar screw trajectory demonstrated an angle of 4° relative to the horizontal plane, a spinolaminar height of 1.5 cm, and a laminar height of 0.61 cm

Trajectory and drilling:

- The Jamshidi wire and guide wire are advanced parallel to the lamina surface and within the intralaminar corridor, reaching the contralateral pars defect and the lateral/superior cortex of the pedicle; thus, the pars neck is traversed at an orientation approaching perpendicular to the defect line.
- A channel is prepared along the lamina and pars defect using a 3–3.5 mm high-speed drill; in cases where the lamina thickness is <7 mm, careful indications should be considered as secure placement of two screws within the same lamina will be difficult.

Cannulated screw placement:

A cannulated screw is placed along a guidewire, following a path from the spinolaminar junction to the base of the pedicle; the screw provides pars fixation by applying compression along the defect line and receives additional support from the strong cortical structure of the pedicle. In the CLS technique, this long path ensures that the screw makes strong contact not only with the lamina but also with the base of the pedicle, and has been reported to increase rigidity in biomechanical tests(11,12). (Figure 18-19)

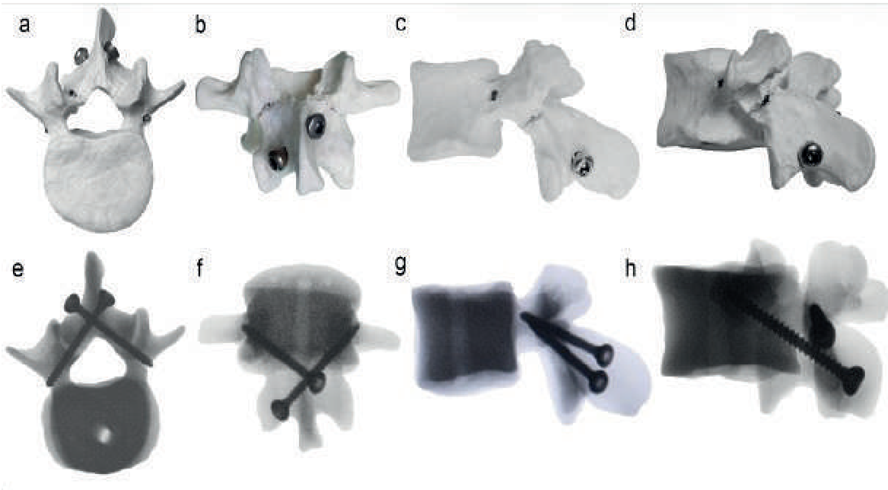

Figure18: Multiplanar views of the L4 vertebral model with bilateral spondylolysis treated with crossing laminar screws. (a) Craniocaudal, (b) anteroposterior, (c) left lateral, and (d) left oblique views of the vertebra model. Corresponding intraoperative fluoroscopic images of the same vertebra are shown in the (e) craniocaudal, (f) anteroposterior, (g) left lateral, and (h) left oblique views

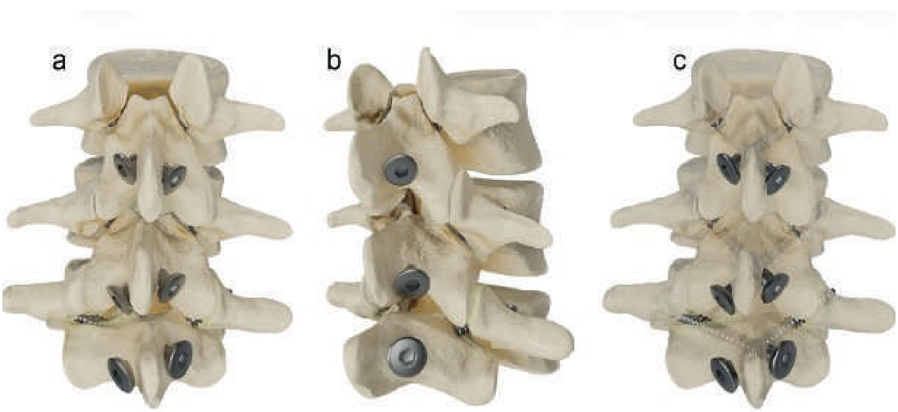

Figure 19: Three-dimensional high-resolution representations of bilateral crossing laminar screw fixation in L3-L4-L5 vertebral segments with spondylolysis. (a) Anteroposterior view, (b) right oblique view, (c) a detailed 3D model demonstrating the screw trajectories crossing through the lamina on both sides of the spinous process and terminating within the pedicles

Decortication and grafting:

Before screw placement, the pars defect must be decorticated, sclerotic tissues removed, and the defect bed filled with autograft/allograft; this ensures mechanical stabilization supported by biological fusion.

In patients with SPL, 4.5 mm diameter and 4-5 cm long CLS screws can be securely placed at the L3, L4, and L5 vertebral levels for transverse laminar screw placement, with an inclined angle of approximately 10° at the L5 level and approximately 25° at the L3 level, and a lateral angle of 40-45°.

7.4. Comparison of CLS Technique with Buck Technique

- **Trajectory length and stability:** In CLS, the screw travels a longer path within the bone; trajectories of 4–5 cm are achievable at the L3–L5 levels in most cases, increasing the screw-bone contact area and thus improving pullout resistance. In the Buck technique, the screw follows a shorter lamina-pars-pedicle line.
- **Bone-screw interface:** In CLS, thanks to the large contact surface, the load is distributed more homogeneously across the lamina and pedicle cortex rather than a narrow segment of the screw; this can be advantageous, especially in patients with high activity levels.
- **Surgical access:** CLS, while increasing fixation strength, typically requires two separate small skin incisions and necessitates careful trajectory planning to minimize the risk of intralaminar collision. Although the Buck-type ipsilateral intralaminar screw uses a unilateral and shorter corridor, secure screw placement can be challenging when the lamina is thin.
- **Risks:** The most significant risk in CLS is collision of the two screws within the lamina or perforation beyond the cortical margin; to prevent this, separation of entry points with cranial–caudal offset, avoidance of the technique in patients with insufficient lamina thickness, and use of navigation/robotic guidance if necessary are recommended(5,6,11).

7.5. Patient Selection and Practical Notes for the Technique

Bilateral CLS technique is a strong alternative, especially in L3–L5 pars defects, for young and active patients with suitable lamina width and height parameters and requiring high fixation strength. L5 stands out as the most favorable segment for this technique due to its longer trajectory and wider lamina structure. This method combines the philosophy of motion-preserving surgery with a level of rigidity close to that of a pedicle screw, demonstrating favorable clinical and biomechanical outcomes in selected cohorts in selected cases with suitable anatomy.

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CHAPTER 8

Classical Surgical Methods

8.1. General Trend: From Segment Preservation Repair to Fusion

The current trend in spondylolysis surgery is to prioritize direct pars repair methods that preserve the motion segment whenever possible, and to only resort to segmental fusion in the presence of advanced degeneration or high-grade spondylolisthesis. The pars compression screw technique described by Buck is one of the direct repair methods with the longest follow-up data in the literature and is positioned as a biomechanically rational alternative to fusion, especially in young patients with preserved disc and facet structures(1–3).

In the original Buck series, radiological union was reported in all cases, and clinical outcomes have mostly been reported as “good” or “excellent”; finite element analyses show that increased L5–S1 disc stresses in L5 spondylolysis are reduced to values close to those of the normal population after Buck repair, thus theoretically reducing the risk of adjacent segment degeneration. However, it has been reported that in longer series and mixed cases, clinical outcomes become heterogeneous as concomitant spondylolisthesis and disc degeneration increase, and persistent pain and a subsequent need for posterolateral fusion may arise. It is emphasized that the Buck technique provides the highest success in the “young patients with low-grade disease and preserved disc and facet structures” (1,2,4–8).

8.2. Scott Wiring and Wire/Cable Based Methods

Scott wiring and similar wire- or cable-based direct repair techniques have historically played an important role, but are less preferred today due to their need for more extensive muscle-lamina dissection and their susceptibility to complications such as implant irritation and fracture. Although clinical outcomes with Scott and modified cable/wire techniques have been reported as mostly good or very good in medium and long-term series, it has been shown that nonunion rates can be significantly higher when evaluated with CT compared to radiography, although clinical outcomes are not always negatively affected.

Meta-analyses comparing Buck, Scott, Morscher, and pedicle screw-based techniques reported that overall positive outcomes (good-excellent) rates were around 84.3% for Buck and 82.5% for Scott; however, complication rates were higher in the Scott and Morscher groups compared to the pars screw and pedicle screw techniques. These data have led to the Scott wiring technique being largely limited to historical references or selected specific cases in current practice(4,9–11).

8.3. Intralaminar Screw and Pedicle Screw – Hook/Rod Systems

In recent years, intralaminar screw and pedicle screw–laminar hook–rod systems (U-rod or "smiley-face rod" constructs) systems have become reconstruction options that complement the Buck technique both biomechanically and clinically, and are used more frequently in many centers.

Intralaminar screw-based repairs:

In series of intralaminar/pars screw repairs performed using minimally invasive or microsurgical approaches, significant reductions in VAS scores, high radiological union rates, and return-to-competitive sports rates in the 70–80% range have been reported in cohorts, mostly consisting of adolescent and young adult athletes; the need for revision fusion is quite low in medium-to-long-term follow-up.

- **Pedicle screw–laminar hook/rod (U-rod, smiley face rod) structures:** In reconstructions using combinations of pedicle screws and lamina hook/rod, union rates reach 90–100% in many series, and Oswestry (ODI) and similar functional scores show significant improvement. In young adult series, radiological union has been reported in all cases with the U-rod technique, with only a very small number of cases reporting delayed union or the need for revision. In cohorts of young athletes where the smiley face rod method was applied, long-term follow-up shows sustained improvement in pain scores, return-to-sport in all patients, and achieving premorbid performance levels in most within 6–8 months.

Biomechanical studies show that these pedicle-lamina based systems can provide higher rigidity than pars screws alone and may be advantageous, especially in cases with bilateral defects or a wide pars defects. Because they offer strong stabilization along the pars line without completely eliminating segment movement, they have gained an important place in the spectrum of motion-preserving surgery(12–16).

8.4. Segmental Fusion: Posterolateral and Interbody Fusion

At the other end of the surgical spectrum are posterolateral or interbody (PLIF/TLIF/ALIF/OLIF) fusion techniques, which are commonly used in the following situations:

- Significant degeneration in the discs and facet joints,
- high-grade spondylolisthesis,
- multilevel pathology,
- persistent instability after failed pars repair

These situations represent the primary indications for fusion strategies.

- Various cohort studies have shown that posterolateral and interbody fusions offer high success rates in terms of pain control and functional improvement; however, due to the loss of the motion segment, they may increase the risk of adjacent segment degeneration and adjacent segment disease in the long term.

Studies and meta-analyses comparing direct pars repair with fusion have shown that in appropriately selected young patients, direct repair provides at least as much pain control as fusion; however, it preserves segment movement and offers a more physiological profile in terms of adjacent segment biomechanics.

Systematic reviews examining return-to-sport after spondylolysis surgery in pediatric and adolescent athletes report that return-to-sport rates range from 76–100% in series undergoing direct pars repair, mostly within 5–12 months; while fusion series show higher pain control, performance level and flexibility may be more significantly restricted compared to pars repair(3,7,8,17–21) (**Figure 1,2,3.)**

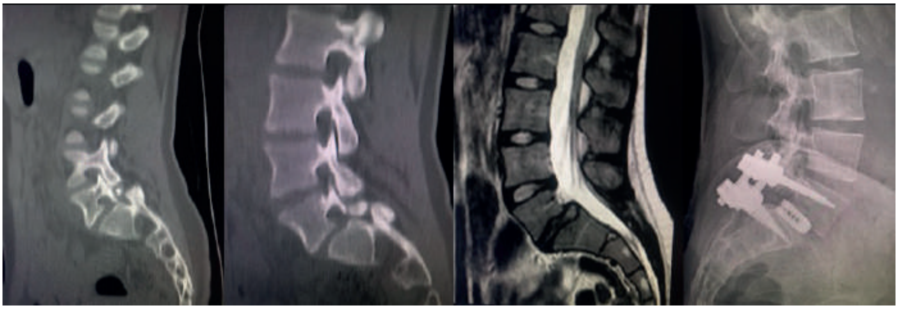

Figure 1. Preoperative CT/MRI and postoperative radiograph in isthmic spondylolisthesis. Preoperative sagittal CT and MRI images of a 22-year-old female patient demonstrating L5–S1 isthmic spondylolisthesis with bilateral pars interarticularis defects. The postoperative lateral radiograph shows L5–S1 posterolateral stabilization and posterior lumbar interbody fusion (PLIF) instrumentation, confirming appropriate implant placement and restoration of lumbosacral alignment.

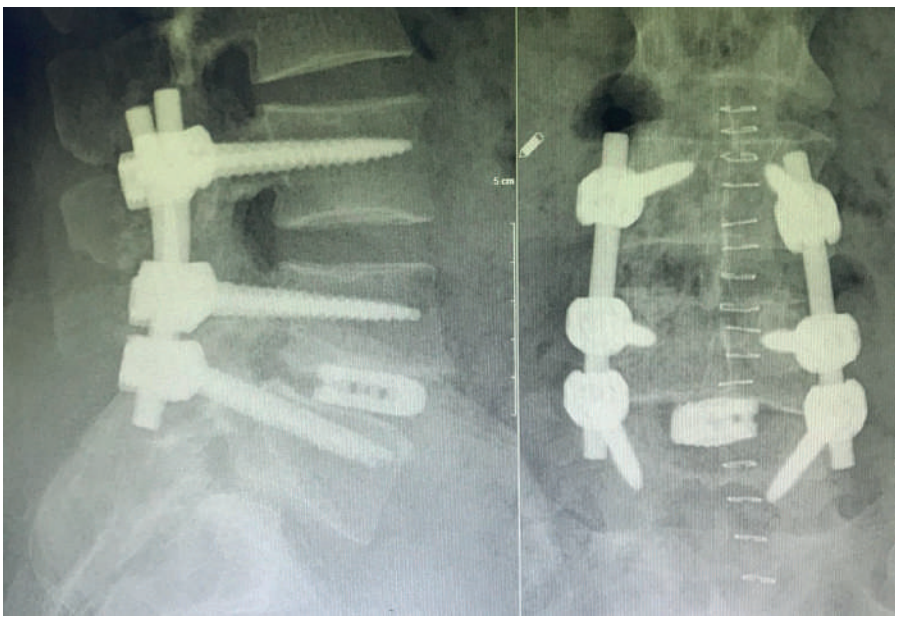

Figure 2. Postoperative radiographs following L5–S1 fusion for isthmic spondylolisthesis. Lateral (A) and anteroposterior (B) lumbar spine radiographs obtained after surgery in a 35-year-old male patient with L4-5 isthmic spondylolisthesis. The images demonstrate posterior pedicle screw–rod instrumentation with posterior lumbar interbody fusion (PLIF) cage placement at the L4–5 level, confirming appropriate implant positioning and restoration of segmental alignment.

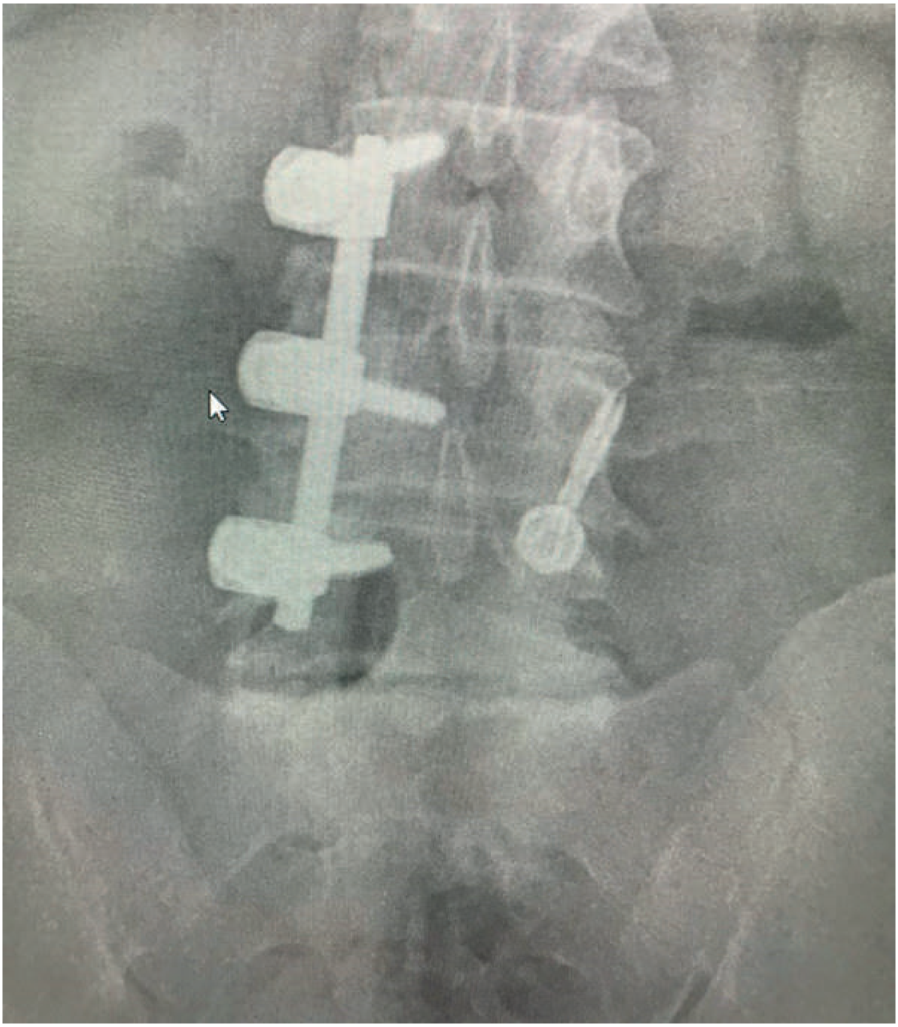

Figure 3. Postoperative radiograph demonstrating combined stabilization procedures. Anteroposterior lumbar spine radiograph of a 53-year-old female patient showing right-sided L3–L5 posterolateral stabilization performed for rotational scoliosis. On the left side, percutaneous fixation was performed at the L4 level for treatment of spondylolysis. The image demonstrates the coexistence of unilateral posterior instrumentation for deformity correction and percutaneous fixation for pars stabilization.

8.5. Summary: Algorithmic Approach

Current surgical approaches in spondylolysis surgery adopt an algorithmic decision-making process based on age, activity level, disc and facet status, and degree of spondylolysis, selecting between segment-sparing direct pars repair and segmental fusion.

- **For young, active patients with low-grade spondylolisthesis and preserved discs:** Buck pars screw, intralaminar screw, and pedicle sc-rew-hook/U - rod-like direct repair methods stand out as first-line surgical options.
- **Advanced degeneration, high-grade spondylosis, multi-level pathology, or failed previous repairs:** Posterolateral and/or interbody fusion techniques become more suitable options for achieving a stab-le, pain-free segment.

In this context, a surgical strategy that evaluates biomechanical, radiological, and functional parameters together for each patient, prioritizes segment-preserving approaches, but maintains the flexibility to switch to fusion when necessary, is supported by current literature as the most rational approach(21–24).

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CHAPTER 9

Complication Profile – Error–Outcome Relationships in Pars Repair Surgery

9.1. General Framework

Minimally invasive techniques such as direct pars repair and intralaminar screw fixation require the surgeon to work with high precision within a narrow bony corridor. The risk of complications is determined not so much by the "minimal" nature of the technique, but rather by the attention paid to preoperative anatomical analysis and intraoperative trajectory precision. Current series and meta-analyses show that most complications fall under two main categories:

- insufficient stabilization
- faulty instrumentation trajectory(1–5).

9.2. Insufficient Stabilization and Instrumentation Failure

One of the most frequent mechanical complications after direct pars repair is screw fracture, particularly seen in unilateral intralaminar or pars screws. The underlying pathophysiology of this condition is the failure to achieve adequate compression at the defect line and the persistence of microinstability in the pseudoarthrosis site; under metal fatigue, the screw eventually fractures.

- In clinically painless, functionally intact patients, a fractured screw may often remain only a radiological finding, and observation may be preferred.

- In cases of persistent or recurrent mechanical low back pain, underlying pseudoarthrosis should be considered, and revision surgery (often segmental fusion or more rigid reconstruction) should be considered in most cases.

Studies have shown that the risk of equipment failure increases when fixation is left unilateral, the defect width is not adequately debrided, or grafting is insufficient(4,6–9).

9.3. Cortical Perforation and Neural Risks

One of the most critical technical errors during intralaminar screw placement is perforation of the spinal canal, lateral recess, or paraspinal soft tissues by penetrating the lamina cortex. The risk of “in-out” trajectory is significantly increased in patients with a thin lamina, pediatric or transitional vertebral anatomy.

To prevent this complication:

- Careful measurement of lamina height, width, and sagittal pars/lamina inclination angle via thin-section CT scan,
- If possible, use navigation or robotic guidance.

It is recommended that cortical perforation not only carries the risk of neural structure damage; it also reduces the screw-bone contact surface, thereby decreasing pull-out resistance and early stability(8,10,11).

9.4. Facet Violation and Mechanical Facet Pain

Incorrect screw placement resulting in a violation of the superior articular facet joint is an error that directly contradicts the philosophy of motion-preserving surgery. Screws inserted into the facet joint can cause the patient to wake up with typical mechanical facet pain, different from the preoperative “pars pain”; this is considered an additional factor that accelerates adjacent segment degeneration.

In preoperative planning, the orientation of the facet joint, the distance of the entry point from the facet, and the position of the screw angle relative to this joint should be calculated with millimeter precision; facet lines should be used as a reference during intraoperative fluoroscopy/navigation(1,11–16).

9.5. “Non-union” and Clinical-Radiological Discrepancy

Although the failure to achieve complete bone fusion radiologically after direct pars screw repair may appear as a technical failure, clinical outcomes do not always align with this finding. In intralaminar or pars screw series, fusion rates assessed by CT are in the 60–80% range, while significant and sustained improvement in VAS, ODI, and SF-36 scores is reported even in patients who do not show union.

This suggests that surgical success depends not only on "anatomical reconstruction" but also on eliminating pathological movement along the pars line with sufficient rigidity. It is emphasized that even without complete bridging on CT after direct repair, the pseudoarthrosis line, along with fibrosis and implant, can provide functional stability, which is often sufficient for clinical satisfaction(2,5,11,17).

9.6. Conclusion: Error-Result Mapping

- Inadequate compression / weak unilateral fixation → microinstability → metal fatigue, screw fracture, pseudoarthrosis, late-stage need for fusion.
- Incorrect lamina trajectory / cortical perforation → risk of canal or foraminal violation, neurological symptoms, poor pull-out, early loss of stability.
- Facet joint disorder → new onset mechanical facet pain, accelerated adjacent segment degeneration, disruption of motion-preserving philosophy.

Radiological non-union (with stable fixation) → often good clinical outcome; failure criteria should focus not only on "imaging alone" but also on symptomatology and functional scores(2,4,7,10,18).

Therefore, the key to reducing the complication profile in spondylolysis surgery is preoperative CT-based morphometric analysis, careful patient selection, and millimeter-precise screw trajectory planning; and intraoperatively, high-accuracy instrumentation achieved through imaging and, if necessary, navigation.

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CHAPTER 10

Long-Term Outcomes in Spondylolysis: Disc, Facet Joints

10.1. Long-Term Effects on the Disc

Isthmic spondylolysis and associated spondylolisthesis are not merely local pars defects, but a dynamic process that alters load sharing across the lumbosacral motion segment(s) over time. Loss of pars integrity and vertebral slippage accelerate disc degeneration by increasing shear and sliding forces on the intervertebral disc, particularly at the L5–S1 and L4–L5 levels. Clinical and radiological series show that as the degree of slippage increases, disc height loss, signal changes, and Modic-type end-plate changes are more frequently observed both at the affected level and in adjacent segments, negatively impacting long-term low back pain and functional limitation scores(1–5).

In patients undergoing direct pars repair, finite element and clinical studies report a significant reduction in abnormal stresses on the L5–S1 disc and a slower rate of disc degeneration compared to fusion. In contrast, while segmental fusion provides stabilization of the surgical-level disc, adjacent segment disc degeneration, associated with increased biomechanical load in the upper segments, has been identified as a long-term complication(1,2,6–12).

10.2. Facet Joints and Posterior Elements

In segments with pars defects, facet joints become passive stabilizers attempting to limit translational gliding and are forced to absorb increased rotational moments. Over time, this overload can result in facet hypertrophy, capsular thickening, and osteophyte formation, leading to facet arthropathy and localized facet-related pain. Radiological studies show an increased prevalence of degenerative changes, particularly in facets above the gliding level, in patients with isthmic spondylolisthesis, contributing to both mechanical pain and postoperative disease of adjacent segments.

Ten-year follow-up studies after fusion surgery have reported that radiographic changes related to facet degeneration and lordosis redistribution in the adjacent segment are frequent, but only a small group of patients have clinically significant adjacent segment disease requiring revision surgery(2,5,6,13).

10.3. Sagittal Balance and Spinopelvic Parameters

Isthmic spondylolysis and spondylolisthesis create a structural alteration affecting lumbar lordosis, pelvic parameters, and global sagittal balance. Studies in adolescents and young adults have shown that patients with isthmic spondylolisthesis, compared to the normal population, tend to have higher spinopelvic parameters, including:

- higher pelvic incidence, sacral slope, and pelvic tilt
- increased lumbar lordosis,
- decreased thoracic kyphosis

These compensatory changes allow patients to maintain an upright posture. In L5–S1 isthmic spondylolisthesis, the local lumbosacral kyphotic segment is typically compensated by hyperlordosis in the upper lumbar segments and by anterior rotation of the pelvis. This compensatory strategy increases muscle fatigue and degenerative load in the upper segments while attempting to maintain global trunk balance.

Therefore, in surgical planning, it is critical not only to correct the local deformity but also to carefully evaluate the patient's preoperative spinopelvic parameters (pelvic incidence, sacral slope, pelvic tilt, global sagittal offset); otherwise, even if the radiographic deformity is corrected, clinically satisfactory sagittal balance may not be achieved(14,15,15).

10.4. Direct Pars Repair vs. Fusion: Long-Term Biomechanical Differences

There is increasing evidence that in young patients with low-grade slippage, segment-preserving direct pars repair can significantly slow the rate of disc and facet degenerative changes. In recent comparative studies:

- In direct pars repair, the range of motion of the surgical segment is largely preserved.

- In fusion techniques such as TLIF/PLIF, surgical segment movement is completely lost.

However, pain control and fusion rates were reported to be similar in both groups. It is emphasized that the direct repair group showed lower kinematic changes and disc degeneration rates in adjacent segments, offering a more physiological biomechanical profile in the long term.

In cases where segmental fusion is performed, although slippage is controlled and pain is reduced, many series have shown that the risk of degenerative changes due to load transfer in adjacent segments increases in the medium-to-long term, and this can result in recurrence of pain, loss of function, and the need for additional surgery over time. However, there are also series reporting lower rates of adjacent segment disease in fusions performed for isthmic spondylolisthesis compared to degenerative spondylolisthesis; this difference has been associated with the initial pathophysiology and preoperative facet status.

Therefore, when evaluating long-term results, it is necessary to consider not only single-level anatomical correction but also the biomechanical loading pattern of the entire lumbar column and the patient's lifetime activity profile(7,16,16–19).

10.5. Complications, Revision, and "Where Did We Go Wrong?"

In spondylolysis and isthmic spondylolisthesis surgery, a significant portion of complications stem not from the technique used, but from errors in indication, inadequate preoperative planning, and disregard for segmental biomechanics. One of the most frequent errors is the failure to select the correct surgical spectrum for the correct patient.

- In young patients with low-grade spondylolisthesis and preserved discs/facets, opting for routine fusion instead of preserving the motion segment may yield good short-term results, but in the long term, it increases the risk of adjacent segment disease and resurgery.
- Conversely, in cases with significant disc degeneration, facet arthrosis, or high-grade slippage, relying solely on pars repair may lead to continued instability, persistent pain, and the need for revision surgery in a short time.

Among technical complications, inadequate decompression and incorrect segment selection are among the most serious; neglecting foraminal/extraforaminal root compression, especially in minimally invasive approaches due to poor planning, is a major cause of persistent radicular pain and early revision. Neurological, vascular, or visceral injuries due to screw placement, although reduced with modern imaging and navigation, still remain a concern in cases with severe deformities. Classic spinal surgery complications such as infection, pseudoarthrosis, and implant failure are closely associated with risk factors such as smoking, obesity, osteoporosis, and long segment fixation

Revision surgery is often an indication that the initial intervention did not fully resolve the underlying biomechanics. In revision after failed pars repair, segmental fusion often becomes unavoidable; here, instead of simply replacing the fractured implant, a reassessment of the proximal/distal segments contributing to instability and sagittal balance is necessary. In cases of failed fusion, adequate preparation of pseudoarthrosis areas, graft selection, and correction of spinopelvic parameters with osteoinductive supports are crucial for the success of the revision.

The most important answer to the question, "Where do we go wrong?", is our inability to adequately integrate imaging findings with the clinical picture: a dramatic-looking slippage may present with minimal symptoms, while low-grade spondylolysis can lead to significant pain and functional loss. Focusing solely on radiology to determine surgical indications lays the groundwork for unnecessary or misguided surgeries. Similarly, in elite athletes, rushing to surgery under time pressure without allowing sufficient time for conservative treatment increases the risk of complications and failure to return to the sport.

The key to reducing complication and revision rates is a multifaceted decision-making process that combines accurate patient selection, individualized surgical planning, and imaging findings with the patient's actual functional status and expectations(7,20,20–23).

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CHAPTER 11

Pars Repair Failure: Why Does It Occur?

11.1. Introduction: What Does Failure Really Mean?

Direct pars repair has become a strong alternative to fusion in selected young and low-grade isthmic spondylolysis cases; however, no technique offers 100% success, and a certain percentage of non-union, equipment failure, or clinical dissatisfaction is encountered. The concept of "pars repair failure" encompasses not only radiological non-union but also persistent pain, loss of function, the need for revision surgery, and sometimes biomechanical failure resulting from incorrect patient/incorrect technique selection.

In this context, analyzing failure at three levels provides a practical conceptual framework

- Wrong indication (wrong patient, wrong surgical spectrum)
- Insufficient biology (defect and disc stage, pars morphology, accompanying anomalies)
- Technical and instrumentation errors

Each level can lead to the same outcome—failure of pars repair—through different cause-and-effect chains(1–6).

11.2. Wrong Patient, Wrong Indication

The literature largely agrees that pars repair yields the most predictable results in two main groups: young, active, single-level, low-grade (or non-spondylolisthesis) isthmic spondylolysis and segments with preserved disc/facet structure. The Buck series also highlighted that the majority of "fair" and "poor" outcomes were concentrated in cases with Grade 1 spondylolisthesis and concomitant disc degeneration, where the underlying disc pathology was likely the primary source of symptoms.

Recent comparative studies and meta-analyses support the following points:

- In high-performance athletes under 25, if the disc and facet are preserved, results after direct pars repair are predictable and revision rates are low.
- In cases of Grade III or higher disc degeneration, a large defect space, terminal (sclerotic) stage lesions, and significant spondylolisthesis, relying solely on pars repair is associated with inadequate early pain control and the need for prompt revision.
- Studies have shown that in patients with spondylolysis and adjacent-segment disc herniation, long-term outcomes may be better in the group undergoing disc and pars repair compared to those undergoing disc surgery alone; however, it is emphasized that this decision should always be individualized.

Consequently, incorrect patient selection is the main area of misconception where **pars repair** has ceased to be a "fusion alternative" and has become an "incomplete or inappropriate treatment."(1,7–10)

11.3. Biological Background: Biological Factors Associated with Failure of Pars Healing

The success of direct pars repair depends not only on the mechanics of the screw and rod, but also on the biological healing capacity of the defect. In recent years, CT-based series and regression analyses have more clearly revealed the biological/pathological factors associated with non-fusion.

In a study of 55 patients (120 defects) using the pedicle screw-lamina hook (PSLH) technique, the overall fusion rate was found to be 84.2%; the factors shown to be significantly associated with non-fusion were listed as follows(11):

- Coexistence of spina bifida occulta in the same segment
- Terminal-stage defect morphology (atrophic, sclerotic edges)
- Large defect gap (the larger the gap, the greater the risk of non-union)
- Grade III and above disc degeneration in the same segment.

These findings demonstrate that the well-known triad of "terminal stage–large defect–advanced disc degeneration" in conservative treatment is also a poor prognostic factor in surgical pars repair. In this group, even if pars repair is technically possible, both the radiological union rate and clinical outcomes are significantly worse; some series have reported that pain and function scores in non-fusion cases are significantly worse than in patients who underwent fusion.

Fracture morphology is also an important determinant. In a patient who failed a series of minimally invasive, percutaneous direct pars repairs, a defect with convoluted, fragmented, irregular cortical edges and an inclination incompatible with the screw trajectory was described, while in a successful case, a linear, smooth-edged fracture oriented perpendicular to the screw axis was reported. This observation suggests that the angular alignment between the pars line and the planned screw axis also plays a role in healing.

Therefore, a terminal, widely spaced pars defect with accompanying advanced disc degeneration and SBO represents a "high-risk biological background" for the surgeon; insisting on pars repair in this background significantly increases the likelihood of failure(11–17).

11.4. Technical Errors and Instrumentation Limitations

In Buck's technique and its derivatives, the causes of mechanical failure are classically summarized under two headings:

- The problem occurs when the screw fails to bridge the defect at the correct angle and completely.
- Inadequate pedicle retention (inadequate purchase)

Insufficient compression leads to microinstability at the defect line and metal fatigue, which in turn causes screw fracture over time. Incorrect axis selection reduces the screw-bone contact area, decreasing both pull-out resistance and compression effectiveness. Unilateral fixation, in particular, may not provide sufficient rigidity in cases with bilateral defects or a large pars gap; revision often requires segmental fusion or more rigid pedicle-lamina based constructions.

Modern series briefly summarize the complication profiles of different direct repair techniques as follows: pmc.ncbi.nlm.nih+2

- Pars direct screw (Buck type, intralaminar screw): Short operation time, minimal blood loss, high healing rates; main complications are screw fracture and a limited number of pseudoarthrosis.pubmed.ncbi.nlm.nih+2
- Pedicle screw + hook/rod (U-rod, smiley rod, etc.): Offers more rigid stability and higher healing rates; however, root irritation, implant

loosening, and pseudoarthrosis rates are reported to be higher, especially in complex systems similar to Morscher.

- Wire/cable (Scott, cable-screw reconstructions): Despite acceptable clinical outcomes, implant fracture, irritation, and non-union rates are higher compared to pars screw and pedicle screw systems.

In both minimally invasive and percutaneous approaches, trajectory error (breaking the lamina cortex, entering the canal or facet), insufficient debridement of the defect, and difficulty in graft placement carry the risk of both non-union and the creation of a new pain focus. Therefore, a careful balance must be struck between minimally invasiveness and biological preparation; a "minimally invasive" approach can become a "maximal problem" in the long term if the portal is too small and debridement is inadequate(1,5,13,18–20).

11.5. Do Clinical and Radiological Failures Always Coincide?

Some series have shown that despite the detection of non-union on CT, improvement in VAS, ODI, and quality of life scores persists, and a significant proportion of patients are clinically satisfied. This suggests that in some pars repair procedures, "functional stabilization" may be more crucial than complete anatomical reconstruction; symptom control can be achieved even without complete bone bridging when pathological movement along the pars line is sufficiently restricted.

However, larger and more recent cohorts have reported that pain and function scores are statistically worse in non-fusion cases compared to patients who achieve fusion, and that revision rates are higher. Therefore, radiological union should still be considered the goal; the concept of "functional stabilization" should be used more to support the decision to avoid a second surgery in carefully selected non-union cases that are asymptomatic or have minimal symptoms(1,11,15,21,22).

11.6. Why Does Pars Repair Fail? Summary Framework

Based on the available evidence, the main points summarizing the Pars repair failure can be framed as follows:

- Wrong patient / wrong indication
- In segments with advanced disc degeneration (Pfirrmann ≥ III), performing only pars repair is generally not recommended
- High-grade spondylosis, marked facet arthrosis, and insistence on segment preservation in multi-level pathology.

- Cases where age, activity level, and spinopelvic parameters were overlooked.
- Unfavorable biological environment
- Terminal stage, widely spaced pars defect with sclerotic edges.
- Coexistence of spina bifida occulta and spondylolysis in the same segment.
- Long-undiagnosed, chronic lesions in the young athlete.
- Technical deficiencies and instrumentation errors.
- Inadequate debridement of the defect and failure to fill it with a graft.
- Incomplete bridging of the defect by the screw, resulting in inadequate retention in the pedicle and weak unilateral fixation.
- Perforation of the lamina or facet cortex; inadequate imaging/navigation in minimally invasive procedures.
- A decision detached from clinical reality.
- An overfocus on the radiological image, neglecting the patient's pain profile and functional expectations.

In elite athletes, time pressure leads to early surgery without giving conservative treatment a real chance(1,4,5,19,23–26).

11.7. Final Word: Minimizing Failure, Redefining Success

The way to reduce "PARS repair failure" is not through a single "better implant," but through the meticulous application of a four-step, holistic approach:

1. Proper patient selection: Evaluating age, activity level, disc/facet status, degree of spondylolisthesis, and spinopelvic parameters together.
2. The right timing: To give conservative treatment a real chance in acute/subacute stress reactions; to question the insistence on pars repair in chronic terminal-stage lesions.
3. Correct technique: Applying instrumentation that effectively prepares the defect, removes sclerosis, fills with graft, and provides rigid fixation; taking into account anatomical variations and pars morphology; and using navigation/robotic support if necessary.
4. The correct definition of success: Not just the bone bridge on CT scan, but also the patient's pain-free functional life, return to sports/daily

life, and long-term biomechanics of adjacent segments are considered "measures of success."

The pars interarticularis is not just a small bone segment, but a critical key to the lumbar mechanism. If we fail to understand the biology, biomechanics, and the patient as a whole when attempting to repair this key, failure becomes not just possible, but inevitable(5,9,27–30).

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Asst. Prof. Burhan Oral GÜDÜ

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