

A Novel Technique of Endoscopic Transforaminal Lumbar Intervertebral Fusion and
Percutaneous Dorsal Spondylodesis in Degenerative Lumbar Spinal Disorders:
an Analysis of 70 Patients

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Abstract

Background: Degenerative lumbar spinal disorders are a leading cause of chronic pain and disability, significantly impacting patients' quality of life. Traditional open surgical techniques, while effective in stabilizing the spine and relieving pain, are associated with considerable tissue trauma, blood loss, and extended recovery times. These challenges are particularly pronounced in elderly patients with multiple comorbidities. In recent years, minimally invasive techniques such as percutaneous dorsal spinal stabilization (pDSS) and endoscopic transforaminal lumbar intervertebral fusion (eTLIF) have been developed to address these issues. However, the combined use of pDSS and eTLIF in treating degenerative lumbar disorders has not been extensively studied, necessitating further research.

Methods: This retrospective study analysed data from 70 patients with degenerative lumbar spinal disorders who underwent a combined pDSS and eTLIF procedure between 2020 and 2022. The patient cohort had a mean age of 71.1 years, and surgeries were performed at various lumbar levels, with L4/5 being the most commonly treated. Key outcomes measured included surgery duration, intraoperative blood loss, length of hospital stay, postoperative pain reduction, and complication rates. Pain levels were assessed using the Numerical Rating Scale (NRS) preoperatively, on the third postoperative day, and at one-year follow-up.

Results: The combined pDSS and eTLIF technique demonstrated significant clinical benefits. The average surgery duration was 172.1 minutes, and the mean hospital stay was 8.7 days, both within acceptable ranges for minimally invasive procedures. Intraoperative blood loss was minimal, with all cases recording less than 200cc, highlighting the reduced surgical trauma associated with this approach. Postoperative pain scores showed a marked reduction from a preoperative mean NRS of 3.6 to 1.6 on the third postoperative day, with sustained pain relief observed at one-year follow-up.

(mean NRS 1.86). Complications were infrequent, with dural tear and cerebrospinal fluid (CSF) leakage being the most common, occurring in 11 patients (15.7%). All dural tears were successfully managed intraoperatively without the need for additional interventions.

Conclusions: The combined pDSS and eTLIF technique offers a promising alternative to traditional open spinal surgeries, particularly for elderly patients or those with multiple comorbidities. The procedure effectively reduces intraoperative blood loss, minimizes postoperative pain, and shortens hospital stays, all while maintaining a low complication rate. These findings suggest that the combined use of pDSS and eTLIF could enhance patient outcomes in the treatment of degenerative lumbar spinal disorders. However, further studies with larger sample sizes and extended follow-up periods are needed to confirm these results and refine the technique. This minimally invasive approach may represent a significant advancement in spine surgery, offering a safer and more effective treatment option for patients with degenerative lumbar conditions

Eine neuartige Technik der endoskopischen transforaminalen lumbalen Intervertebralfusion und perkutanen dorsalen Spondylodese bei degenerativen lumbalen Wirbelsäulenerkrankungen: eine Analyse von 70 Patienten

Zusammenfassung

Hintergrund: Degenerative lumbale Wirbelsäulenerkrankungen sind eine führende Ursache für chronische Schmerzen und Behinderungen und beeinträchtigen die Lebensqualität der Patienten erheblich. Traditionelle offene chirurgische Techniken sind zwar wirksam bei der Stabilisierung der Wirbelsäule und Schmerzlinderung, gehen jedoch mit erheblichen Gewebeschäden, Blutverlust und verlängerten Erholungszeiten einher. Diese Herausforderungen sind besonders ausgeprägt bei älteren Patienten mit mehreren Begleiterkrankungen. In den letzten Jahren wurden minimalinvasive Techniken wie die perkutane dorsale Wirbelsäulenstabilisierung (pDSS) und die endoskopische transforaminale lumbale Intervertebralfusion (eTLIF) entwickelt, um diese Probleme anzugehen. Die kombinierte Anwendung von pDSS und eTLIF zur Behandlung degenerativer Lumbalerkrankungen wurde jedoch noch nicht umfassend untersucht, was weiteren Forschungsbedarf erfordert.

Methoden: Diese retrospektive Studie analysierte Daten von 70 Patienten mit degenerativen lumbalen Wirbelsäulenerkrankungen, die zwischen 2020 und 2022 einem kombinierten pDSS- und eTLIF-Verfahren unterzogen wurden. Die Patienten hatten ein Durchschnittsalter von 71,1 Jahren, und die Operationen wurden auf verschiedenen Lumbalebenen durchgeführt, wobei L4/5 am häufigsten behandelt wurde. Zu den gemessenen Ergebnissen gehörten die Operationsdauer, der intraoperative Blutverlust, die Dauer des Krankenhausaufenthalts, die postoperative Schmerzreduktion und die Komplikationsraten. Die Schmerzintensität wurde präoperativ, am dritten postoperativen Tag und beim einjährigen Nachsorgetermin anhand der Numerischen Rating-Skala (NRS) bewertet.

Ergebnisse: Die kombinierte pDSS- und eTLIF-Technik zeigte signifikante klinische Vorteile. Die durchschnittliche Operationsdauer betrug 172,1 Minuten und der

durchschnittliche Krankenhausaufenthalt 8,7 Tage, was beides im akzeptablen Bereich für minimalinvasive Verfahren liegt. Der intraoperative Blutverlust war minimal, in allen Fällen lag er unter 200 ml, was die geringere chirurgische Traumatisierung bei dieser Methode unterstreicht. Die postoperativen Schmerzwerte zeigten eine deutliche Reduktion von einem präoperativen mittleren NRS-Wert von 3,6 auf 1,6 am dritten postoperativen Tag, wobei die Schmerzreduktion auch nach einem Jahr anhielt (mittlerer NRS-Wert 1,86). Komplikationen traten selten auf, wobei Duraverletzung die häufigsten waren und bei 11 Patienten (15,7%) auftraten. Alle Duraverletzungen wurden intraoperativ erfolgreich behandelt, ohne dass zusätzliche Eingriffe erforderlich waren.

Schlussfolgerung: Die kombinierte pDSS- und eTLIF-Technik bietet eine vielversprechende Alternative zu traditionellen offenen Wirbelsäulenoperationen, insbesondere für ältere Patienten oder solche mit mehreren Begleiterkrankungen. Das Verfahren reduziert wirksam den intraoperativen Blutverlust, minimiert postoperative Schmerzen und verkürzt die Krankenhausaufenthalte, bei gleichzeitig niedriger Komplikationsrate. Diese Ergebnisse deuten darauf hin, dass die kombinierte Anwendung von pDSS und eTLIF die Behandlungsergebnisse bei degenerativen lumbalen Wirbelsäulenerkrankungen verbessern könnte. Es sind jedoch weitere Studien mit größeren Stichproben und längeren Nachbeobachtungszeiträumen erforderlich, um diese Ergebnisse zu bestätigen und die Technik weiter zu verfeinern. Dieser minimalinvasive Ansatz könnte einen bedeutenden Fortschritt in der Wirbelsäulenchirurgie darstellen und eine sicherere und effektivere Behandlungsoption für Patienten mit degenerativen lumbalen Erkrankungen bieten.

Table of Contents

Abstract	iii
Zusammenfassung	v
List of Abbreviations	ix
1. INTRODUCTION.....	1
1.1. Causes of chronic back pain	2
1.1.1. Degenerative spinal diseases	2
1.1.2. Spinal infections	4
1.1.3. Vertebral fractures	6
1.1.4. Spinal tumours.....	7
1.2. A history of surgical approaches in treating lumbar spinal disorders.....	10
1.3. Surgical techniques of spinal stabilisation and transforaminal lumbar intervertebral fusion	12
1.3.1. Open dorsal spinal stabilisation (oDSS) and open transforaminal lumbar intervertebral fusion (oTLIF)	12
1.3.2. Percutaneous transpedicular dorsal spinal stabilization (pDSS).....	14
1.3.3. Endoscopic transforaminal lumbar intervertebral fusion (eTLIF).....	16
2. MATERIALS AND METHODS.....	20
2.1. Clinical flowchart	20
2.2. Patients.....	22
2.3. Institution and surgeon	22
2.4. Inclusion criteria	22
2.5. Exclusion criteria	23
2.6. pDSS and eTLIF surgical technique.....	23
2.6.1. Instruments	23
2.6.2. Postoperative management.....	38
2.7. Data collection and spread sheets	38
2.8. Criteria for outcome analysis.....	47
2.9. Statistics.....	47
3. RESULTS.....	48
3.1. Demographics	48
3.2. Surgical details	49
3.2.1. Duration of surgery	49
3.2.2. Levels of the surgery	50
3.3. Clinical outcomes	54

3.3.1.	Duration of hospital stay	54
3.3.2.	Presurgical and postsurgical pain	54
3.4.	Complications	58
4.	DISCUSSION	59
4.1.	A detailed case discussion	59
4.1.1.	Presentation of an illustrative case	59
4.1.2.	Surgical intervention	60
4.1.3.	Postoperative course and outcome	61
4.2.	pDSS and eTLIF technique and its advantages	62
4.3.	Feasibility of the combined pDSS and eTLIF technique for treating multi-level degenerative lumbar spinal disorders	67
4.4.	Future perspectives and emerging technologies	69
4.5.	Current applications of augmented reality in spine surgery	71
4.6.	Further research and limitations of this study	71
5.	CONCLUSIONS	73
	LITERATURE	74
	Figures and Tables	81
	Ehrenwörtliche Erklärung	83
	Acknowledgements and Expression of Gratitude	84

List of Abbreviations

AP - Anteroposterior

ALIF - Anterior Lumbar Interbody Fusion

CPK - Creatine Phosphokinase

CT - Computed Tomography

eDSS - endoscopic Dorsal Spinal Stabilization

eTLIF - endoscopic Transforaminal Lumbar Interbody Fusion

K-wire - Kirschner-guidewire

LLIF - Lateral Lumbar Interbody Fusion

miTLIF - minimally invasive Transforaminal Lumbar Interbody Fusion

MIS - Minimally Invasive Surgery

MRI - Magnetic Resonance Imaging

NRS - Numerical Rating Scale

NSAIDs - Non-Steroidal Anti-Inflammatory Drugs

oDSS - open Dorsal Spinal Stabilization

OLIF - Oblique Lumbar Interbody Fusion

PBR - Pedicle-Based Retraction

PLIF - Posterior Lumbar Interbody Fusion

pDSS - percutaneous Dorsal Spinal Stabilization

SAP - Healthcare Document Management Software

SD - Standard Deviation

TLIF - Transforaminal Lumbar Interbody Fusion

VAS - Visual Analog Scale

1. INTRODUCTION

Lower back pain and back pain in general bring about physical discomfort and substantially decreases the quality of life of the individual, besides having economic implications: it disrupts daily routines, restricts participation in regular activities and undermines the overall well-being of the patient (Hoy et al., 2014; Maetzel & Li, 2002). In 2020, low back pain affected approximately 619 million individuals worldwide, with this number projected to rise to 843 million by 2050 (Ferreira et al., 2023). Moreover, back pain is among the top causes of sick leave worldwide. In Brazil, workers average 100 days of absence per person annually due to low back pain, with productivity losses accounting for 79% of the 2.2 billion (USD) total cost of the condition (Carregaro et al., 2020). In the USA, 15.4% of the workforce reports missing an average of 10.5 workdays per year due to chronic low back pain, resulting in about 264 million lost workdays each year (Yelin et al., 2016).

Figure 1 - 1 illustrates the age-standardized rates of low back pain prevalence globally in 2020. It is evident that countries with older populations, such as those in Europe and the USA, experience the highest rates of back pain.

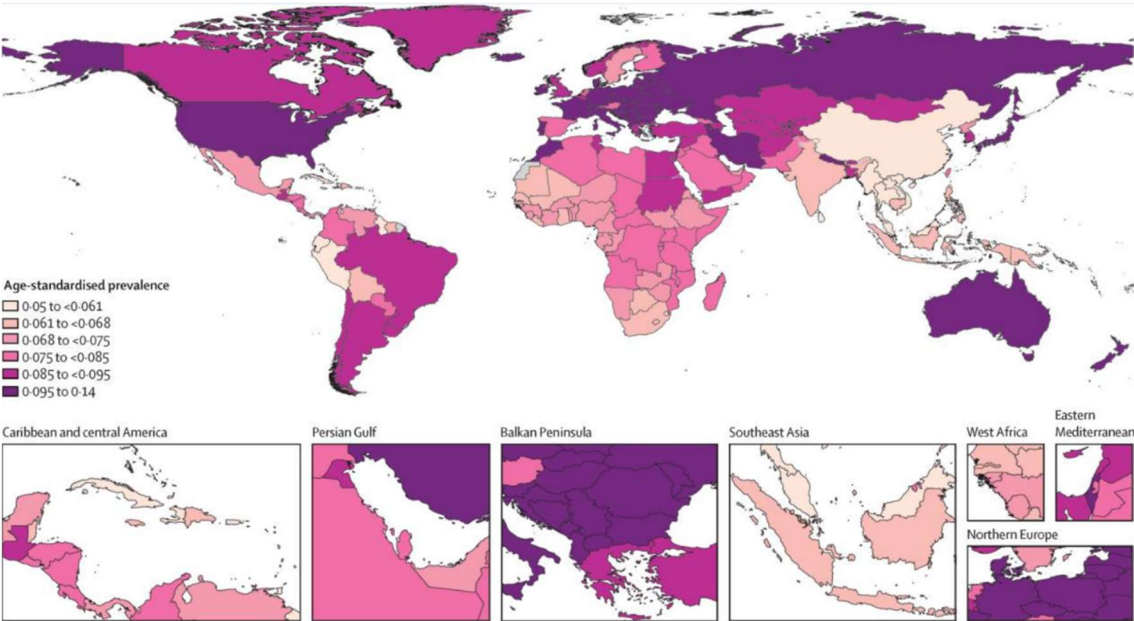


Figure 1 - 1: Prevalence of low back pain. This map demonstrates that low back pain is a significant health issue affecting populations worldwide, with notable variations in prevalence across different regions. The map highlights those countries with older populations, such as those in Europe and North America, exhibit the highest prevalence rates of low back pain, ranging from 9500 to 14000 per 100,000 individuals, as indicated by the dark purple colour. These regions include countries such as the United States, Russia, and several European nations, where the aging demographic contributes to the higher incidence of back pain. From: Ferreira et al, 2023 Global, regional, and national burden of low back pain, 1990–2020, its attributable risk factors, and projections to 2050: a systematic analysis of the Global Burden of Disease Study, 2021.

1.1. Causes of chronic back pain

Chronic back pain is caused by various spinal disorders divided into four broad categories:

1.1.1. Degenerative spinal diseases

These encompass a spectrum of conditions that impact the spine, often resulting in discomfort, pain, and diminished mobility. Herniated and migrated intervertebral disc prolapses, spondylolisthesis, and spinal stenosis are prominent among these disorders.

- a. **A herniated disc:** defined as the protrusion of the soft, gel-like centre (nucleus pulposus) through the tough outer layer (annulus fibrosus) of an intervertebral disc, leads to the irritation of adjacent nerves. Factors such as age-related wear and tear, injury, or improper lifting techniques contribute to disc herniation, manifesting symptoms such as pain, tingling, numbness, weakness in the lower back, often radiating down the legs and weakness of the target muscles. Treatment involves conservative measures like physical therapy, pain management, and rest, with surgery, such as discectomy or spinal fusion, reserved for severe cases (Chen et al., 2018) [Figure 1.2].

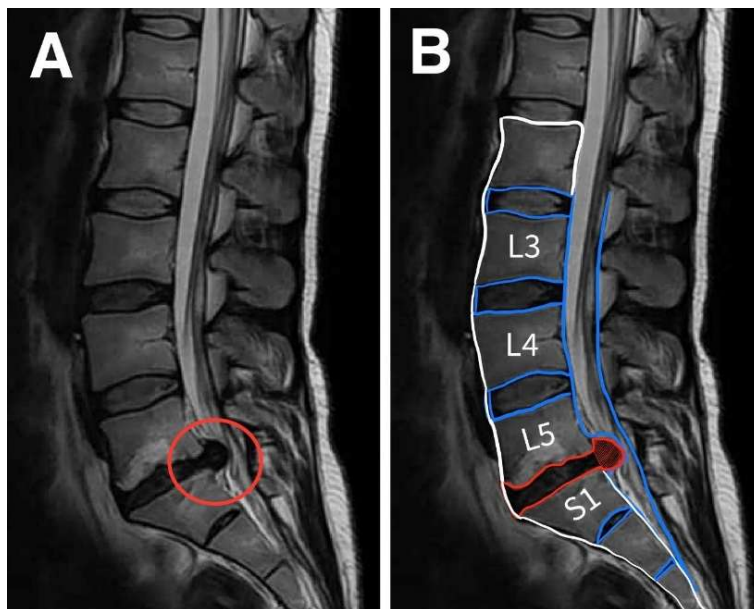


Figure 1.2: shows a Sagittal MRI with L5/S1 disc prolapse. This MRI demonstrates a sagittal view of the lumbar spine, focusing on the L3-S1 levels. In image A, there is a circled area at the L5-S1 intervertebral disc, showing a significant posterior disc herniation. The herniation is compressing the adjacent nerve roots, involving the S1 nerve root. This would explain potential radicular symptoms, such as sciatica, manifesting in the S1 dermatome. In image B, the vertebrae from L3 to S1 are labelled, with the disc herniation clearly delineated in red at the L5-S1 level. The

blue lines show the spinal curvature. Given the degree of herniation, surgical intervention like microdiscectomy might be considered if conservative treatments fail to resolve the patient's symptoms.

- b. **Spondylolisthesis:** involves the slipping of one vertebra over the one below it, disrupting the spine's normal alignment (Kalichman & Hunter, 2008). Degeneration of spinal discs, fractures, or congenital anomalies are common

causes, resulting in lower back pain, muscle tightness, and, in severe cases, nerve compression leading to radiating pain and weakness in the legs. While conservative approaches like physical therapy and bracing may suffice, severe cases necessitate surgical intervention, such as spinal fusion (Rangwalla et al., 2024) [Figure 1.3:].

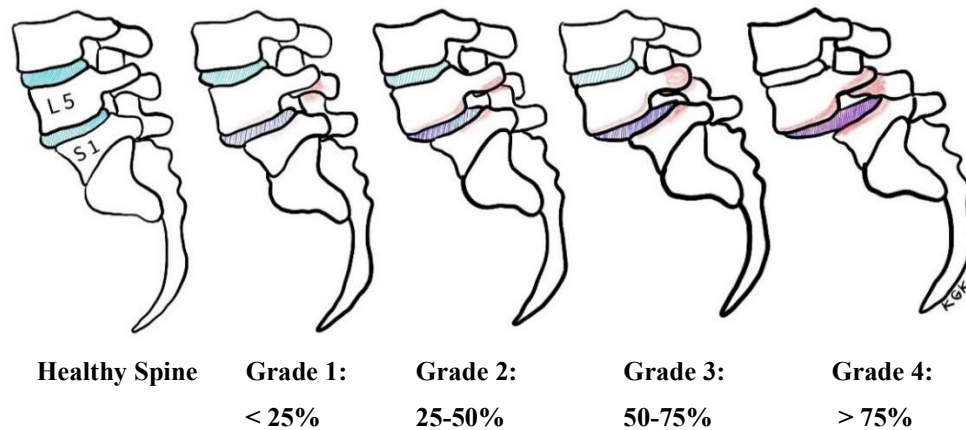


Figure 1.3: A schematic representation of the different Meyerding Grades for spondylolisthesis. On the left is a healthy spine. As the above vertebra, L5 in this example, slides forward relative to the lower vertebra S1, a condition known as anterolisthesis, it progresses through the grades: Grade 1 is characterized by a forward slip of less than 25% of the vertebral width, Grade 2 by a slip of 25-50%, Grade 3 by a slip of 50-75%, and Grade 4 by a slip of more than 75%.

- c. **Spinal canal stenosis:** is characterized by the narrowing of the spinal canal, causing compression of the spinal cord or nerve roots. Aging, degenerative changes, or conditions like arthritis contribute to spinal stenosis, presenting symptoms like pain, numbness, or weakness in the legs, particularly with walking, i.e. spinal claudication, or extended periods of standing. Advanced cases require surgical procedures like decompression, laminectomy or spinal fusion (Thomé et al., 2008) [Figure 1.4].

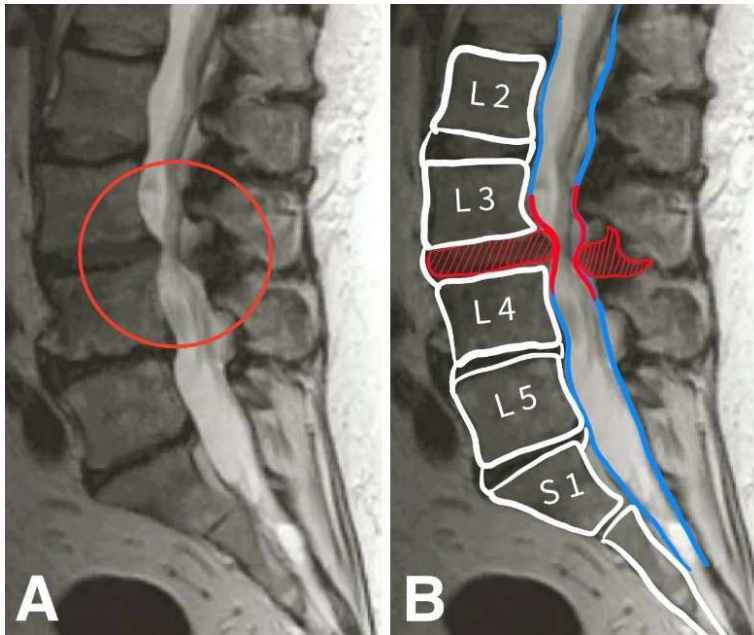


Figure 1.4: Sagittal MRT of lumbar spinal canal stenosis. This MRI demonstrates a sagittal T2-weighted view of the lumbar spine, focusing on the L2-S1 levels, and reveals significant lumbar spinal stenosis, particularly at the L3-L4 level. In Image A, the red circle highlights severe narrowing of the spinal canal, primarily due to a combination of disc bulging and likely hypertrophy of the ligamentum flavum.

The compression along the posterior border of the thecal sac results in a reduction of available space for the spinal cord and cauda equina. The high signal intensity of the cerebrospinal fluid (CSF), which typically surrounds the neural elements, is markedly reduced, indicating a significant compromise in the space for the neural structures within the canal. In Image B, the lumbar vertebrae from L2 to L5 and S1 are labelled, providing clear anatomical context for the stenotic level. Additionally, the image shows hypertrophy of the facet joints, indicated in red, which further reduces the canal's anteroposterior diameter. The blue lines along the lateral borders of the vertebral bodies emphasize the natural curvature of the spine. The thecal sac is visibly compressed, and there is a loss of CSF signal around the cauda equina, consistent with severe central canal stenosis, which could lead to neurogenic claudication or radicular symptoms in the corresponding dermatomes.

In terms of clinical significance, this patient presents with a classic case of lumbar spinal stenosis at L3-L4, where both disc pathology and hypertrophy of the posterior elements contribute to the narrowing of the canal. The degree of stenosis is severe, as evidenced by the deformation of the thecal sac and the marked reduction of CSF signal. This correlates with symptoms such as leg pain, weakness, and potentially bowel or bladder dysfunction if the condition worsens. The clinical findings should be correlated with the patient's neurological exam to assess whether conservative management is sufficient or if surgical intervention, such as a laminectomy or decompression with fusion, is necessary.

1.1.2. Spinal infections

Spinal infections including intra and extra spinal abscesses and infections of the disc space and adjacent vertebrae pose a serious threat to function and/or life, if not diagnosed

and treated promptly. An intraspinal abscess involves pus within the spinal canal from blood-borne spread, direct extension, or complications from spinal surgery or trauma. Extrapinal abscesses affect areas like the epidural space or nearby tissues. Discitis involves inflammation and infection of intervertebral discs introduced via bloodstream spread, usually caused by bacteria (Campbell et al., 2023). Spondylitis involves infection of the vertebral body, while Spondylodiscitis is a term reserved for infections involving both disc spaces and vertebral bodies [Figure 1.5].

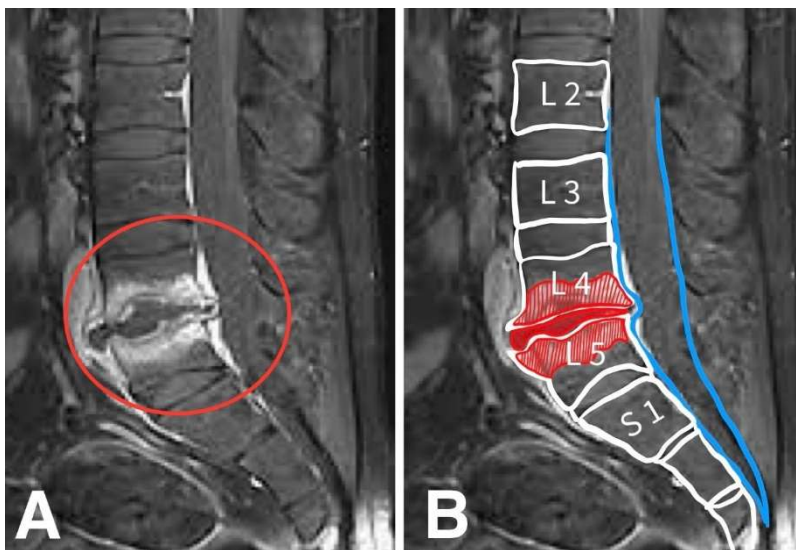


Figure 1.5 Spondylodiscitis.

The MRI image depicts a case of lumbar spondylodiscitis, an infectious condition involving the intervertebral disc and adjacent vertebral bodies. In Image A (on the left), the pathology is clearly localised around the L4-L5 vertebral levels, as marked by the red circle. There is

significant destruction of the disc space between L4 and L5, consistent with discitis. The vertebral endplates adjacent to this disc are irregular and show evidence of erosion, which is characteristic of spondylitis. The hypointense signal in the vertebral bodies and disc on T1-weighted with contrast agent images suggests oedema, inflammation, and the presence of infection, typical of spondylodiscitis. The pus extends anteriorly also, which may suggest psoas abscess. In Image B (on the right), we see a more annotated version of the same region, with the affected vertebrae (L4 and L5) highlighted in red. The blue line represents the dural sac, which is displaced by the adjacent infection. This suggests that the infection could be exerting pressure on the surrounding neural elements, leading to potential neurological symptoms such as radiculopathy or even cauda equina syndrome, depending on the extent of compression. Spondylodiscitis can often lead to severe complications, such as epidural abscess formation or spinal instability, both of which would warrant urgent surgical intervention.

Common causes of spinal infections include bacterial or fungal infections, such as *Staphylococcus aureus*, with heightened risk associated with conditions like diabetes or weakened immunity (Rajasekaran et al., 2018). Symptoms encompass severe back pain, neurological deficits, fever, and spinal deformities, necessitating rapid diagnosis to prevent permanent damage. Treatment involves intravenous antibiotics and surgical drainage of the abscess and stabilisation of the spine. Early recognition and intervention

are crucial for preventing neurological complications and life-threatening conditions, if left untreated.

Due to significant advancements in surgical implants and techniques, coupled with the widespread accessibility of surgical centres, surgical interventions have started to ascend as the primary method of treatment, potentially overcoming the conservative therapy, as first-line treatment for spinal infection (Stoffel et al., 2011).

1.1.3. Vertebral fractures

These fractures result from various causes including trauma, osteoporosis, and metastatic disease, each with distinct characteristics and management strategies. Traumatic lumbar fractures stem from sudden, forceful injuries like falls, car accidents, or sports-related incidents, leading to compression, burst, or flexion-distraction patterns that may impact the stability and alignment of the lumbar spine (Gardner et al., 2005). Osteoporotic lumbar fractures [Figure 1.6], on the other hand, are associated with weakened bones, often due to age-related bone loss and osteoporosis (Al Taha et al., 2024). Prevention is crucial, involving osteoporosis management to enhance bone density. Metastatic lumbar fractures result from the spread of cancer to the lumbar spine, compromising bone integrity, and necessitate addressing the underlying cancer through oncological interventions, along with spine stabilisation. The diverse array of lumbar fractures requires a tailored approach based on the pathology, often involving surgical intervention to stabilise the spine and mitigate the associated complications.

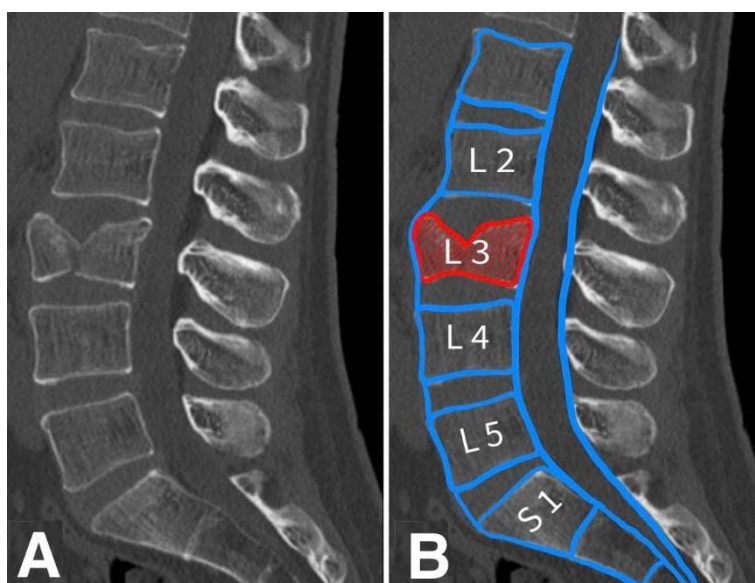


Figure 1.6: shows a sagittal section of a lumbar-CT scan (L3 Fracture). In Image A, we observe an osteoporotic lumbar fracture, at the L3 vertebra. There is a clear loss in vertebral height at L3 compared to the adjacent vertebrae, indicative of a compression fracture. The fractured vertebra shows a characteristic shape, which is typical in osteoporotic compression fractures. In Image

B, the same region is annotated. The L3 vertebra is highlighted in red, marking it as the site of the fracture. The surrounding vertebrae, L2, L4, L5, and S1, are outlined in blue and appear to maintain their structural integrity in comparison. The blue line running along the anterior and posterior borders of the vertebrae represents the general curvature and alignment of the spine, showing that the primary deformity is confined to the fractured L3 vertebra, with no major disruption to the overall spinal alignment. This kind of fracture is common in elderly patients with osteoporosis and could lead to chronic pain or further instability if not properly managed.

1.1.4. Spinal tumours

Spinal tumours present a diverse classification system, categorized into extradural and intradural, the latter further divided into intramedullary or extramedullary, based on the tumour location, with additional distinctions between benign and malignant tumours. Extradural tumours are located outside the dura and predominantly resides within the vertebrae [Figure 1.7]. Lung, breast, and colon cancer are the major primary metastatic tumours in the spine. Intramedullary tumours originate within the spinal cord itself, primarily of glial origin. These tumours, often slow-growing, present with nonspecific symptoms, and surgical intervention carries a high risk of iatrogenic injury due to the compact nature of the spinal cord. In contrast, extramedullary tumours arise from various tissues within the space between the dura and spinal cord, including nerves, blood vessels, and meningeal layers. These tumours commonly manifest with pain. They are almost always benign and well-demarcated, making them suitable for successful surgical resection (Esperança-Martins et al., 2023).

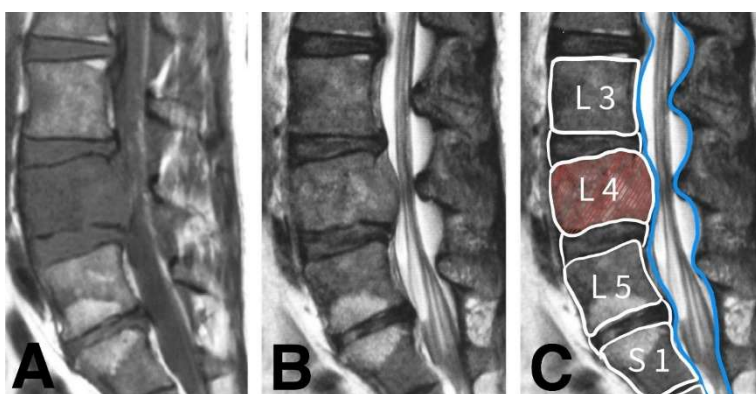


Figure 1.7: shows an MRI of a tumour in the L4 vertebra. This sagittal MRI reveals a collapse of the L4 vertebra along with an extradural mass compressing the dura mater. The lesion, extending from the L4 vertebral body, exhibits intermediate signal intensity on T1-weighted images

(Image A) and heterogeneous signal intensities with a mix of high and intermediate signals on T2-weighted images (Image B). In Image C, the same region is annotated. The infiltrated L4-vertebra is highlighted in red.

All these conditions cause compression of spinal nerve root[s] to an extent varying in severity, leading to local and radiating pain, numbness, sensory impairment, and weakness/palsy of the target muscles corresponding to the affected nerve roots. Some of these diseases lead to instability of the intervertebral facet joints leading to compensatory osteophyte growth, which in turn leads to spinal cord and nerve root compression that cause symptoms. Conservative treatment strategies such as physical therapy, pain medications, and facet joint as well as peri-radicular injections might reduce the symptoms for a time being. However, in cases where these approaches fail to alleviate the pain and improve functionality, surgical interventions aimed at treating the cause become necessary.

The aims of surgical treatment are to

- (1) remove space occupying lesions that cause spinal cord and nerve root compression (spinal and/or nerve root decompression),
- (2) prevent the vertebral bodies from collapsing, whenever necessary (spinal stabilisation) and
- (3) attain fusion of two pathological vertebral bodies, whenever necessary (intervertebral fusion, or vertebral body replacement in case of tumours).

There are two major ways to achieve these aims:

- (a) by means of open microsurgical instrumented stabilisation, decompression and fusion
or
- (b) by using minimally invasive techniques, percutaneous stabilisation, endoscopic or microscopic decompression and fusion.

We live among an aging population in today's Europe. Co-morbidities present in elderly individuals pose high risks for lengthy surgical interventions that are associated with long periods of prone positioning of the patient and blood loss. Thus, minimally invasive techniques have come to play an increasingly important role in strategies employed in all surgical disciplines. Spine surgery is no exception (Jain et al., 2020).

Whereas percutaneous dorsal spinal stabilisation techniques are known for fractures and endoscopic spinal surgery is applied for removal of migrated intervertebral disc prolapses,

there are very few recourses that describe these minimally invasive techniques for chronic degenerative diseases of the spine.

In this thesis, we will review the historical aspects and contemporary surgical approaches and their results in treating spinal disorders. More importantly, we will describe a novel method of minimally invasive, percutaneous dorsal spinal stabilisation (pDSS) of the lumbar spine combined with endoscopic transformational lumbar intervertebral fusion (eTLIF) for degenerative diseases of the spine.

1.2. A history of surgical approaches in treating lumbar spinal disorders

The evolution of surgical interventions for lumbar spinal disorders is marked by a fascinating journey through medical history. Over the decades, advancements in medical knowledge and technology have transformed the landscape of spinal surgery, shaping the contemporary approaches that we are now investigating in this study.

Historical records reveal attempts made to alleviate the suffering caused by lumbar spinal disorders that date as far back as ancient civilizations. Primitive surgical procedures, often accompanied by significant risks and limited understanding of anatomical complexities, were conducted in pursuit of pain relief and improved mobility. However, these early interventions were characterised by high morbidity rates and limited success. One of the pioneers to attempt surgery for back pain was Paul of Aegina, a Greek physician who lived in the 7th century AD. He described a procedure called laminectomy, which is the surgical removal of part of a vertebra to relieve pressure on the spinal cord or nerves (Markatos et al., 2018).

The 19th and 20th centuries marked a turning point in the history of spinal surgery. Pioneering surgeons began to explore innovative techniques that aimed to enhance patient outcomes whilst minimising invasiveness. Initially, efforts towards fusion relied on techniques such as the Hibbs method, involving bone graft placement over a fusion bed without instrumentation. Over time, advancements led to the development of various instrumentation methods, including steel wires introduced by Hadra in 1891, and the evolution continues with contemporary tools like screws, rods, and intervertebral devices (Virk et al., 2020).

Open lumbar fusion procedures, the prevailing standard approach for many decades now, provided a reliable approach for stabilisation, often at the cost of extensive tissue damage, prolonged recovery times, and increased complications. The primary approaches for intervertebral fusion in the lumbar spine encompass posterior lumbar intervertebral fusion (PLIF), transforaminal lumbar intervertebral fusion (TLIF), oblique lumbar intervertebral fusion (OLIF), lateral lumbar intervertebral fusion (LLIF), and anterior lumbar intervertebral fusion (ALIF) (Mobbs et al., 2015) [Figure 1.8].

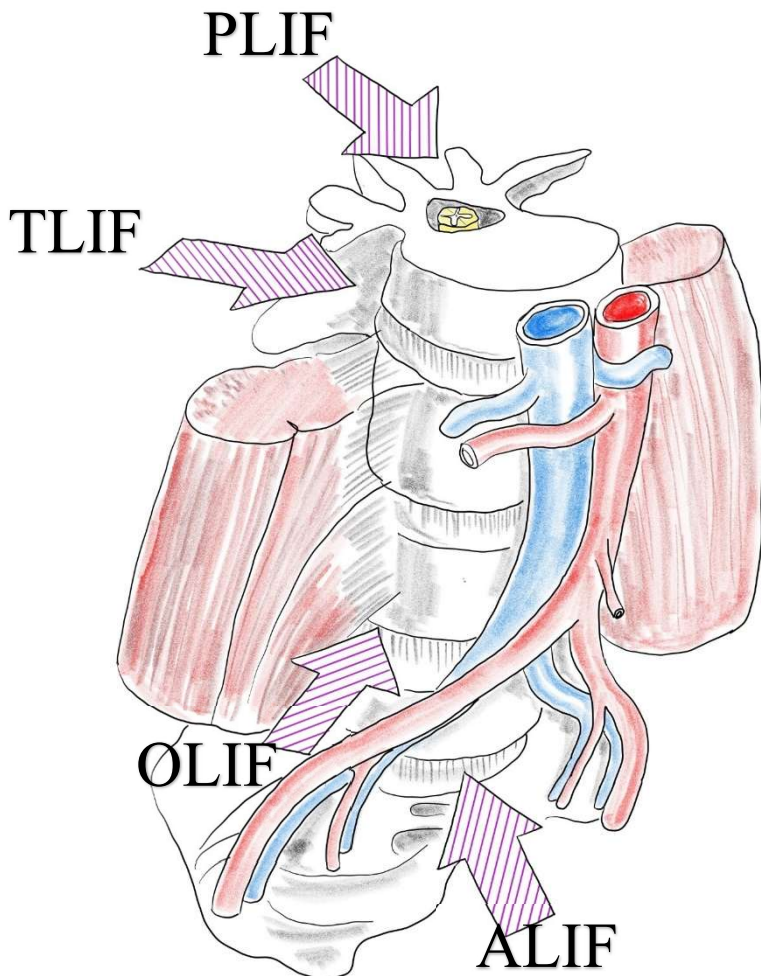


Figure 1.8: This schematic diagram illustrates the approaches for Lumbar Interbody Fusion. Posterior lumbar interbody fusion (PLIF), transforaminal lumbar interbody fusion (TLIF), oblique lumbar interbody fusion (OLIF), and anterior lumbar interbody fusion (ALIF). The PLIF approach involves accessing the intervertebral disc space through a posterior midline incision, passing between the lamina and thecal sac. The TLIF approach provides access through a more lateral posterior entry, allowing a less invasive path to the disc space via the intervertebral foramen. The OLIF approach, by contrast, involves an oblique entry through the lateral

abdominal wall, carefully navigating past the psoas muscle and avoiding direct manipulation of the major vascular structures such as the aorta and vena cava. The ALIF approach accesses the disc space from an anterior abdominal incision, which provides a direct view but requires careful dissection and retraction of the vascular structures, particularly the aorta and vena cava. Each approach is selected based on the patient's anatomy, surgeon's preference, and specific pathology being treated, with considerations made for spinal stability, disc height restoration, and the avoidance of complications involving surrounding neurovascular structures.

The late 20th and early 21st centuries witnessed remarkable changes in reasoning and rationale in spine surgery. The advent of minimally invasive surgical techniques introduced a new era of patient-centred care. These techniques, including endoscopic transforaminal lumbar intervertebral fusion (eTLIF) and percutaneous Spondylodesis, emerged as potential solutions to the limitations of traditional open procedures (Kim & Phillips, 2021). By utilising small incisions, specialised instruments, and advanced imaging technologies, surgeons aimed to achieve stabilisation, whilst reducing surgical tissue damage and accelerating patient recovery.

1.3. Surgical techniques of spinal stabilisation and transforaminal lumbar intervertebral fusion

1.3.1. Open dorsal spinal stabilisation (oDSS) and open transforaminal lumbar intervertebral fusion (oTLIF)

The procedure of open Transforaminal Lumbar Intervertebral Fusion (oTLIF) involves several sequential steps. First, the level of incision is localised using radiographic landmarks with the help of C-Arm. After prone positioning of the patient on a radiolucent frame and prepping the surgical field, a midline incision of approximately 12-30 cm in length is made overlying the spinous processes between the paraspinal muscles, followed by the dissection of subcutaneous tissue down to the fascia and the insertion of retractors for fascial exposure. The lumbodorsal fascia over the spinous processes is cauterised and dissected to the transverse process. Subperiosteal dissections are performed along the spinous processes, followed by a subperiosteal dissection of the lamina in a cranial to caudal direction. A probe is placed under the lamina for radiographic identification of the level. Facet capsules are exposed by stripping laterally along the lamina using the Cobb instrument, and transverse processes are dissected out by separating the paraspinal muscles from the intertransverse membrane. Deep retractors are placed for improved visualisation.

Laminectomy and decompression involve the removal of spinous processes using a rongeur, saving them for bone graft material. The lamina is removed, and the origin of the ligamentum flavum is identified. Decompression into the canal is initiated, and the medial aspect of the facet is decompressed using a burr. Ligamentum flavum is gently retracted and resected with Kerrison rongeurs. Lateral recess/foraminal decompression is performed by locating the pedicle, undercutting the superior facet with a Kerrison rongeur, and identifying osteophytes that might impinge the exiting nerve root. Pedicle screw instrumentation involves identifying the entry point and decorticating the site using a burr. The pedicle screws are inserted, and their positioning is verified radiographically.

The intervertebral facet joint on the side of the TLIF is partially or totally removed. Now, the disk space and the nerve root are exposed. Disk space preparation involves mobilising the thecal sac with a nerve root retractor, incising the annular ligament to create a window,

and performing a thorough discectomy with shavers, dilators, curettes, and rongeurs. Interbody arthrodesis includes trialling the implant size, packing graft material, and placing the intervertebral cage centrally, see [Figure 1.9].

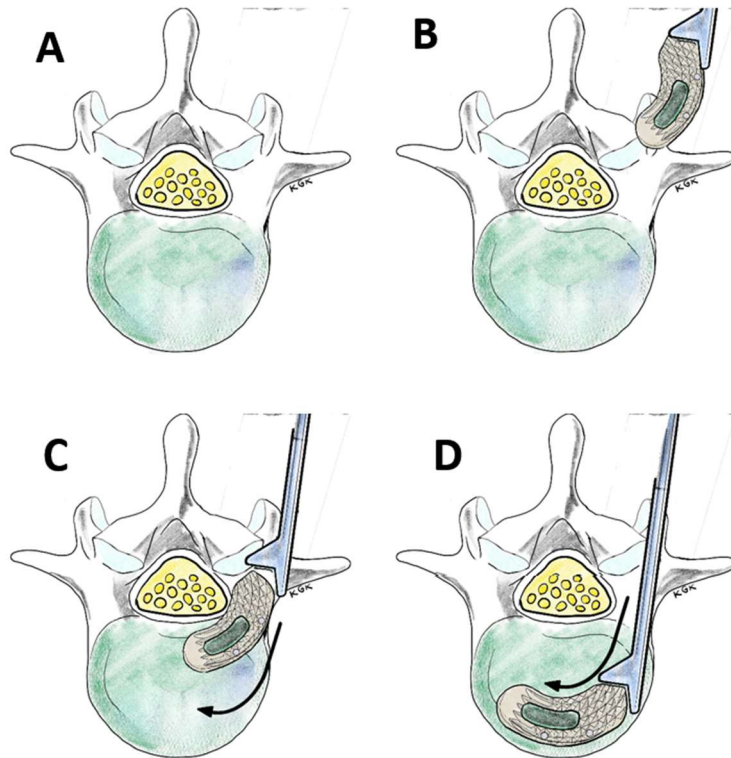


Figure 1.9: This figure shows an illustration of the TLIF technique. Image (A) shows an axial view of a lumbar vertebra, highlighting the nerves and spinal canal in yellow and the intervertebral disc space shaded in green. Image (B) shows the Introduction of the intervertebral cage through the foramen, demonstrating the initial entry angle of the cage. Image (C) represents the rotational movement of the cage as it is manoeuvred through the foramen towards the intervertebral space. Image (D) shows the final

placement of the cage within the intervertebral disc space, lying nearly horizontally to promote stabilisation and fusion.

During all these manipulations, extreme care is taken not to injure the thecal sac or the nerve roots. The implant's position is confirmed radiographically. Contoured rods are brought in to be fixed to the previously placed pedicle screws. The fixation screws affixing the rods to the pedicle screw-heads are tightened after the desired laterally lordotic and frontally straightened positions of the vertebral bodies are achieved by distraction or compression of the pedicle screws. After achieving haemostasis, insertion of drains, the surgical wound is closed in several layers beginning with the deep fascia and ending with the skin.

In summary, oDSS and oTLIF involves a careful sequence of steps to address spinal pathology, achieve stabilisation, and promote intervertebral fusion in the lumbar spine (*Orthobullets Team (2016)*). It is important to mention that exact technique may vary among different institutions and even among different surgeons within the same institution.

Open-TLIF procedures exhibit several drawbacks that stem from the extensive dissection of paraspinal muscles required to access the spine. This approach might result in heightened intraoperative blood loss (especially in patients with coagulation disorders or on anticoagulation medication for vital reasons), increased tissue trauma, and a susceptibility to complications such as dural tears, infections, hematomas and wound healing problems. Additionally, there exists a potential for postoperative pain, prolonged hospital stays, and delayed resumption of daily activities. The larger incisions inherent to oTLIF can lead to more noticeable scarring, prompting concerns about both cosmetic outcomes and functional impairment due to muscle trauma. Furthermore, the substantial tissue disruption in oTLIF impedes patients' immediate mobility and hinders their involvement in early rehabilitation efforts (Hammad et al., 2019).

1.3.2. Percutaneous transpedicular dorsal spinal stabilization (pDSS)

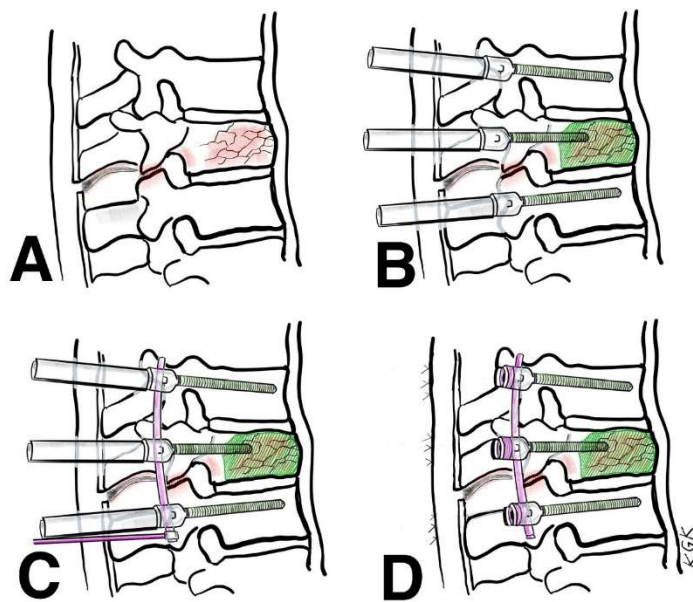


Figure 1.10: A schematic representation of the pDSS technique for vertebral fracture. shows the steps in percutaneous screw fixation. (A): shows the fractured vertebra, highlighted in red to indicate the fracture site. No instruments have been inserted at this stage. (B): After insertion of the ES2 screws, positioned into the pedicles to provide structural support. The fractured vertebra has been augmented with poly methyl

methacrylate (PMMA) self-hardening bone cement (green shading) (C): The rod is attached to the screws to stabilise the vertebrae, ensuring proper alignment and support across the fracture. (D): shows the removal of the blades from the ES screws and closure of the skin with stitches, completing the procedure.

Percutaneous dorsal spinal stabilisation is a procedure commonly used for vertebral body fractures [Figure 1.10]. For the percutaneous transpedicular placement of pedicle screws, the patient is positioned prone on a radiolucent operating table. Attention is given to maintaining lordosis, padding bony prominences, and suspending the abdomen. The arms are abducted onto padded boards, and the legs are extended. Anteroposterior (AP) and

lateral fluoroscopic images are acquired to determine the target vertebrae for instrumentation, with markings denoting midline, lateral pedicular, and interpedicular lines on the skin using the C-Arm. The pedicular screws are placed via several cutaneous stab incisions of approximately 0.5 cm in length. Through these incisions transpedicular channels are established using the Jamshidi needle, guided by fluoroscopy, penetrating the upper outer quadrant of the pedicle. The Jamshidi-needle is advanced approximately 30 mm into the bone, avoiding the medial border. Subsequently, Kirschner-guidewires (K-wire) are inserted through the J-needles into the pedicles and confirmed fluoroscopically. Thereafter, self-cutting cannulated screws are introduced over the K-wires into their trajectory through the pedicles into the vertebral bodies. Then the K-wires are removed. The system employs screw-head-extenders lined up, measuring rod length with a rod inserter, and inserting rods percutaneously via a small incision, passing through the screw-head extenders. Screws attach to C-shaped towers with an extender sleeve, allowing rod implantation through a single incision, secured with set screws. Reduction and compression are feasible, finishing the procedure by removal of instruments and closure of skin incisions (Mohi Eldin & Hassan, 2016). Minor variations to this technique are possible depending on the manufacturer of the system used for percutaneous stabilisation.

As opposed to the open technique, percutaneous placement of screws does not warrant long skin incisions, extended tissue dissection and blood loss.

1.3.3. Endoscopic transforaminal lumbar intervertebral fusion (eTLIF)

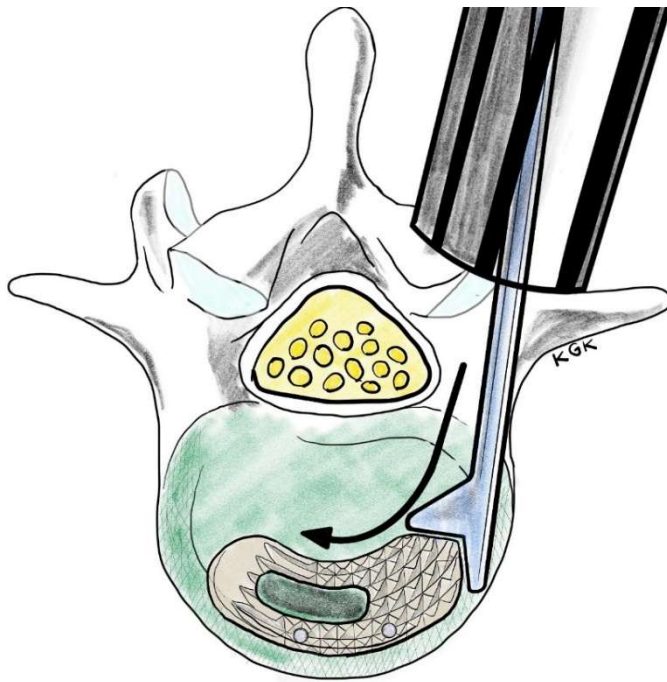


Figure 1.11: Illustration of a lumbar vertebra showcasing the endoscopic transforaminal lumbar interbody fusion (eTLIF) technique in an axial view. The spinal canal (yellow) contains the nerves. The intervertebral disc space is shaded in green. The TLIF cage is visible in place after insertion, providing structural support within the intervertebral space. The endoscope (black) allows for visual guidance during the procedure, while the cage inserter (blue) is used to advance the cage forward in a rotational motion (curved arrow).

The tubular endoscopic TLIF in combination with the pDSS is the main subject of this manuscript. eTLIF is a recent development and has not been widely written about. The patient is positioned prone on a radiolucent table, and general anaesthesia is administered. A skin incision, approximately 1 cm in length, is performed at the target disc space level, situated about 5-6 cm laterally to the midline. Subsequently, a guide wire is introduced through the incision and advanced under fluoroscopic guidance to the superior articular process of the lower vertebra. A sequence of dilators is then introduced over the guide wire, creating a functional channel for the endoscope-shaft. The endoscope-shaft, coupled with a camera and light source, is introduced through this established channel. Endoscopic visualization the superior articular process. The superior articular process is removed using a high-speed burr to create a triangular window, thereby facilitating access to the disc space. The annulus fibrosus is incised, enabling the removal of the nucleus pulposus using forceps or shavers. Preparation of the endplates is undertaken using curettes or rasps, ensuring the generation of bleeding bone surfaces conducive to fusion. A spacer (Cage) containing bone graft material is introduced through the endoscopic channel into the disc space, see [Figure 1.11]. Upon insertion the spacer restores disc height, foraminal height, and lordosis. Concluding the procedure, the endoscope is withdrawn, and the wound is meticulously closed in three layers- fascia, subcutaneous and cutaneous sutures.

Compared to open surgery, minimally invasive surgical techniques have been demonstrated to result in significantly reduced tissue injury and trauma. Only small incisions are made rather than large open wounds, resulting in less damage to skin, muscle, nerves, and other tissues. This decreased tissue injury leads to substantially less blood loss during the procedure. Patients experience markedly reduced pain after minimally invasive surgery compared to open surgery, owing to the smaller incisions and limited tissue trauma. Postoperative pain management requirements are also substantially lower. The reduced tissue injury and trauma also allows patients to recover faster after minimally invasive surgery. Patients are able to mobilise, walk, and return to daily activities much sooner compared to open surgery. Fast recovery enables shorter hospital stays. The risks of postoperative complications are minimal (Antonacci et al., 2024).

There is however one major disadvantage of eTLIF, namely restricted visualisation of the anatomical structures hidden from the view of the endoscope. In severe structural spinal deformities such as scoliosis and multiple vertebral deformations combined with stenoses, the eTLIF is contraindicated in our opinion. Most of all the combination of pDSS and eTLIF is best suited for pathologies focused on one to maximally three levels of the lumbar spine.

The combination of pDSS and eTLIF is a novel technique we describe here. However, the principle is not completely unknown. A descriptive analysis in the way we present it here is not published in the literature available to us. There exist only a handful of articles that detail the outcomes for patients following endoscopic TLIF and percutaneous screw insertion, with the majority originating from Asian countries (Ahn et al., 2019; He et al., 2022; C. Liu & Zhou, 2018; Zhang et al., 2023). The absence of published articles that assess the outcomes of such surgeries in the western hemisphere is quite noticeable. This scarcity of information from these regions underscores a gap in the existing literature, prompting the need for comprehensive studies that explore the efficacy and results of endoscopic TLIF procedures.

In their study, (He et al., 2022) conducted a comparison between two endoscopic lumbar intervertebral fusion techniques, namely percutaneous endoscopic posterior lumbar intervertebral fusion (ePLIF) and open posterior lumbar intervertebral fusion (PLIF). Thirty patients were included in each group, and their progress was tracked over a two-

year period. The results demonstrated that ePLIF exhibited clinical and radiological outcomes comparable to open PLIF, while showcasing advantages such as reduced blood loss, shorter hospital stays, and decreased back and leg pain during the initial six months following surgery. Consequently, the authors concluded that ePLIF represents a secure and effective alternative for achieving minimally invasive lumbar intervertebral fusion.

In another study, (C. Liu & Zhou, 2018) , compared the efficacy of two minimally invasive techniques, endoscopic transforaminal lumbar intervertebral fusion (eTLIF) and minimally invasive transforaminal lumbar intervertebral fusion (miTLIF), for the treatment of single-segment lumbar spondylolisthesis. A total of 62 patients were included, with 32 undergoing eTLIF and 30 undergoing miTLIF, all of which were performed by the same surgeon. eTLIF was characterised by smaller incisions, the utilisation of an endoscope, and the application of expandable cages as opposed to miTLIF, aiming to minimise tissue damage. The comparison revealed that eTLIF exhibited advantages such as reduced blood loss, shorter ambulation time, faster recovery, and better early outcomes in terms of back pain and disability scores as opposed to miTLIF. However, both techniques demonstrated comparable results in leg pain scores, fusion rates, and complications. Notably, the eTLIF approach did entail some downsides, including increased intraoperative x-ray radiation exposure, longer operation duration, and a flat learning curve. It was also noted that the feasibility of eTLIF was influenced by factors like the height of the iliac crest and endplate preparation. In conclusion, the study suggests that for single-level lumbar spondylolisthesis, eTLIF could potentially be a more favourable choice over miTLIF, although larger-scale studies with extended follow-up periods are imperative to substantiate these findings.

Similar results were published by (Ao et al., 2020). This prospective cohort study aimed to compare surgical trauma and medium-short term outcomes associated with eTLIF and miTLIF techniques in the context of treating lumbar degenerative diseases. The study included patients who underwent either eTLIF (n=35) or miTLIF (n=40). The results indicated that eTLIF exhibited significantly reduced surgical trauma, as evidenced by lower levels of postoperative inflammatory marker C-reactive protein and muscle damage marker creatine kinase. Moreover, eTLIF showed advantages in terms of diminished overall blood loss, intraoperative blood loss, postoperative drainage, hidden blood loss, and postoperative low back pain when compared to miTLIF. Patients who underwent

eTLIF experienced faster recoveries, characterised by shorter hospital stays and decreased analgesic usage. Conversely, no notable differences emerged in medium-short term patient-reported outcomes, including visual analogue scale pain scores, Oswestry Disability Index, Macnab criteria, and fusion rates, between the two techniques. In conclusion, Ao's study emphasised that eTLIF holds promise for reduced surgical trauma and expedited recovery compared to miTLIF. However, it was noted that the application of eTLIF is limited to specific indications and requires surgeons to navigate a flat learning curve, highlighting the necessity for careful patient selection.

As it is clearly evident, there is a lack of research on eTLIF and pDSS. In this thesis, we describe the novel technique of the combination of pDSS and eTLIF as we perform it. We could not find a similar description in the literature resources available to us.

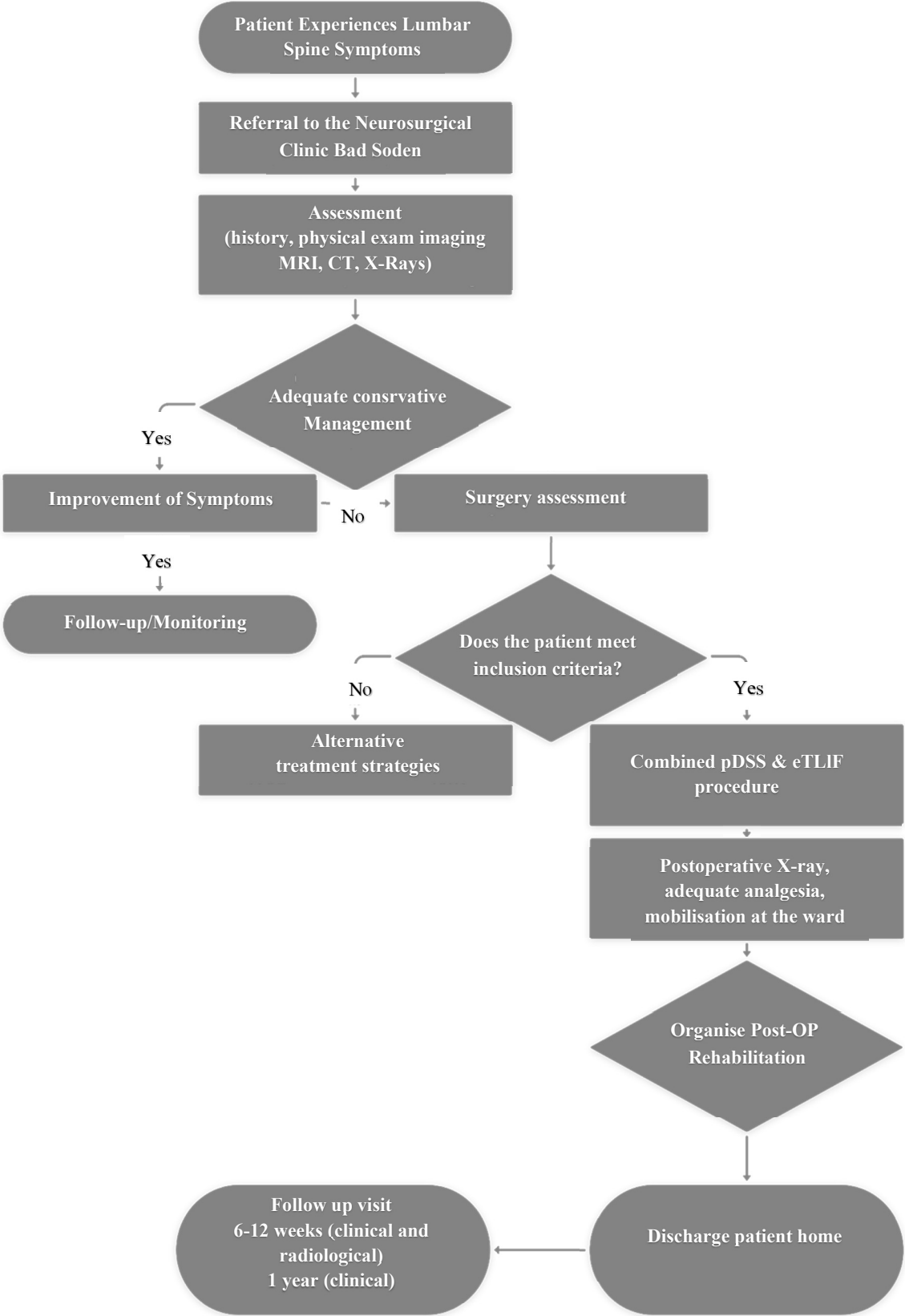
The goal of this study is to describe the surgical technique and retrospectively analyse the efficacy of our technique in a cohort of 70 patients with regards to speed of recovery, pain, blood loss and surgical time. To our knowledge this is the largest series of this category, for treating degenerative lumbar spine pathologies, presented so far in the literature.

2. MATERIALS AND METHODS

2.1. Clinical flowchart

The patient management pathway is outlined in the flowchart below [[Chart 2. 1: Clinical Flowchart](#)]. Beginning with the presentation of lumbar spine symptoms, patients underwent a comprehensive evaluation, including a physical examination and imaging review. Those who experienced insufficient improvement with conservative therapy proceeded to surgical consultation. Patients meeting the predefined inclusion and exclusion criteria then underwent the combined pDSS and eTLIF procedure. Postoperatively, all patients received standardized care, including pain management and mobilization. A rehabilitation assessment determined the need for further rehabilitative care. Follow-up visits were conducted at 6-12 weeks and 1 year postoperatively to assess clinical and radiological outcomes.

Chart 2. 1: Clinical Flowchart. Flowchart of the Clinical Pathway for Managing Lumbar Spine Disorders at Bad Soden Neurosurgical Clinic, outlining the process from initial patient consultation through diagnostic evaluation, conservative and surgical treatment options, to postoperative care and discharge.



2.2. Patients

The study included a total of 70 patients diagnosed with degenerative lumbar spinal disorders, encompassing conditions such as herniated and migrated intervertebral disc prolapses, spondylolistheses and spinal stenosis. Among the 70 patients 32 were male and 38 were female. The mean age at the time of surgery was 71.29 +/- 13.8 (range: 22 - 87 years, median age: 74.1 years). In our cohort, 43 patients underwent surgery for a single level, whereas 27 patients had surgery on multiple levels. In total, 101 segments were stabilized among the 70 patients.

All patients were treated using the novel technique of combined percutaneous dorsal spinal stabilisation (pDSS) and endoscopic transforaminal lumbar intervertebral fusion (eTLIF). Informed consent was obtained from each patient for the surgery, and the study was conducted in accordance with ethical guidelines and approval from the institutional review board The Ethics Committee of the Faculty of Medicine at Justus Liebig University Giessen (Permit number: Votum der Ethik-Kommission AZ 206/23).

2.3. Institution and surgeon

All surgeries were performed at the Varisano Hospital Bad Soden am Taunus, Germany by the consultant of this thesis, Professor Kartik G. Krishnan, who focusses on minimally invasive surgical techniques and technology. The procedures were conducted in the hospital equipped with C-Arm fluoroscopy and advanced imaging technologies (CT and MRI Machines).

2.4. Inclusion criteria

- Patients with degenerative lumbar spinal disorders where an indication for pDSS and eTLIF was confirmed.
- Only patients older than 18 years with no upper age limit were included
- Patients who underwent pDSS and eTLIF at the Varisano Hospital Bad Soden between 01.01.2020 and 31.03.2023
- Only patients that were in regular follow-up were included

2.5. Exclusion criteria

- Other spinal diseases which will affect the results of the study (e.g. Ankylosing Spondylosis, scoliosis, Infections, Tumours)
- Previous surgeries in the lumbar spine before beginning of the study
- Patients who explicitly refused to participate in the study

2.6. pDSS and eTLIF surgical technique

This section will explain our particular procedural methodology, the combined pDSS and eTLIF, acknowledging its similarities with existing literature while emphasising the differences of our unique sequence and instrumentation employed in practice.

2.6.1. Instruments

Percutaneous pedicle screws and rods manufactured by Stryker (ES-2, Stryker GmbH & Co. KG, Duisburg, Germany) of the line ES-2 was used for all the pDSS procedures described here, [Figure 2. 1].

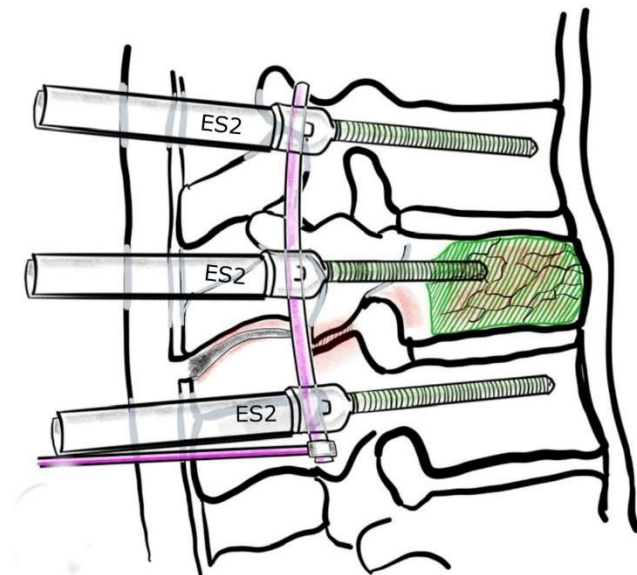


Figure 2. 1: This is a schematic drawing that shows the percutaneous ES2 screws and rod system manufactured by Stryker GmbH & Co KG., Duisburg, Germany

The cages for eTLIF are made of polyetheretherketone (PEEK) with radiopaque markers on the edges manufactured by Ulrich (pezo-T™, Ulrich GmbH & Co. KG, Ulm, Germany) [Figure 2. 2].



Figure 2. 2: A photograph of pezo-T™ PEEK from Ulrich. The material used is radiolucent PEEK, which includes X-RAY markers for secure positioning and ensures artifact-free CT and MRI imaging. The device allows for a large filling volume for bone or bone substitute material.

The Easy GO Endoscope was designed by surgeons Gaab and Oertel (thus GO) and manufactured by Karl Storz Company (KARL STORZ SE & Co. KG, Tuttlingen, Germany). See [Figure 2. 3] and [Figure 2. 4]. This system was initially developed for dorsal tubular approaches for endoscopic removal of migrated disc prolapses (Oertel et al., 2009). Later the system was used for dorsal decompression of the spinal canal.

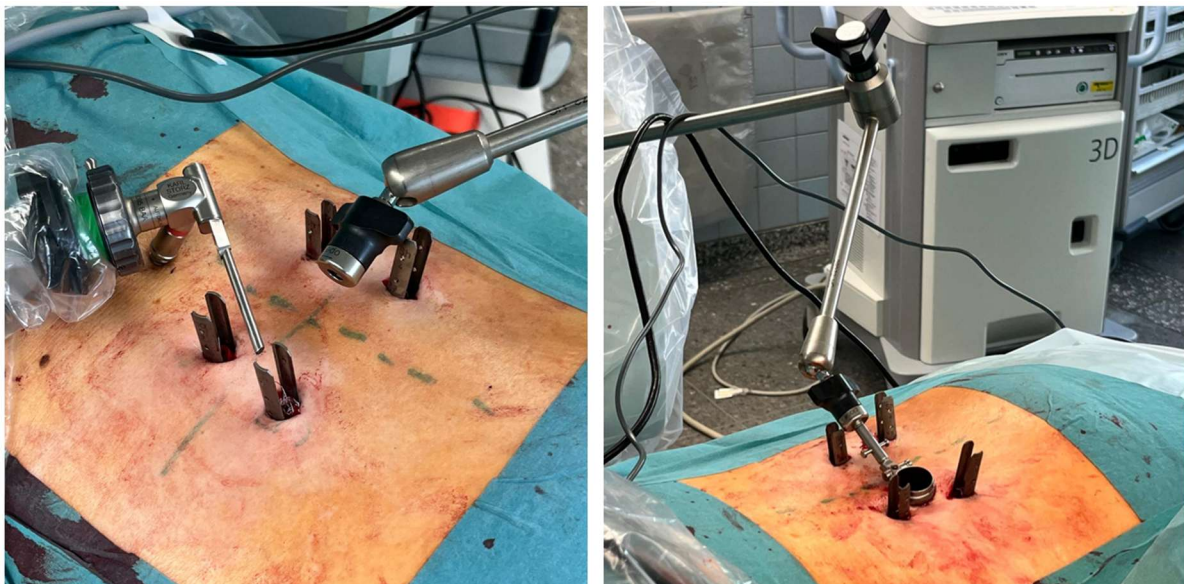


Figure 2. 3: A photograph showing the intraoperative use of the EasyGO system. The incision is small, and the dorsal musculature of the lumbar spine is gently displaced using a dilation system. The photo on the left captures the holding arm which the optic shaft will be secured in and the endoscope camera. The photo on the right shows the attached optic shaft to the holding arm where the camera will be inserted.



Figure 2. 4: The EasyGO Endoscopic System setup demonstrates the configuration of the holding arm attached to the endoscope shaft, with the endoscope camera securely positioned within the shaft. The system is carefully aligned over the target spinal region, in this case, the inferior articular facet of the superior vertebra.

The system is made of three components:

- (1) The serial bougie dilators, used for making the approach.
- (2) The optic shaft, which is brought on top of the bougie dilator and placed at the level of the approach. The optic shaft is provided with a turret-like mechanism for fixing the endoscope to its rim. The optic shaft is solidly fixed with a mechanical or pneumatic holding arm, so that it does not move during the manipulations, and
- (3) The endoscope itself. This has a 45-degree bevelled optic to offer a bird's eye perspective of the surgical field

Step 1: Patient positioning and preparation

The patient is positioned in a prone position on the operating table, Prone-Andrews frame are used to allow optimal access to the lumbar spine.

We use two C-Arms during the procedure, with one designated for anterior-posterior (AP) projection and the other for lateral views. Each C-Arm is positioned on opposite sides of the patient, and a collision test is conducted beforehand to ensure precise placement. This approach not only enhances efficiency but also preserves a more sterile surgical field, as opposed to relying on a single C-Arm and repeatedly adjusting its position for different projections.

Standard sterile washing and draping procedures are carried out to maintain aseptic conditions throughout the procedure, See [Figure 2. 5].

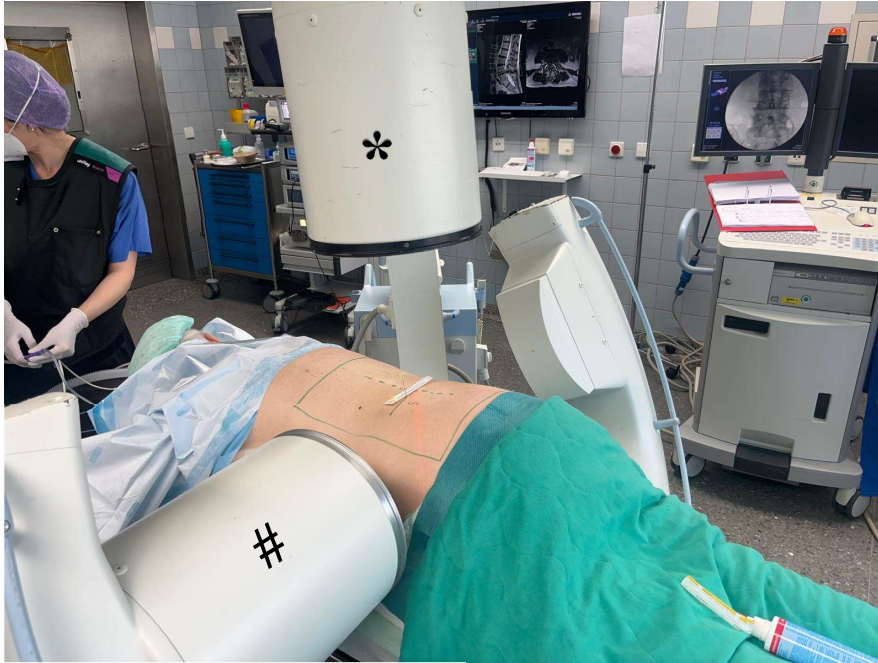


Figure 2. 5: Shows a photograph for patient positioning and preparation. The patient is positioned prone with the surgical field marked on their back. Two C-Arms are positioned for anteroposterior (AP) and lateral imaging to guide the procedure. A spinal needle is inserted as a radiographic marker to help identify the surgical level precisely on the X-ray. (Asterisk *: C-Arm for AP, Hash-sign #: C-Arm for lateral imaging)

Step 2: Pedicle screw placement

Under the precise guidance of fluoroscopy, small incisions are made bilaterally at the levels of the lumbar vertebrae for instrumentation. A minor skin vertical incision of around 1cm in length is made using a size 10 blade, cutting through both the skin and deeper layers down to the fascia, see [Figure 2. 6].

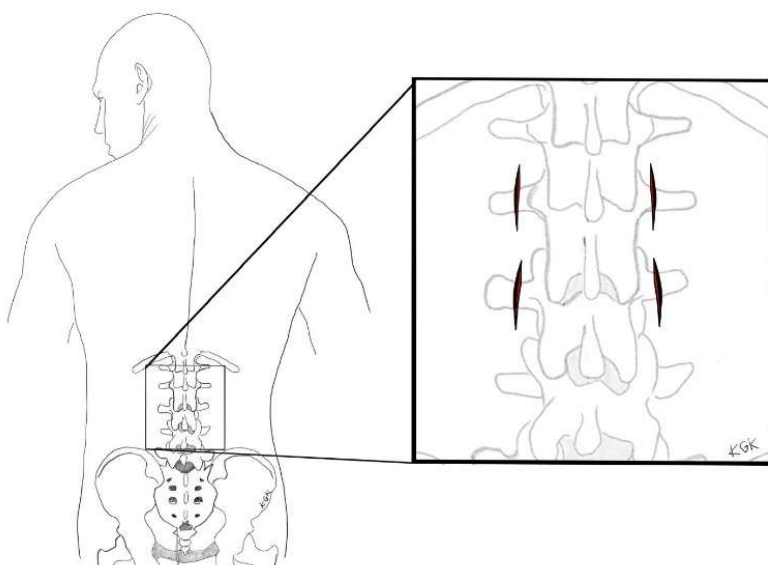


Figure 2. 6: This Illustration shows four small incisions made on either side of the lumbar spine. These incisions provide access points for Jamshidi-needle, and subsequently the percutaneous screws, allowing surgeons to reach the affected vertebral levels while minimising tissue disruption.

Subsequently, using Jamshidi needles, the pedicles are meticulously accessed bilaterally to ensure accurate screw placement. The precise positioning of the tip of the Jamshidi needle and its alignment with the pedicle is consistently evaluated using fluoroscopy. K-wires are then carefully inserted, providing a pathway for the subsequent placement of ES2 screws (Stryker) using the K-wire guide. The K-wire is advanced until it reaches the anterior wall of the vertebral body. The Jamshidi needle is cautiously withdrawn, ensuring that the K-wire remains securely in place and does not inadvertently dislodge.

The ES2 screw is then carefully placed over the K-wire and securely inserted into the pedicle, See [Figure 2. 7] and [Figure 2. 8].

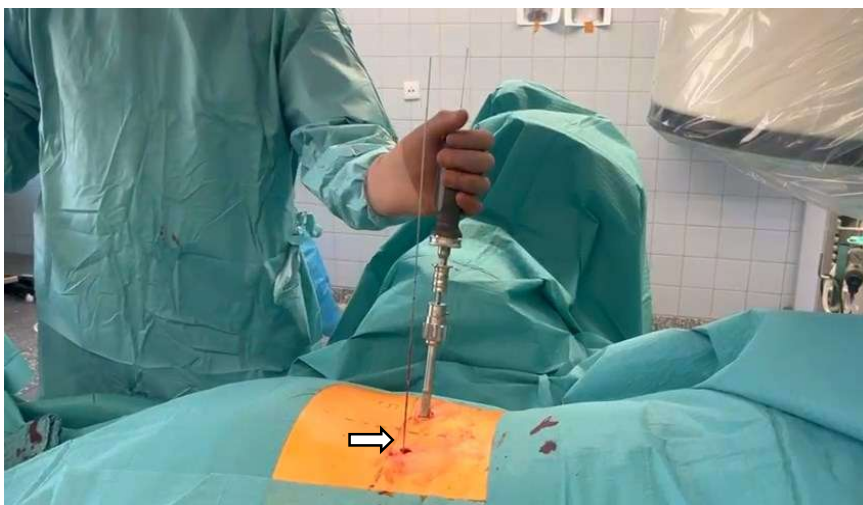


Figure 2. 7: This photograph shows the inserted K-wire (white arrow) on the patient's right side, while on the left, the ES2 screw is being carefully advanced over the K-wire, using it as a precise guide for optimal positioning.

The dimensions of the screws (length and diameter) are chosen prior to surgery based on the measurements in the preoperative CT or MR scans.

Confirmation of screw placement is verified with fluoroscopic imaging to ensure optimal screw positioning.

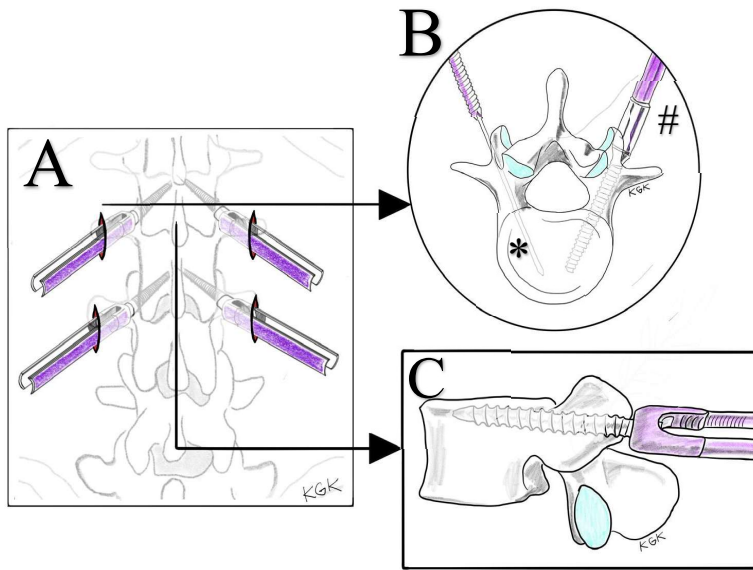


Figure 2. 8: This drawing illustrates the status after screw insertion. (A): Posterior view showing the placement of four screws, two on each side, with protruding blades shaded in purple. (B): Cross-sectional view of the vertebra, highlighting the process of screw insertion. The screw on the left side is shown sliding over the K-Wire (indicated by an asterisk *), ensuring precise guidance into the vertebra. On the opposite side, a fully inserted screw is shown in place (indicated by a hash #). (C): Lateral view of the vertebra, demonstrating the final position of the screw within the vertebral body

The screwdrivers are then withdrawn, leaving the screw blades protruding from the incision, facilitating potential later adjustments or Pedicle-Based Retraction (PBR) if required, see [Figure 2. 9].

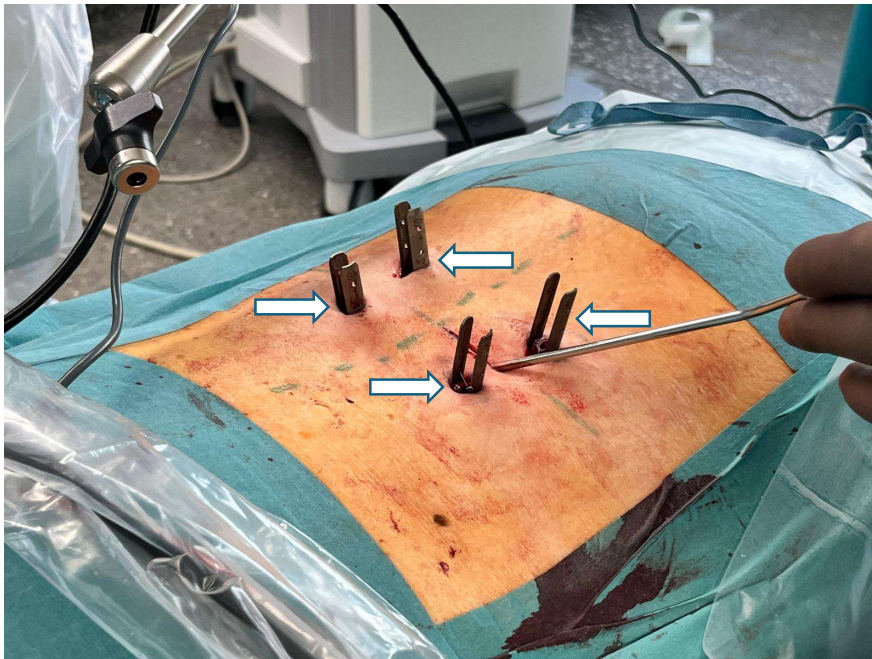


Figure 2. 9: This photograph displays the ES2 screw blades protruding from the incision following the removal of the K-wires. The four doubled screw blades (white arrows) , visible here, represent fixation at a single spinal level (K-wires have been already removed).

Now the C-Arm for the anteroposterior projection is removed. The table mount for the endoscope holding arm is fixed and the procedure carries on to eTLIF, see [Figure 2. 10].



Figure 2. 10: This photograph shows the holding arm (white arrow) secured to the surgical table from the opposite side, along with the endoscope camera head (star), which is prepared for attachment to the holding arm.

Step 3: Endoscopic transforaminal lumbar intervertebral fusion (eTLIF)

A transverse incision of around 2-3 cm is made between the screw incisions on the side, through which the eTLIF is intended, specifically targeted at the level of the disc space to be addressed.

A special bougie dilator system (EasyGO, Karl Storz GmbH & Co AG, Tuttlingen, Germany) is used to access the approach to the intervertebral space. This is done by sequentially gently dilating the incision until the bony structures are felt, see [Figure 2. 11].

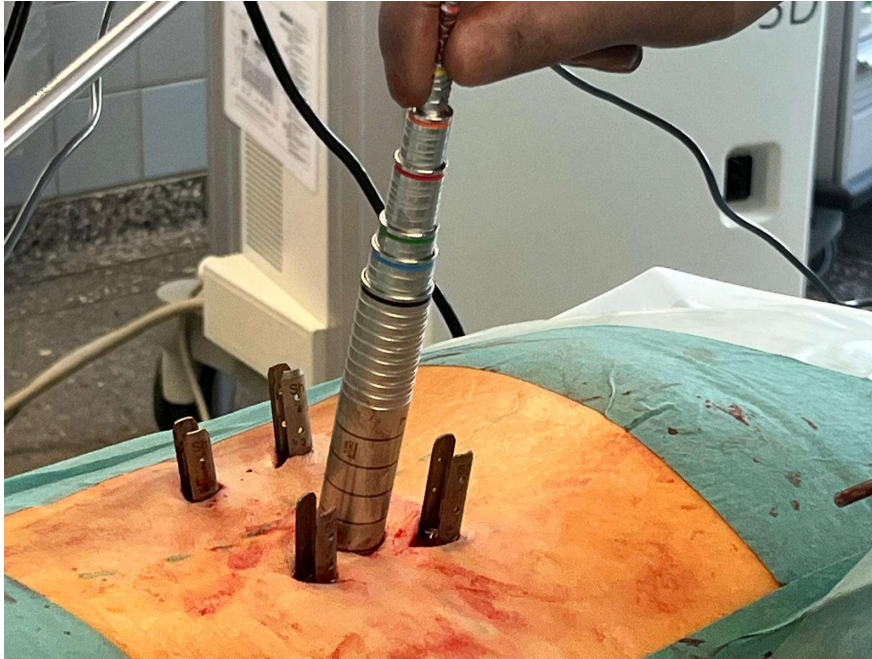


Figure 2.11 shows the bougie dilator system (EasyGo) inserted at the targeted level. The coloured metal dilators are introduced sequentially until the desired diameter is achieved, each subsequent dilator is larger in diameter.

The endoscope shaft is brought on the bougie dilator and fixed to the holding arm, mounted earlier to the table. Now the bougie dilators are removed. The shaft is placed exactly on top of the medial portion of the facet joint and the lamina of the vertebral bone. See [Figure 2.12] and [Figure 2.13].

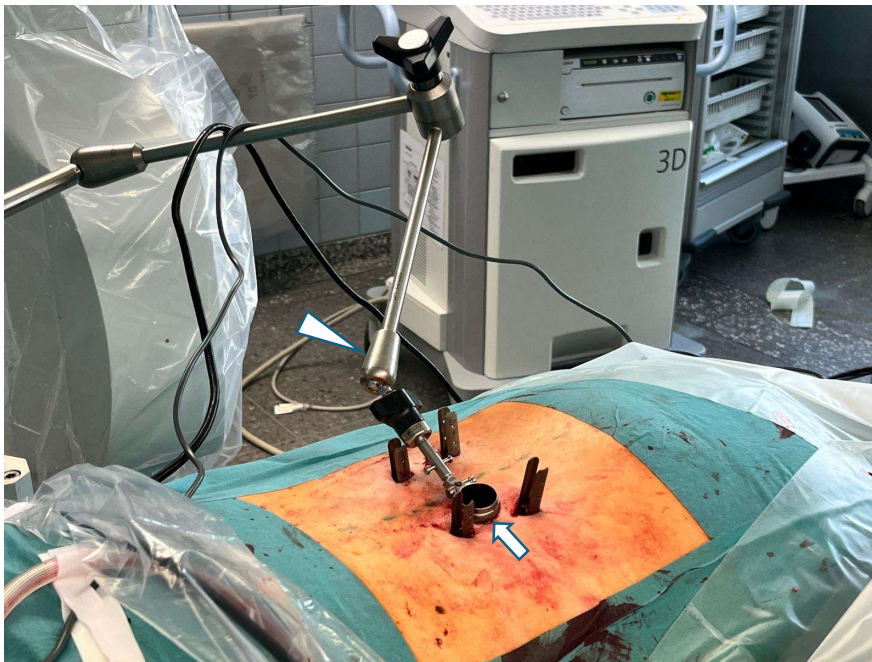


Figure 2.12: Shows the Endoscope shaft (arrow) attached to the holding arm (arrowhead).

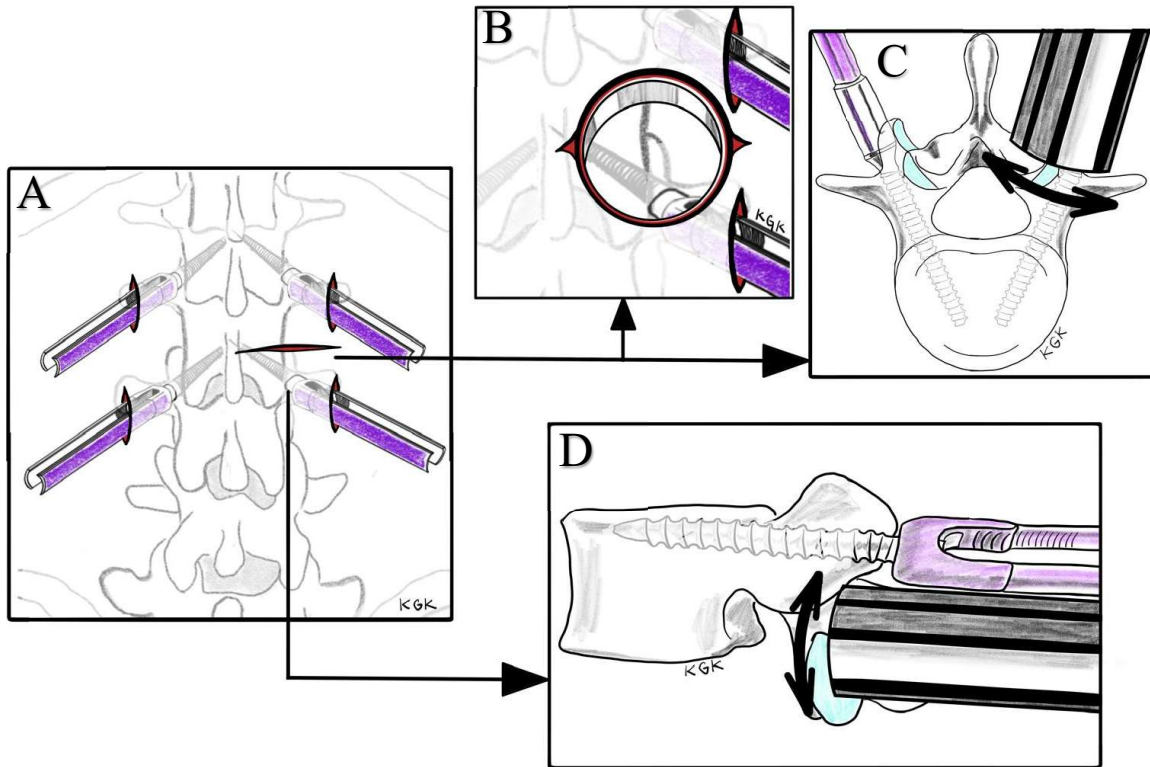


Figure 2. 13: This Illustration depicting the minimally invasive posterior approach with endoscopic access in spinal surgery. (A): Location of the transverse incision positioned between the screw blades, marking the entry point for the endoscope shaft. (B): Posterior view of the surgical field following shaft insertion, demonstrating the alignment of the endoscope shaft relative to the screws and vertebrae. (C): Axial view after shaft insertion, where the double-headed curved arrow indicates the shaft's mobility, allowing adjustment for a broader endoscopic field of view. (D): Lateral view of the vertebra, screws, and inserted endoscope shaft, with the double-headed arrow illustrating the shaft's range of motion, which enhances visibility and access within the surgical site. This figure highlights the placement and flexibility of the endoscope shaft within the minimally invasive spinal procedure, enabling enhanced visualisation and precision in the operative area.

The endoscope is then assembled, white-balance is performed. The endoscope is now securely attached to endoscope shaft, see [Figure 2. 15] and [Figure 2. 14].

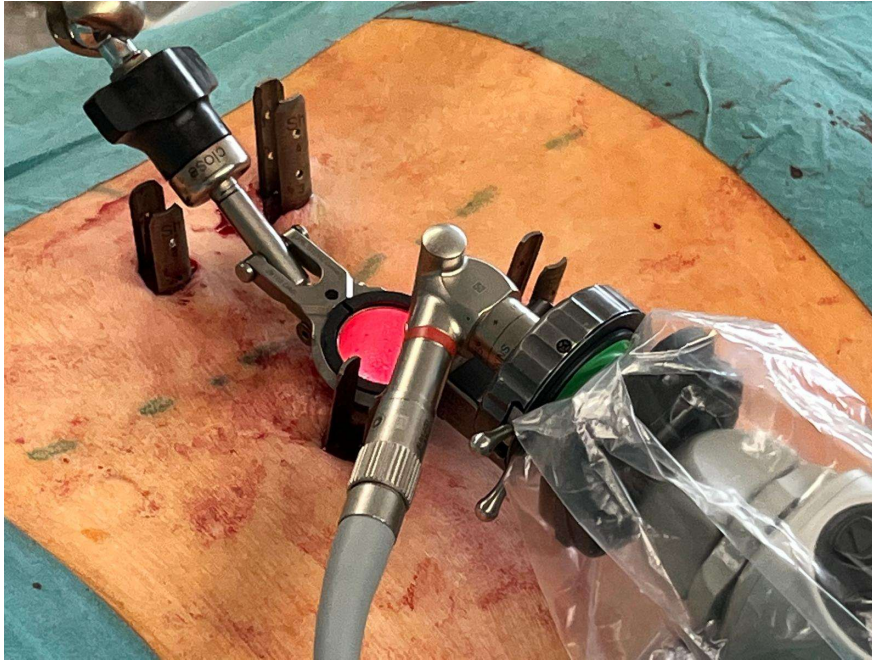


Figure 2. 15: shows the endoscope and the light source attached to the optic shaft, which is securely fixed in place using the holding arm.



Figure 2. 14: This photograph captures the surgical theatre setup, showcasing the surgical team during an endoscopic spinal procedure.

The endoscope is attached to the shaft, and the surgeon operates with real-time visualisation on the 4K monitor positioned in front of them. This setup provides a clear, magnified, and vivid view of the surgical field, enhancing visibility for the entire team, including the scrub nurse and assistant, fostering

active engagement in the procedure. The ergonomic standing posture afforded by the endoscopic system offers a significant advantage over traditional microscope-based techniques, reducing physical strain on the surgeon while maintaining precise visual control.

Under the visualisation provided by the endoscope, a partial medial arthroctomy of the facet joint is performed. By placing the optic shaft in different positions, a hemilaminectomy is performed undercutting the bone in cranial, caudal and the contralateral directions. For the hemilaminectomy, a high speed drill is used (Stryker Core, Stryker GmbH & Co. KG, Duisburg, Germany), both an aggressive bits (for cortical

bone layers) as well as diamond bits (for diploic layer of the bone) are used. Once this is done and the ligamentum flavum has been exposed, the latter is carefully separated from the underlying, compressed dura mater, using blunt hooks and a Tönnis dissector. In severe stenosis this manipulation is not quite without perils of dural injury. Extreme care is taken to protect the dura mater from injuries. However if a dural tear does occur (11 Cases out of 70), the location of the tear is immediately identified, two or three separate 6-0 Polypropylene Suture (PROLENE®, Ethicon, New Jersey, USA) sutures are used to close the dural tear. This manipulation is also done under endoscopic vision. Finally a piece of self-adherent fibrin fleece (TachoSil®, Takeda Pharmaceutical Co Ltd, Linz, Austria) is placed on top of the sutures and the dura mater is sealed watertight. A Valsalva maneuver is made and any occult dural tear and CSF leakage is identified. If found, additional sutures and sealants are used, until finally watertight closure is achieved.

Once the ligamentum flavum is removed and dural sac is decompressed, it becomes easy to identify course of the nerve root lateral to the lateral recess. The nerve root should be now decompressed, See [Figure 2. 16]. In the “axilla” between the nerve root exit and the theca sac, we identify the posterior longitudinal ligament (PLL), the prominent epidural veins and the disc space proper. The veins can be cauterised and transacted without any consequences.

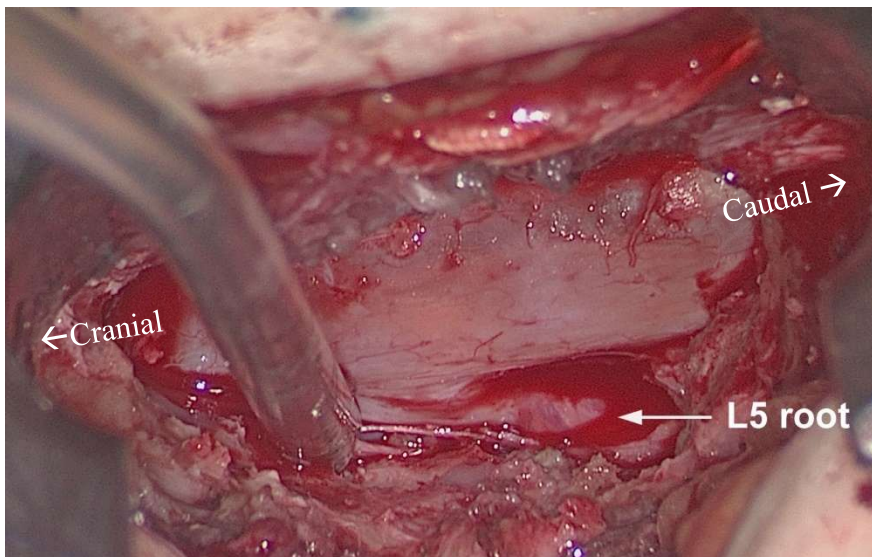


Figure 2. 16: Endoscopic view displaying the L5 nerve root branching out from the thecal sac. This image demonstrates the advantages of endoscopic surgery, providing a clear, magnified view with vivid colours, enhancing the surgeon's ability to visualise fine anatomical details crucial for precise manipulation and safe dissection around the nerve structures.

The disc space is carefully accessed, incised with a number 15 blade. A lateral view X-ray is performed to confirm the location. Sometimes the PLL is ossified and entry into the disc space is impossible with a scalpel. In this case the diamond drill bit is used to drill of the ossified PLL at this particular spot and then the disc space is entered.

Now the disc space is thoroughly cleaned using disc space shavers of serially increasing sizes and rongeurs to remove fragments. Finally, the disc space is irrigated under pressure so that any free fragments of degenerated discs swim out. These are removed. Then the ground plate of the upper vertebral body and the roof plate of the lower vertebral body are scratched with Volkmann spoons until all free fragments are removed.

As we have removed the facet joint on the side of the approach and also the disc contents, the two vertebral bodies become unstable now. A dummy cage of an appropriate size is introduced into the disc space and the size is confirmed using lateral view fluorography, see [Figure 2. 17].

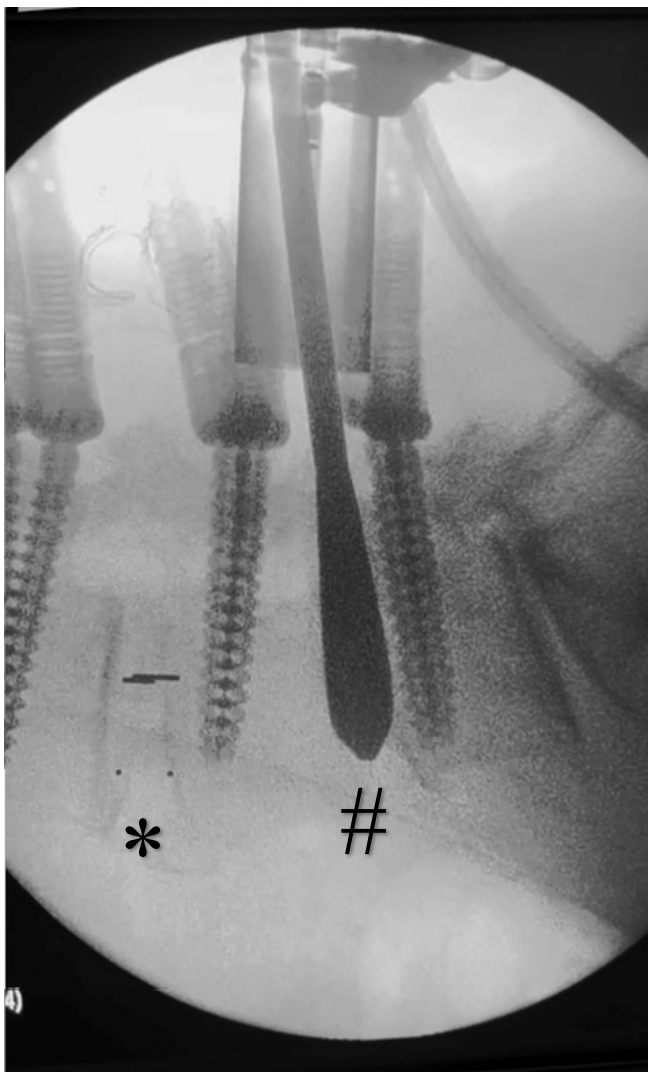


Figure 2. 17: Intraoperative lateral radiograph showing the placement of a dummy cage trial (#) with the cage inserter instrument, positioned through the endoscope shaft, which is also visible on the X-ray, determining the ideal size of the cage. The asterisk (*) marks a PEEK cage that has already been inserted into its designated position within the intervertebral disc space. This cage features radiopaque markers—two dots anteriorly and two lines posteriorly—allowing for precise positioning and orientation verification during the procedure.

Now a PEEK TLIF cage (pezo-T™, Ulrich GmbH & Co. KG, Ulm, Germany) of the thus determined height, is carefully inserted into the disc space. Positioning is by means of a special positioning hitter. The positioning is performed under x-ray control until the

desired alignment is achieved. The cage usually fits snugly (press-fit-manner) between the vertebral bodies.

Now the eTLIF fusion is complete. The optic shaft is removed. An absorbable gelatine haemostatic sponge (SPONGOSTAN™, Ethicon, New Jersey, USA) soaked in a cocktail of local anaesthetic and triamcinolone is placed on the dura-nerve root junction, so that a peri-radicular infiltration effect ensues during the postoperative phase.

Step 4: Rod placement and distraction:

Lateral rods are attached to the previously placed screws, utilizing the lowest incision, and their secure positioning is confirmed under fluoroscopic guidance before being locked in place with screw nuts.

Controlled distraction is applied to the instrumented levels to carefully widen the spaces between vertebrae, ensuring optimal decompression of the neuroforamina and reducing pressure on spinal nerves.

Step 5: Wound closure

Following successful rod placement and distraction, the screw blades are meticulously removed from the surgical site.

The surgical incisions are precisely closed in layers, ensuring optimal wound adaptation and minimising the risk of infection.

The subcutaneous layers of the wounds are infiltrated with local anaesthetic for postoperative pain management Ropivacain 7,5mg (Naropin 0,75%, Fresenius Kabi, Bad Homburg, Germany)

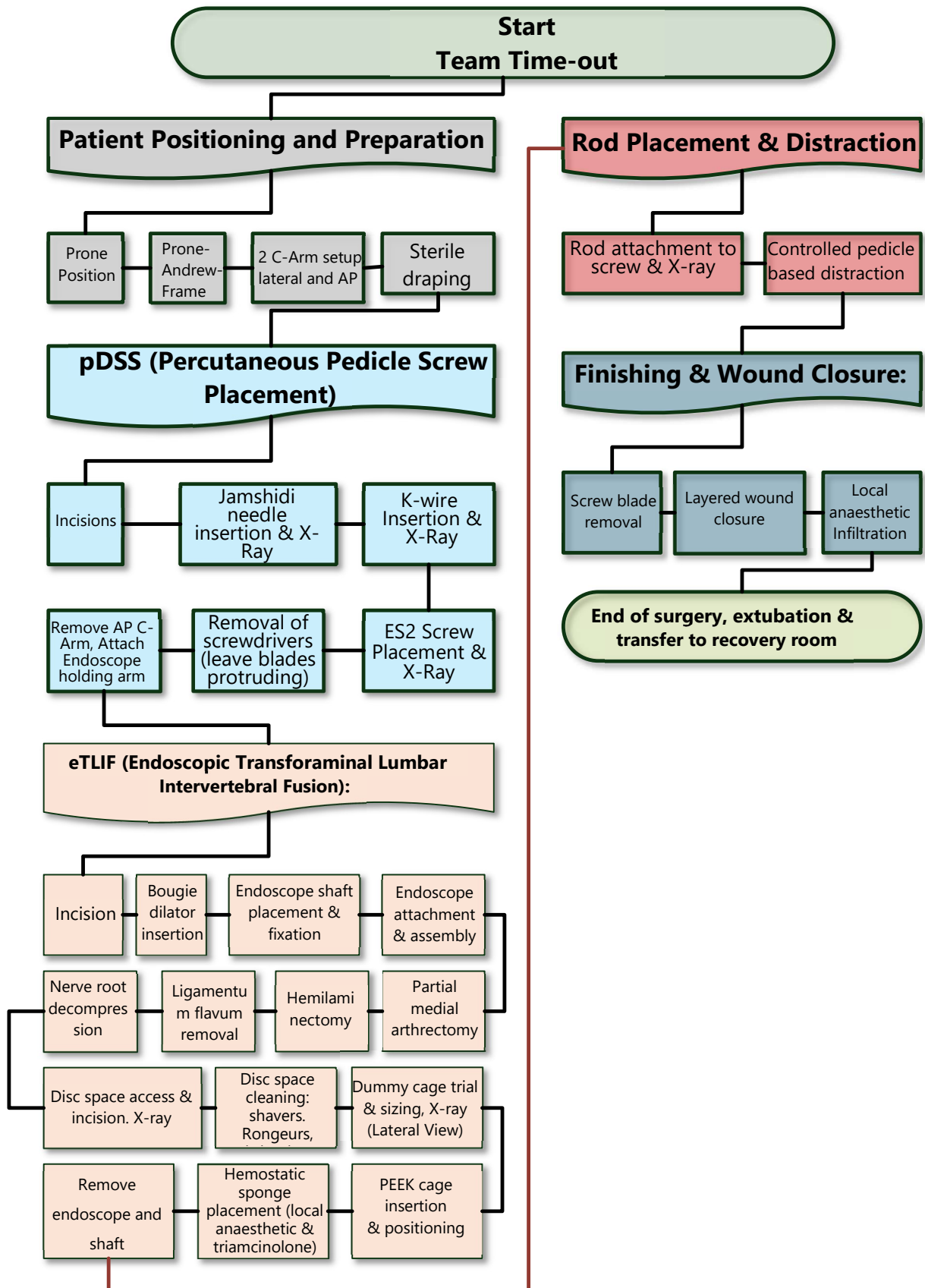
The fascia and subcutaneous tissue are typically sutured with braided self-absorbable sutures (Vicryl, Ethicon, New Jersey, US) whereas the skin is closed using 4-0 monofilament self-absorbable sutures (Monocryl, Ethicon, New Jersey, USA) employing the intracuticular technique.

Finally, sterile dressings are applied to the surgical site to promote a clean and protected healing environment.

With the above described technique, the blood loss is usually quite minimal. The muscle tissue is not widely released or retracted from the vertebral laminae, thus minimising soft tissue trauma. Therefore, there is no need for placing wound drains.

The following flowchart, [Chart 2. 2], provides a visual, step-by-step summary of the procedure for the combined percutaneous dorsal spinal stabilisation (pDSS) and endoscopic transforaminal lumbar intervertebral fusion (eTLIF) techniques utilised in this study.

Chart 2. 2: Flowchart summary of the surgery. This flowchart shows Step-by-Step Workflow of the Combined Percutaneous Dorsal Spinal Stabilisation (pDSS) and Endoscopic Transforaminal Lumbar Intervertebral Fusion (eTLIF) Procedure, detailing the surgical preparation, execution, and postoperative closure. This chart outlines each stage of the combined technique, including patient positioning, screw placement, endoscopic fusion, rod attachment, and wound closure.



2.6.2. Postoperative management

Following a brief stay in the recovery room, the patient is transferred to the normal ward. Postoperative analgesics are prescribed (Rojals et al., 2022), including opioids such as Oxycodone or Hydromorphone for the first two days, along with NSAIDs such as Ibuprofen, or Metamizole.

Patients are encouraged to mobilise on the same day as the surgery, with additional assistance provided by the physiotherapy team to facilitate ambulation. In case of an intraoperative dural tear and repair, the patient is asked to remain in prone position for 3 days.

A postoperative X-ray in two projections with the patient standing are made on the day after mobilisation to confirm correct placement of the pedicle screws and the cages. In case of a complication, further imaging is agreed upon as required.

We have a tradition of post-operative rehabilitation for spinal disorders (Bahns et al., 2021). After pDSS and eTLIF, we recommend beginning the rehabilitation 3-4 weeks after surgery. We complete the application forms (insurance coverage and rehab clinic acceptance) for later rehabilitation treatment as the patient is still in our inpatient treatment.

The patient is typically discharged 4-5 days after surgery, depending on compliance, pain levels, and mobility status. However, the actual duration of hospital stay can be longer due to factors such as the patient's age, lack of social support or family assistance, and bureaucratic processes in Germany that may delay discharge due to the need for social worker involvement.

2.7. Data collection and spread sheets

The list of patients who underwent spinal surgery was extracted from the hospitals Healthcare Document Management Software (SAP, Walldorf, Baden-Württemberg, Germany) and organised into Excel sheets (Microsoft® Excel® for Microsoft 365 MSO Version 2406, Redmond, Washington, USA). Subsequently, the list was filtered to contain only those patients who underwent the combined techniques of percutaneous dorsal spinal stabilization (pDSS) and endoscopic transforaminal lumbar intervertebral fusion (eTLIF). An additional Excel sheet was generated, featuring anonymised patient IDs, age, gender, date of surgery, specific level of the procedure, surgery duration in minutes, blood

loss, pre and postoperative pain assessed using a numerical pain rating scale (NRS) at day 3 Postop as well as after 1 year, duration of hospital stay, recurrence, and any encountered complications. Any missing data that was not documented in the SAP program was obtained by directly contacting the patients via phone calls.

Table 2.1: Patients' Demographics and Diagnosis. This table lists the cases of this study, detailing patient demographics, spinal diagnoses along with the levels, and dates of surgery. Diagnoses include spinal canal stenosis, spondylolisthesis, disc herniations. The cases are grouped into single-level, two-level and three-level-surgeries.

Patient Nr.	Gender	Age (yrs)	Diagnoses	Date of Surgery
SINGLE-LEVEL PATHOLOGIES (n = 43)				
1	Female	84.7	Spinal canal stenosis L1/2	17/08/2020
2	Male	21.7	Disc herniation L1/2 with severe spinal canal stenosis	15/09/2020
3	Female	81.7	Spinal canal stenosis L1/2	06/05/2021
4	Female	77.5	Spondylolisthesis L2/3 with Spinal canal stenosis	19/06/2020
5	Male	74.3	intraforaminal disc protrusion L2/3 with foraminal stenosis and spinal instability	14/05/2021
6	Male	62.6	Disc herniation L2/3 with spinal canal stenosis and Spondylolisthesis L2/3	31/10/2022
7	Female	82.1	Spondylolisthesis L3/4 with spinal canal stenosis	20/04/2020
8	Female	73.9	Spondylolisthesis L3/4 with spinal canal stenosis	02/06/2020
9	Female	82.9	Spondylolysis and Spondylolisthesis L3/4	16/07/2021
10	Female	82.3	Spondylolisthesis L3/4 with spinal canal stenosis	16/08/2021
11	Male	57.3	Spondylolysis and Spondylolisthesis L3/4	25/03/2022
12	Female	75.0	Spondylolisthesis L3/4 with spinal canal stenosis	05/08/2022
13	Female	52.8	Disc herniation L3/4 with spinal canal stenosis and Spondylolisthesis L3/4 and instability	08/08/2022
14	Female	35.7	Spondylolisthesis L3/4 with spinal canal stenosis	19/09/2022
15	Male	73.5	Disc herniation L3/4 with Spondylolisthesis L3/4	13/10/2022
16	Male	71.8	Spondylolisthesis L3/4 with spinal canal stenosis	08/12/2022
17	Male	52.6	Spondylolisthesis L3/4 with spinal canal stenosis	05/01/2023
18	Female	79.4	Spondylolisthesis L4/5 with spinal canal stenosis	29/05/2020
19	Female	85.4	Spondylolisthesis L4/5 with spinal canal stenosis	08/06/2020
20	Female	86.8	Spondylolisthesis L4/5 with spinal canal stenosis and instability	14/09/2020
21	Female	86.4	Extraforaminal disc herniation L4/5 with instability	13/10/2020
22	Female	85.1	Spondylolisthesis L4/5 with spinal canal stenosis and instability	26/10/2020
23	Male	64.9	Spondylolisthesis L4/5 with spinal canal stenosis	22/02/2021
24	Male	62.3	Spinal canal stenosis L4/5 with neuroforaminal stenosis and instability	26/04/2021
25	Female	64.3	Spondylolisthesis L4/5 with spinal canal stenosis	29/11/2021

26	Female	67.9	Spondylolisthesis L4/5 with spinal canal stenosis	29/11/2021
27	Female	78.6	Spondylolisthesis L4/5 with spinal canal stenosis	06/12/2021
28	Male	65.5	Disc herniation and Spondylolisthesis L4/5 with spinal canal stenosis	11/02/2022
29	Male	81.4	Disc herniation and Spondylolisthesis L4/5 with spinal canal stenosis	04/04/2022
30	Male	69.7	Spondylolisthesis L4/5 with spinal canal stenosis	29/04/2022
31	Female	84.9	Spondylolisthesis L4/5 with spinal canal stenosis	09/05/2022
32	Male	80.0	Spondylolisthesis L4/5 with spinal canal stenosis	10/06/2022
33	Male	64.6	Disc herniation and Spondylolisthesis L4/5	11/07/2022
34	Female	87.1	Spondylolisthesis L4/5 with spinal canal stenosis	05/09/2022
35	Female	60.4	Spondylolisthesis L4/5 with spinal canal stenosis	10/10/2022
36	Male	66.7	Disc herniation and Spondylolisthesis L4/5 with spinal canal stenosis	31/10/2022
37	Female	78.6	Spondylolisthesis L4/5 with spinal canal stenosis	02/01/2023
38	Male	36.8	Disc herniation and Spondylolisthesis L4/5 with spinal canal stenosis	16/01/2023
39	Female	52.6	Spondylolisthesis L4/5 with spinal canal stenosis and instability	13/02/2023
40	Female	65.2	Spondylolisthesis L4/5 with spinal canal stenosis	06/03/2023
41	Male	83.9	Spondylolisthesis L4/5 with spinal canal stenosis	20/03/2023
42	Male	53.5	Spondylolisthesis L5/S1	01/09/2020
43	Male	36.2	Spondylolisthesis L5/S1	12/12/2022
TWO-LEVEL PATHOLOGIES (n = 24)				
44	Female	80.0	Spinal canal stenosis L2/3 L3/4	24/04/2020
45	Male	82.0	Spondylolysis and Spondylolisthesis L2/3 L3/4	15/06/2020
46	Male	70.2	Spondylolisthesis L2/3 L3/4 with spinal canal stenosis	22/01/2021
47	Female	87.4	Spinal canal stenosis L2/3 L3/4 with instability	08/02/2021
48	Female	65.8	Spinal canal stenosis L2/3 L3/4	07/05/2021
49	Female	82.6	Spinal canal stenosis L2/3 L3/4	16/09/2022
50	Female	80.0	Spondylolisthesis L2/3 L3/4 with spinal canal stenosis	17/10/2022
51	Male	70.6	Spinal canal stenosis L3/4 L4/5	04/05/2020
52	Female	79.8	Spondylolisthesis L3/4 L4/5 with spinal canal stenosis	08/05/2020
53	Male	84.0	Spondylolysis and Spondylolisthesis L3/4 L4/5	12/06/2020
54	Female	82.4	Spinal canal stenosis L3/4 L4/5	29/06/2020
55	Female	82.2	Spondylolisthesis L3/4 L4/5 with spinal canal stenosis	24/07/2020
56	Male	66.5	Spondylolisthesis L3/4 L4/5 with spinal canal stenosis	25/09/2020
57	Female	81.2	Spondylolisthesis L3/4 L4/5 with spinal canal stenosis	12/03/2021

58	Male	83.9	Spondylolysis and Spondylolisthesis L3/4 L4/5	07/06/2021
59	Female	75.9	Spondylolisthesis L3/4 L4/5 with spinal canal stenosis	09/08/2021
60	Male	83.5	Spinal canal stenosis L3/4 L4/5	20/08/2021
61	Female	63.1	Spondylolisthesis L3/4 L4/5 with spinal canal stenosis	08/11/2021
62	Male	62.7	Disc herniation L3/4 L4/5 with spinal canal stenosis	22/11/2021
63	Female	67.7	Spinal canal stenosis L3/4 L4/5	06/02/2023
64	Male	64.7	Spondylolisthesis L1/2 and Spondylolisthesis L4/5	10/10/2022
65	Male	59.9	Spondylolisthesis L4/5 L5/S1 with instability	01/02/2021
66	Male	65.4	Spondylolisthesis L4/5 L5/S1 with instability	22/03/2021
67	Female	60.0	Spondylolisthesis L4/5 L5/S1 with spinal canal stenosis	16/05/2022
THREE-LEVEL PATHOLOGIES (n = 3)				
68	Male	83.4	Spinal canal stenosis L1/2 2/3 3/4	06/01/2022
69	Male	69.5	Spinal canal stenosis L1/2 2/3 3/4	07/01/2022
70	Female	85.8	Spinal canal stenosis L2/3 3/4 4/5	14/04/2022

Table 2.2 Details of single-level surgery. This table lists single level lumbar spine surgeries, detailing procedure level, duration in minutes, blood loss, hospital stay in days, pain scores (NRS) preoperatively and postoperatively (3 days and 1 year), and complications.

Patient Nr.	level of the procedure	Duration of surgery (minutes)	Blood loss	Hospital stay (days)	NRS preop 0-10	NRS postop (d3)	NRS postop (1 Year)	Complications
1	L1/2	126	< 200cc	9	5	3	3	
2	L1/2	195	< 200cc	13	3	3	1	dural tear
3	L1/2	169	< 200cc	7	3	1	2	-
4	L2/3	120	< 200cc	7	5	3	3	-
5	L2/3	133	< 200cc	6	4	0	1	-
6	L2/3	151	< 200cc	5	4	0	1	-
7	L3/4	197	< 200cc	7	5	2	3	-
8	L3/4	198	< 200cc	8	6	2	3	-
9	L3/4	231	< 200cc	7	5	2	3	dural tear
10	L3/4	199	< 200cc	8	4	2	2	-
11	L3/4	235	< 200cc	13	3	1	1	dural tear
12	L3/4	120	< 200cc	9	4	1	2	-
13	L3/4	171	< 200cc	9	4	2	1	-
14	L3/4	125	< 200cc	7	3	1	2	-
15	L3/4	136	< 200cc	8	3	1	1	-
16	L3/4	158	< 200cc	6	4	2	1	-
17	L3/4	161	< 200cc	4	3	2	2	-
18	L4/5	169	< 200cc	8	3	0	1	dural tear
19	L4/5	150	< 200cc	19	5	3	2	-
20	L4/5	209	< 200cc	15	3	2	2	-
21	L4/5	172	< 200cc	9	6	2	4	-
22	L4/5	191	< 200cc	12	4	1	2	-
23	L4/5	133	< 200cc	4	5	1	2	-
24	L4/5	190	< 200cc	4	4	2	1	-
25	L4/5	103	< 200cc	9	3	0	1	-
26	L4/5	449	< 200cc	3	3	1	1	injury to iliac artery
27	L4/5	126	< 200cc	5	3	0	1	-

28	L4/5	224	< 200cc	6	3	1	1	-
29	L4/5	140	< 200cc	5	2	1	1	-
30	L4/5	110	< 200cc	6	3	1	2	-
31	L4/5	201	< 200cc	5	3	0	1	dural tear
32	L4/5	242	< 200cc	19	2	1	1	-
33	L4/5	145	< 200cc	8	3	1	2	-
34	L4/5	109	< 200cc	8	4	2	2	-
35	L4/5	151	< 200cc	15	3	1	2	-
36	L4/5	132	< 200cc	6	2	0	1	-
37	L4/5	159	< 200cc	8	3	3	2	dural tear
38	L4/5	111	< 200cc	8	2	1	1	-
39	L4/5	121	< 200cc	8	3	2	2	-
40	L4/5	113	< 200cc	8	3	1	1	-
41	L4/5	143	< 200cc	6	4	1	2	-
42	L5/S1	125	< 200cc	9	5	2	6	-
43	L5/S1	130	< 200cc	4	4	2	2	-

Table 2.2 Details of two-level surgery. This table lists two-level lumbar spine surgeries, detailing procedure level, duration in minutes, blood loss, hospital stay in days, pain scores (NRS) preoperatively and postoperatively (3 days and 1 year), and complications.

Patient Nr.	Level of the procedure	Duration of surgery (minutes)	Blood loss	Hospital stay (days)	NRS preop (0-10)	NRS postop (d3)	NRS postop (1 Year)	Complications
44	L2/3 3/4	N/A *	< 200cc	11	4	3	2	dural tear
45	L2/3 3/4	200	< 200cc	24	2	1	1	-
46	L2/3 3/4	214	< 200cc	7	6	2	3	-
47	L2/3 3/4	165	< 200cc	12	4	0	2	-
48	L2/3 3/4	146	< 200cc	12	1	0	1	-
49	L2/3 3/4	208	< 200cc	7	4	0	2	dural tear
50	L2/3 3/4	181	< 200cc	5	2	1	3	-
51	L3/4 4/5	230	< 200cc	5	6	2	4	-
52	L3/4 4/5	110	< 200cc	9	4	2	2	-
53	L3/4 4/5	110	< 200cc	16	5	2	2	dural tear
54	L3/4 4/5	179	< 200cc	8	1	1	1	-
55	L3/4 4/5	270	< 200cc	15	5	2	3	-
56	L3/4 4/5	83	< 200cc	7	5	2	3	-
57	L3/4 4/5	218	< 200cc	7	3	0	1	-
58	L3/4 4/5	191	< 200cc	9	2	1	1	-
59	L3/4 4/5	174	< 200cc	12	4	0	1	-
60	L3/4 4/5	222	< 200cc	11	3	2	2	dural tear
61	L3/4 4/5	185	< 200cc	7	2	0	1	dural tear
62	L3/4 4/5	149	< 200cc	5	4	2	2	-
63	L3/4 4/5	225	< 200cc	8	4	1	1	-
64	L1/2 L4/5	179	< 200cc	5	2	1	1	-
65	L4/5 L5/S1	146	< 200cc	8	2	3	1	-
66	L4/5 L5/S1	152	< 200cc	14	4	2	2	-
67	L4/5 L5/S1	235	< 200cc	10	5	1	2	-

* N/A (Not Available): The duration of the surgery, possibly due to a technical error, was not recorded properly in SAP.

Table 2.3: Details of three-level surgeries. This table lists three-level lumbar spine surgeries, detailing procedure level, duration in minutes, blood loss, hospital stay in days, pain scores (NRS) preoperatively and postoperatively (3 days and 1 year), and any complications.

Patient Nr.	Levels of the procedure	Duration of surgery (minutes)	Blood loss	Hospital stay (days)	NRS preop	NRS postop (d3)	NRS postop (1 Year)	Complications
68	L1/2 2/3 3/4	202	< 200cc	6	4	0	2	-
69	L1/2 2/3 3/4	237	< 200cc	8	3	1	1	-
70	L2/3 3/4 4/5	191	< 200cc	12	6	2	3	-

2.8. Criteria for outcome analysis

Patients were regularly followed up in our outpatient setting. Patient outcomes were assessed using the numerical pain rating scale (NRS), which was recorded in the patient file before surgery, on the third postoperative day, and one year after surgery during the follow-up visit. If the patient did not attend the follow-up or if data was not recorded in the clinic, the missing data was obtained by directly calling the patients. Additionally, the following data were collected: duration of surgery (in minutes), starting from the beginning of anaesthesia induction until the patient was delivered to the recovery room, as recorded in the SAP program; hospital stay (in days); exact levels of surgery as noted in the surgery report; blood loss as recorded in the SAP program and confirmed by the anaesthesia report; and any complications as recorded in both the surgery report and discharge notes.

2.9. Statistics

Statistical analysis was conducted to assess the significance of the reported NRS by comparing the preoperative NRS to the NRS recorded on the third postoperative day. Additionally, the NRS reported one year after surgery was compared to both the preoperative NRS and the NRS recorded on the third postoperative day.

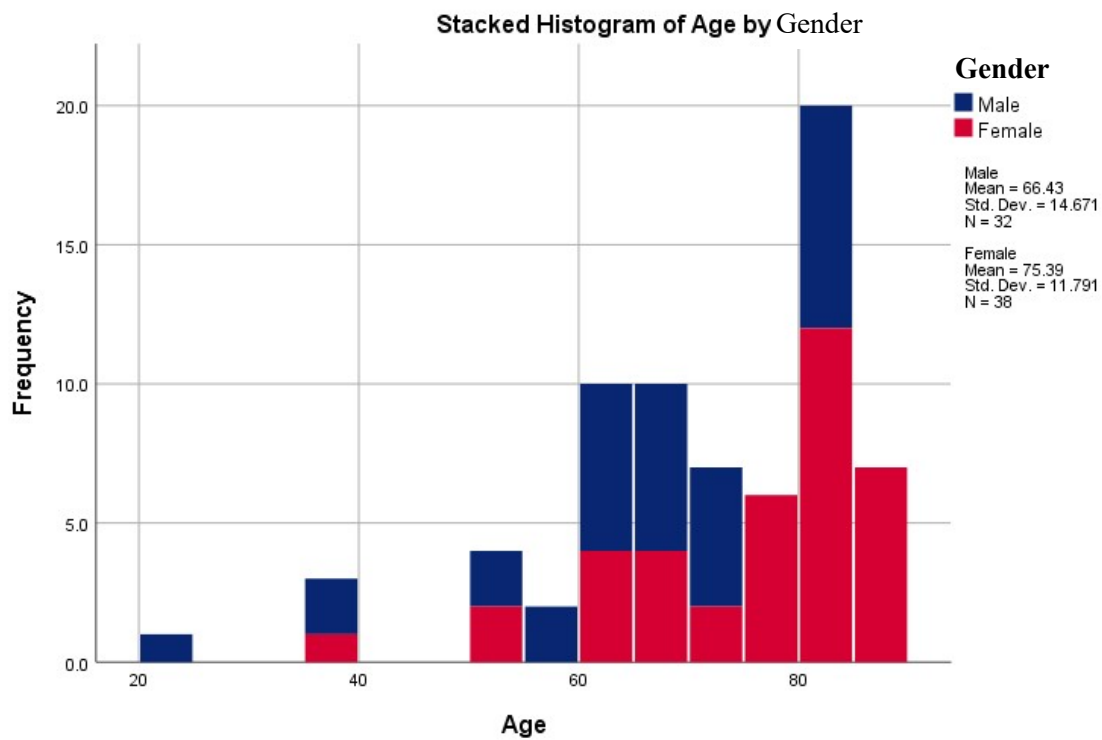
Descriptive statistics and inferential analyses were performed using IBM SPSS Statistics for Windows (IBM® SPSS® Statistics, Version 25, Chicago, IL, USA) . The Wilcoxon Signed Rank Test was employed, after determining that the data did not follow a normal distribution, to compare pre-surgical NRS with post-surgical NRS at day 3, and one-year post-surgical NRS with both preoperative and day 3 postoperative NRS. Descriptive analysis utilized mean and standard deviation, along with minimum and maximum values, to describe the age (in years), the duration of surgery (in minutes) and hospital stay (in days). Frequencies were calculated to quantify the occurrence of specific surgery levels as well as the complications and for gender quantification. Since blood loss was recorded as minimal (less than 200cc) in all 70 surgeries, no further statistical analysis was conducted for this parameter. A p-value of < 0.05 was set as the threshold for statistical significance.

3. RESULTS

This study analysed data from 70 patients who underwent the combined pDSS and eTLIF procedure for degenerative lumbar spinal disorders at Varisano Hospital Bad Soden am Taunus, Germany, between January 2020 and March 2023.

3.1. Demographics

The patient cohort consisted of 38 females (54.3%) and 32 males (45.7%), with an average age of 71.3 years (range: 22- 87 years, SD +/- 13.8) [Graph 3.1].

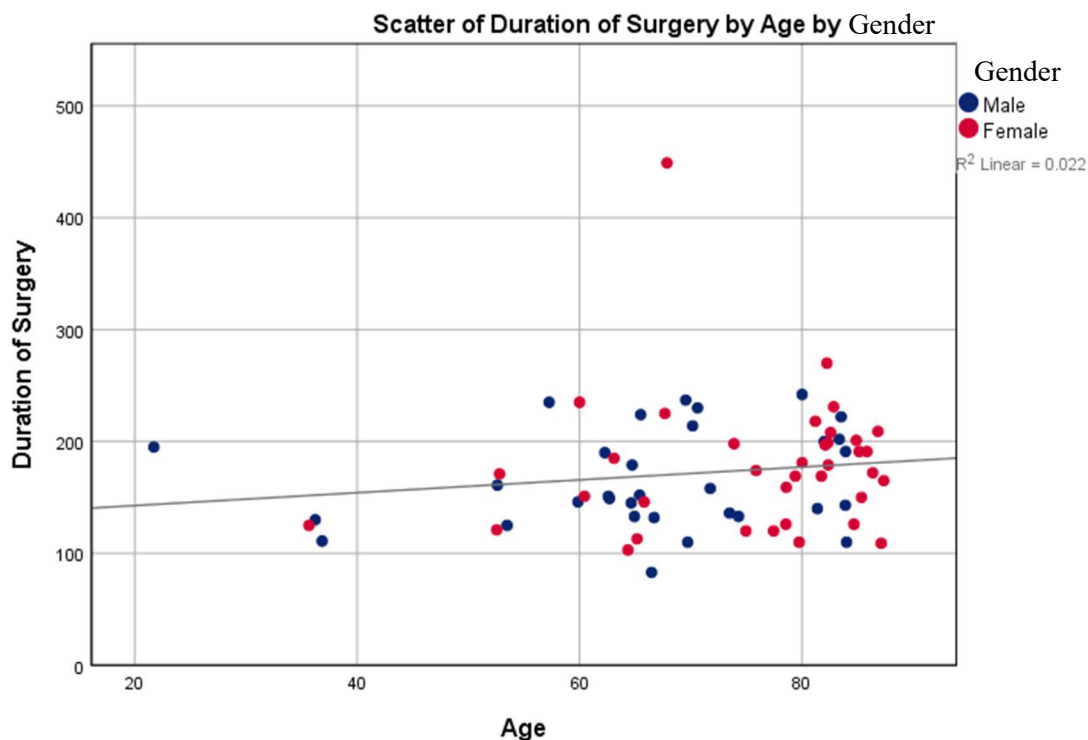


Graph 3.1: The stacked histogram illustrates the age distribution of patients, separated by gender. The x-axis represents the age of the patients while the y-axis represents the frequency of patients in each age group. The blue bars representing male patients and red bars representing female patients. From the histogram, it is evident that the majority of patients are aged between 60 and 85 years. Male patients have a mean age of 66.43 years with a standard deviation of 14.671, based on the sample size of 32. Female patients have a mean age of 75.39 years with a standard deviation of 11.791, based on a sample size of 38. The highest frequency is observed in the age group of around 80 years, with a notable concentration of female patients in this category.

3.2. Surgical details

3.2.1. Duration of surgery

In our cohort, the duration of surgery was measured in minutes from the beginning of induction of anaesthesia until the patient was delivered to the recovery room. We found that the average operative time was 172.1 minutes (n=69, range: 83-449 minutes, SD \pm 54.0). However, one patient had an operative time of 449 minutes. Excluding this outlier, the average operative time was 168.0 minutes (n=68, range: 83-270 minutes, SD \pm 42.4) [Graph 3.2]. The extended surgery duration for the outlier was due to a suspected injury to the iliac artery, however, the bleeding itself was minimal (less than 200cc). The vascular team was called in urgently. After a thorough investigation, it was determined that the artery was not actually injured.

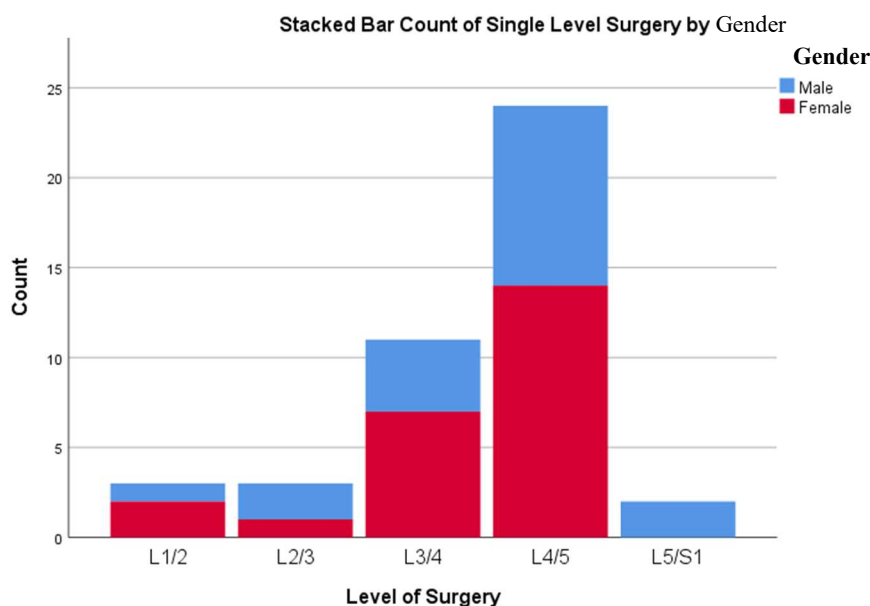


Graph 3.2 : The scatter plot depicts the relationship between patient age and the duration of surgery, with data points differentiated by Gender. The x-axis represents the age of the patients, ranging from 22 to 87 years, while the y-axis represents the duration of surgery, measured in minutes. Each data point corresponds to an individual patient, with blue dots representing male patients and red dots representing female patients. A linear regression line is included, indicating the overall trend in the data. The slope of this line suggests a slight positive correlation between age and the duration of surgery, although the R² value of 0.022 suggests a weak correlation. There is one outlier with a surgery duration of around 449 minutes. This outlier is due to a suspicion of injury to the iliac artery; however, the bleeding itself was minimal, less than 200cc. The vascular team was emergently called for the surgery, and after a thorough investigation, it was determined that the artery was not actually injured.

3.2.2. Levels of the surgery

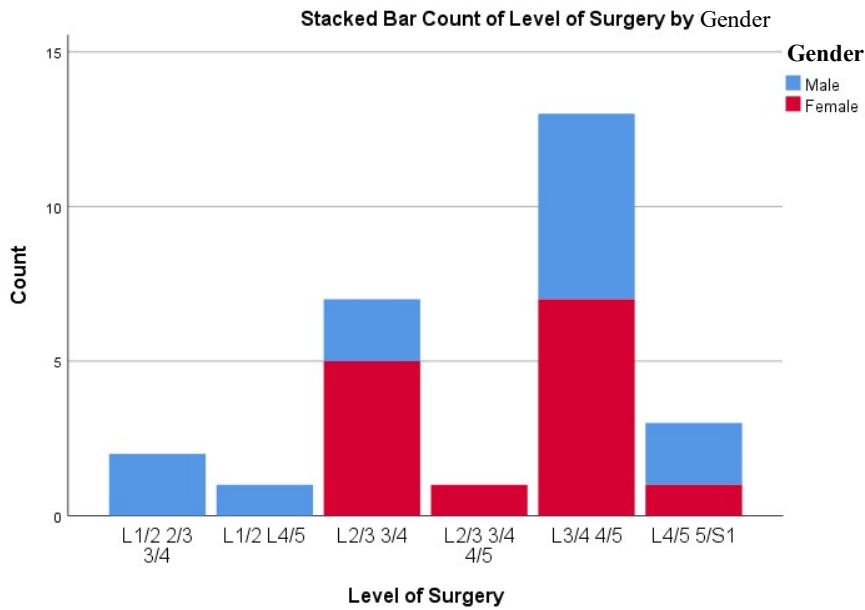
The charts [Graph 3.3] and [Graph 3.4] illustrate the distribution of surgical procedures performed at various spinal levels in our cohort. The x-axis represents the specific spinal levels where the procedures were conducted, ranging from L1/2 to L5/S1. The y-axis indicates the count of procedures performed at each level. The first chart illustrates the frequency for single-level treated patients, while the second chart illustrates the frequency for patients treated on multiple levels. The data reveals that the most frequently operated level is L4/5, with 24 procedures conducted, significantly higher than any other level. This is followed by L3/4, where 11 procedures were performed. For L1/2, 3 patients were treated; for L2/3, 3 patients; and for L5/S1, 2 patients. This sums up to 43 patients treated on single level.

For patients treated on multiple levels, the data reveals that the most frequently operated levels are L3/4 and L4/5, with 13 procedures conducted. Specifically, 2 patients were treated at levels L1/2, L2/3, and L3/4; 1 patient at levels L1/2 and L4/5; 7 patients at levels L2/3 and L3/4; 1 patient at levels L2/3, L3/4, and L4/5; 13 patients at levels L3/4 and L4/5; and 3 patients at levels L4/5 and L5/S1, summing up to 27 patients treated on multiple levels.



Graph 3.3: illustrates the distribution of surgical procedures performed at various spinal levels in our cohort for single-level treated patients. The x-axis represents the specific spinal levels where the procedures were conducted, ranging from L1/2 to L5/S1.

The y-axis indicates the count of procedures performed at each level. The data reveals that the most frequently operated level is L4/5, with 24 procedures conducted. L1/2: 3, L2/3: 3, L3/4: 11, L4/5: 24, L5/S1: 2 Patients. Total: 43 Patients.

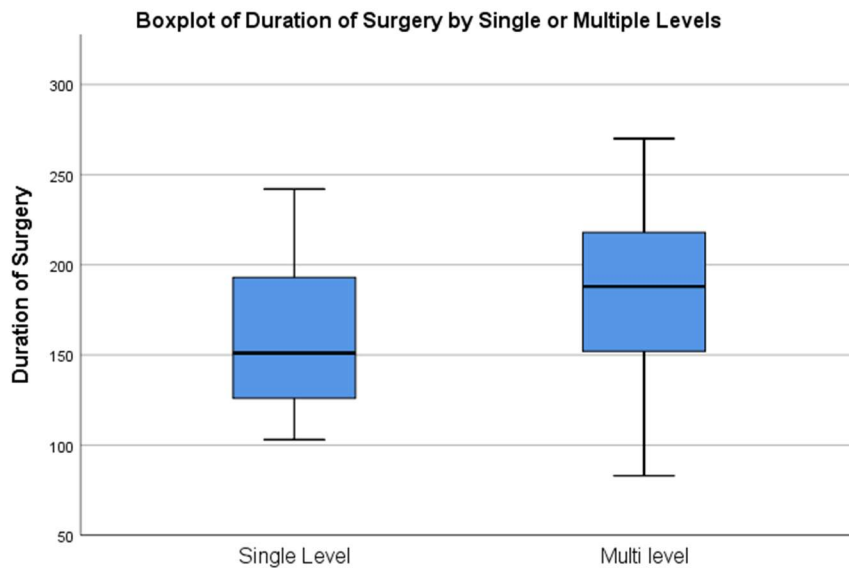


Graph 3.4:

illustrates the distribution of surgical procedures performed at various spinal levels in our cohort for multiple-level treated patients. The x-axis represents the specific spinal levels where the

procedures were conducted, ranging from L1/2 to L5/S1. The y-axis indicates the count of procedures performed at each level. The data reveals that the most frequently operated multiple levels are L3/4 L4/5, with 13 procedures conducted. L1/2 L2/3 L3/4: 2 patients, L1/2 and L4/5: 1 patient, L2/3 L3/4: 7 patients, L2/3 L3/4 L4/5: 1 patient, L3/4 L4/5: 13, L4/5 L5/S1: 3 patients. Total: 27 Patients.

In our study, we also analysed the relationship between the level of surgery and its duration. Our findings indicate that the duration of surgery does not significantly increase when operating on multiple levels compared to a single level. The average surgery time for single-level treated patients is 164.5 minutes (\pm SD 58.4), whereas for multiple-level treated patients, it is 184.7 minutes (\pm SD 43.9), p-value = 0.13, [Graph 3.5]. A plausible explanation for this result could be that the bulk of the time of the surgery is taken by the presurgical preparation and the postsurgical waiting time until the patient is delivered to the recovery room from the anaesthesia.

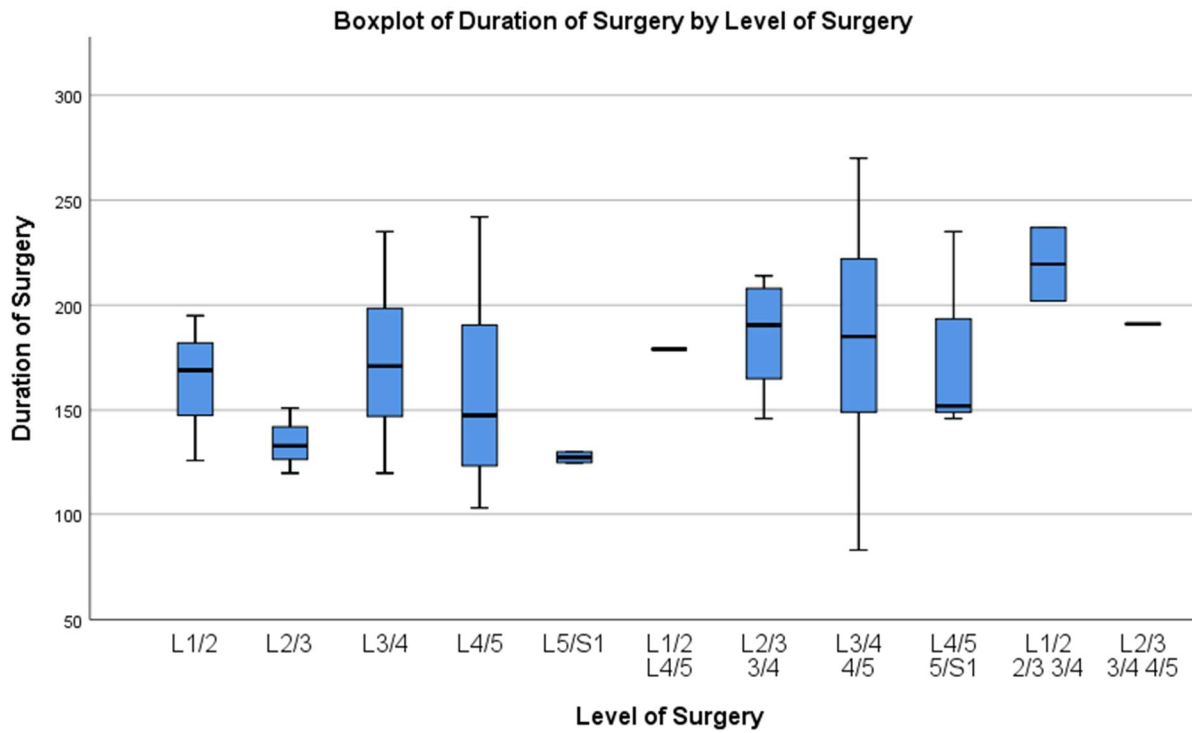


Graph 3.5: This boxplot illustrates the duration of surgery segmented by single level or multiple levels. Each box represents the interquartile range (IQR), encapsulating the middle 50% of the data, with the line inside the box indicating the median duration. Whiskers extend to the minimum and maximum values within 1.5 times the IQR from the first and third quartiles, respectively.

The following [Table 3.1] lists the mean, standard deviation, median, minimum, and maximum for each of the different levels and segments operated upon, while [Graph 3.6] represents this data visually for better comprehension.

Table 3.1: Shows the duration of surgery segmented by the level of the surgery

Level of Surgery	Mean	N	Std. Deviation	Median	Minimum	Maximum
Single-level Surgery						
L1/2	163.33	3	34.847	169.00	126	195
L2/3	134.67	3	15.567	133.00	120	151
L3/4	175.55	11	39.836	171.00	120	235
L4/5	166.38	24	71.560	147.50	103	449
L5/S1	127.50	2	3.536	127.50	125	130
Two-level Surgery						
L1/2 L4/5	179.00	1	.	179.00	179	179
L2/3 3/4	185.67	6	26.568	190.50	146	214
L3/4 4/5	180.46	13	54.911	185.00	83	270
L4/5 5/S1	177.67	3	49.743	152.00	146	235
Three-level Surgery						
L1/2 2/3 3/4	219.50	2	24.749	219.50	202	237
L2/3 3/4 4/5	191.00	1	.	191.00	191	191

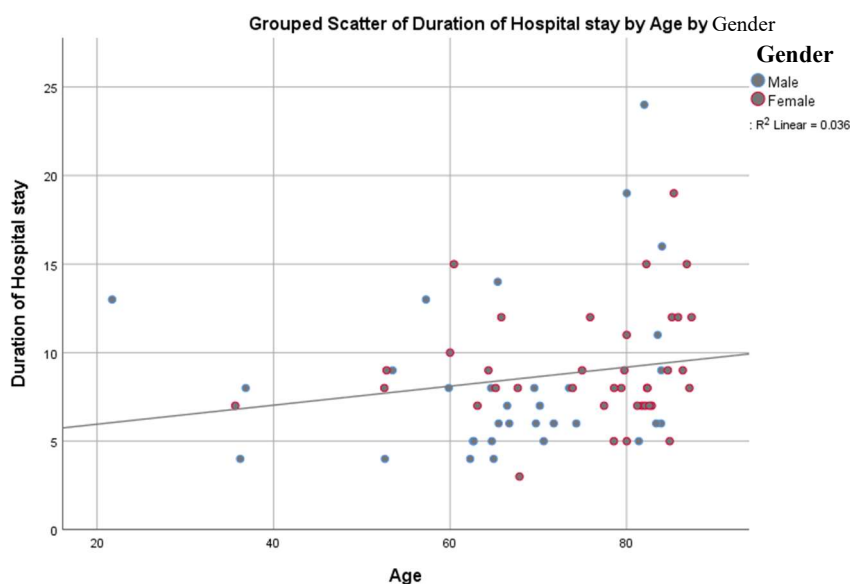


Graph 3.6: boxplot illustrates the duration of surgery segmented by different levels of surgery, for a better visual comparison across various spinal levels. Each box represents the interquartile range (IQR), encapsulating the middle 50% of the data, with the line inside the box indicating the median duration. Whiskers extend to the minimum and maximum values within 1.5 times the IQR from the first and third quartiles, respectively. Also refer to Table 3.1.

3.3. Clinical outcomes

3.3.1. Duration of hospital stay

In our study, the duration of hospital stay is measured in days. It started from the day the patients were labelled as neurosurgical patients in the SAP program. This means that if the patient was transferred from another department, such as internal medicine or geriatrics, those days were not included in the duration. The duration ended when the patients were discharged home or transferred to another department for rehabilitation. In this cohort, the average duration of hospital stay was 8.7 days (range: 3-24 days, SD ± 3.9). The scattered plot [Graph 3.7] represents the data visually, depicting the duration of hospital stay in relation to age. There is a weak positive correlation between the duration of hospital stay and age.



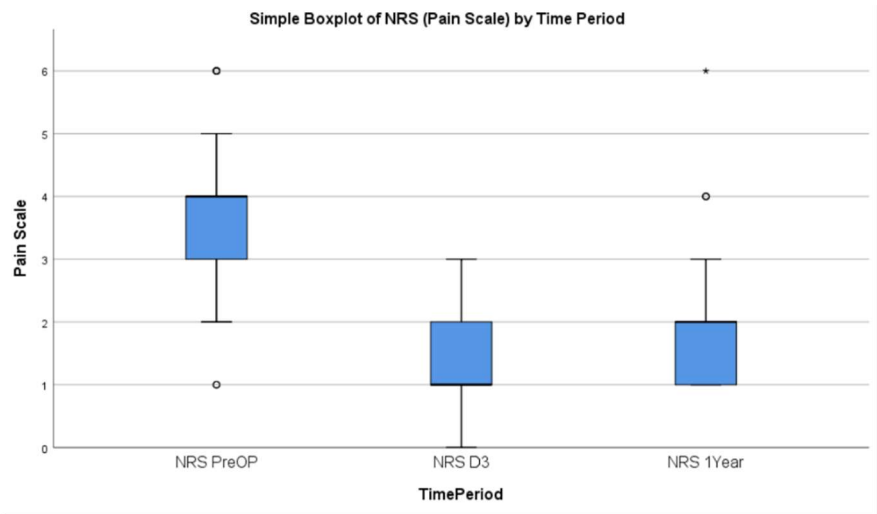
Graph 3.7: The scatter plot illustrates the relationship between patients' ages and the duration of their hospital stays, differentiated by gender. Blue dots represent males and red dots represent females. The x-axis represents the age of patients, while the y-axis represents the duration of their hospital stay in days. The plot includes a linear trend line indicating a weak positive correlation between age and the length of hospital stay, as evidenced by the R^2 value of 0.036.

The plot includes a linear trend line indicating a weak positive correlation between age and the length of hospital stay, as evidenced by the R^2 value of 0.036.

3.3.2. Presurgical and postsurgical pain

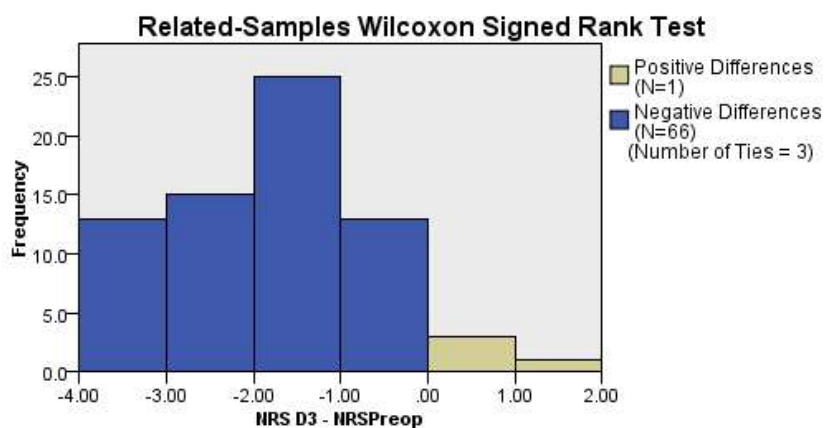
Although it is challenging to quantify a highly subjective experience like pain, we aimed to make our assessment as objective as possible. For this study, we measured pain using the well-known Numeric Rating Scale (NRS), a widely used tool in healthcare to assess and quantify a patient's pain intensity. The NRS uses a 0-10 scale, where 0 represents no pain and 10 represents the worst pain imaginable. Pain levels were documented prior to surgery, on Day 3 post-operation, and one year after surgery.

In our cohort, pain significantly decreased following surgery. The average pre-operative pain score was 3.6, which dropped notably to 1.6 post-operatively. This is evident in [Graph 3.8], which illustrates the distribution of pain scores across the recorded time periods: pre-operative (NRS PreOP), three days post-operative (NRS D3), and one year post-operative (NRS 1Year). The chart visually supports the observation of a substantial reduction in pain over time, reinforcing the hypothesis that the surgical intervention resulted in sustained pain relief.



Graph 3.8: illustrates the significant reduction in pain scores from pre-operative to post-operative (Day 3 and 1 year) periods, showing sustained pain relief after surgery.

The Related-Samples Wilcoxon Signed Rank Test was conducted to assess the difference between NRS postoperative Day 3 (D3) and NRS prior to the surgery (NRSPreop). The results revealed a significant difference between the two time points ($Z = -7.108$, $p < 0.001$, $N = 70$) [Graph 3.9]. These results indicate that the surgical procedure had a significant effect on the NRS scores.

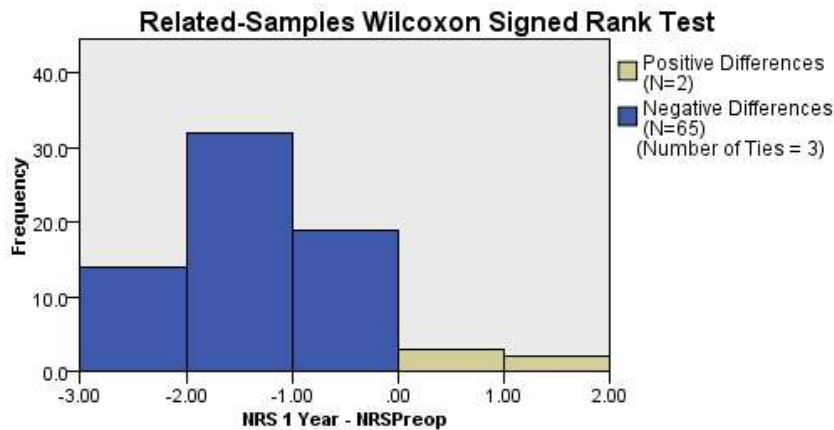


Total N	70
Test Statistic	7.500
Standard Error	158.525
Standardized Test Statistic	-7.138
Asymptotic Sig. (2-sided test)	.000

Graph 3.9: illustrates

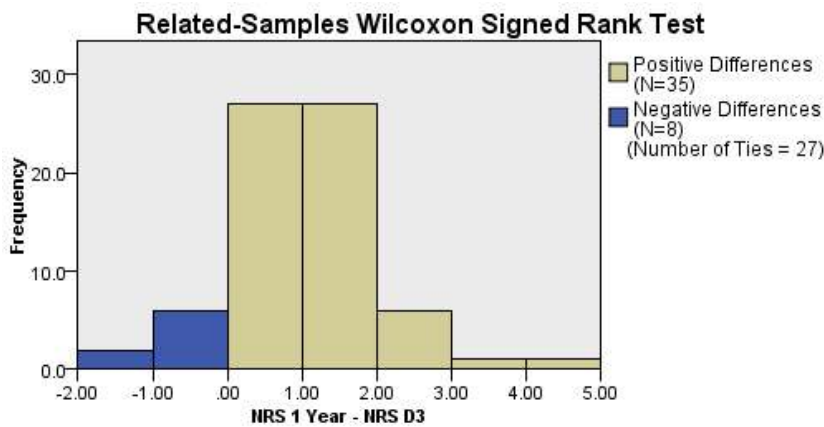
Related-Samples Wilcoxon Signed Rank Test comparing two measurements (NRS-D3 and NRS-Preop) across the 70 Patients. The graph displays the distribution of differences between these measurements, with blue bars showing negative differences and tan bars representing positive differences.

After 1 year, the pain is still significantly better compared to before the surgery. The mean NRS at 1 year is 1.86, which is significantly improved compared to preoperative pain ($Z = -7.138$, $p < 0.001$, $N = 70$; see [Graph 3.10]). However, pain at 1 year is statistically significantly higher than the pain documented 3 days postoperative ($Z = 3.79$, $p < 0.001$, $N = 70$; see Figure XYZ), although this difference may not be clinically significant.



Total N	70
Test Statistic	22.000
Standard Error	157.150
Standardized Test Statistic	-7.108
Asymptotic Sig. (2-sided test)	.000

Graph 3.10 illustrates Related-Samples Wilcoxon Signed Rank Test comparing two measurements (NRS at 1 Year and NRS Preoperatively) across the 70 Patients. The graph displays the distribution of differences between these measurements, with blue bars showing negative differences and tan bars representing positive differences.



Total N	70
Test Statistic	769.000
Standard Error	78.102
Standardized Test Statistic	3.790
Asymptotic Sig. (2-sided test)	.000

Graph 3.11: illustrates Related-Samples Wilcoxon Signed Rank Test comparing two measurements (NRS at 1 Year and NRS at day 3 postoperatively) across the 70 Patients. The graph displays the distribution of differences between these measurements, with blue bars showing negative differences and tan bars representing positive differences.

3.4. Complications

While the combined pDSS and eTLIF technique demonstrated promising results in terms of pain reduction and faster recovery, it is important to acknowledge the potential complications associated with any surgical procedure (Camino-Willhuber et al., 2021). In this study, several complications were observed.

Dural tear and cerebrospinal fluid leakage: The most frequent complication encountered in this study was a cerebrospinal fluid leak (CSF leakage), occurring in 11 out of 70 patients (15.7%). This complication arose due to unintended dural tears, which are a known risk factor in any spinal surgery, even in minimally invasive procedures. Fortunately, all dural tears in this study were managed successfully during the same surgery, eliminating the need for repeat procedures. All patients were instructed for bed rest for 3 days (Dong et al., 2023).

Iliac artery injury: One case in this study involved a suspected injury to the iliac artery. This is a rare complication, but also reported (Busardò et al., 2015; Leech et al., 2014; Shih et al., 2009; Yi et al., 2010; Yıldız et al., 2013), it highlights the importance of meticulous surgical technique and careful anatomical knowledge, particularly when working near major vascular structures. The patient experienced blood loss, and the vascular team was urgently called in for further evaluation. A thorough investigation ultimately determined that the artery was not actually injured, preventing a potentially life-threatening situation.

Other potential complications: nerve root injury, screw malpositioning instability, cage malposition, infection, hardware failure were not observed during the follow-up period.

4. DISCUSSION

This study presents the outcomes of a novel combined technique, percutaneous dorsal spinal stabilization (pDSS) and endoscopic transforaminal lumbar intervertebral fusion (eTLIF), for treating degenerative lumbar spinal disorders in 70 patients. This minimally invasive approach, combining two established techniques, offers several advantages over traditional open surgical procedures, potentially leading to improved patient outcomes and faster recovery.

4.1. A detailed case discussion

In this section we present a comprehensive case analysis of a selected patient, providing a detailed account of the diagnosis, treatment, and outcomes within the context of this study on combined percutaneous dorsal spinal stabilization (pDSS) and endoscopic transforaminal lumbar intervertebral fusion (eTLIF) for degenerative lumbar spinal disorders.

4.1.1. Presentation of an illustrative case

The patient, a 37-year-old female, presented with a chief complaint of persistent lower back pain radiating to her right leg, significantly impacting her mobility and daily activities. Her history was notable for several years of intermittent lower back pain, which had progressively worsened in recent months. Upon physical examination, she exhibited weakness in her right iliopsoas and quadriceps muscles, graded 4/5 on the Medical Research Council (MRC) scale. Further, she experienced pain with both lumbar flexion and extension. Importantly, she reported no bowel or bladder dysfunction, suggesting the absence of cauda equina syndrome.

Imaging studies, including MRI and CT scans, revealed spondylolisthesis at the L3/4 level, characterized by a forward slippage of the L3 vertebra over L4, Meyerding grade 1, see [Figure 4.1]. This slippage, combined with degenerative changes in the intervertebral disc and facet joints, resulted in spinal canal stenosis, with resultant compression of the exiting nerve roots at this level. The stenosis likely contributed to the patient's radicular pain and muscle weakness. The diagnosis of L3/4 spondylolisthesis with associated spinal stenosis and radiculopathy was made, aligning with the inclusion criteria of this study.



Figure 4.1: This illustration shows a side-by-side sagittal view of preoperative imaging, including both sagittal view of an MRI T2-weighted sequence (left) and a CT scan (right), for the patient discussed in the case study. The images depict a spondylolisthesis at L3/4 (Meyerding Grade 1), which has resulted in spinal canal stenosis.

4.1.2. Surgical intervention

Given the patient’s persistent symptoms and radiological findings, conservative management options, including physical therapy and pain medication, were deemed insufficient. After thorough discussion of the risks and benefits, the patient consented to undergo the combined pDSS and eTLIF procedure.

The surgery was performed under general anaesthesia, utilizing the technique described in Section 2.5. Percutaneous pedicle screws were placed at the L3 and L4 levels, bilaterally, followed by endoscopic decompression of the spinal canal at L3/4 from the right side. A transforaminal lumbar interbody fusion (TLIF) was then performed using the endoscope at the same level using a PEEK cage. Fluoroscopic guidance was employed throughout the procedure to ensure accurate placement of screws and the interbody cage. See [Figure 4.2].



Figure 4.2: This image shows the anteroposterior (AP) view (left) radiograph of the lumbar at day 1 postoperatively, illustrating an instrumented spinal fusion with four pedicle screws positioned bilaterally and linked by longitudinal rods, effectively stabilizing the spine to treat instability caused by lumbar spondylolisthesis, with good alignment and symmetry indicating a well-executed surgical fixation and minimal deviation from the

alignment and symmetry indicating a well-executed surgical fixation and minimal deviation from the

optimal position, while the lateral view (right) provides a sagittal perspective demonstrating the screws inserted into the pedicles of L4 and L5, with the hardware properly positioned, showing a reduction in spondylolisthesis, restoration of lordosis, and no signs of loosening or misalignment, reflecting successful fusion intervention.

4.1.3. Postoperative course and outcome

The patient's postoperative course was pleasant. She reported significant improvement in her right leg pain immediately after surgery. On the third postoperative day, her NRS pain score decreased to 1, indicating substantial pain relief. She was mobilized on the same day of surgery, with assistance from the physiotherapy team, and began ambulating independently with minimal discomfort. She was discharged from the hospital on the seventh postoperative day, well within the average range for this procedure in our study. At the follow-up visit, she continued to experience improvement in her symptoms. Her NRS pain score remained low at 2. The improvement in her right leg pain and low back pain persisted. She had returned to most of her regular activities, with minimal limitations. Radiographic imaging confirmed stable fusion at the L3/4 level, see [Figure 4.3].



Figure 4.3: This image shows the anteroposterior (AP) view (left) and lateral view (right) radiograph of the lumbar spine at the follow-up visit, typically conducted 6-12 weeks after commencing rehabilitation. In alignment with the previous lumbar radiograph, there is no displacement or dislocation of

the screws or the cage, indicating a successful surgery.

This case highlights the benefits of the combined pDSS and eTLIF technique for treating degenerative lumbar spinal disorders. The minimally invasive nature of the procedure resulted in reduced tissue trauma, minimal blood loss, significant pain reduction, and rapid recovery.

However, the relatively quick return to regular activity following this minimally invasive procedure must be counterbalanced by a thorough patient education in order to avoid early overloading the operated segments. The patient's emotional and psychological well-

being before and after surgery plays a crucial role in her recovery process, and must be taken in consideration for patient counselling.

By meticulously analysing such cases and refining the surgical technique, the long-term goal is to make pDSS combined with eTLIF a safe and effective treatment option for a wider range of patients suffering from degenerative lumbar spinal disorders.

4.2. pDSS and eTLIF technique and its advantages

The combined pDSS and eTLIF technique offers several advantages over traditional open procedures. By utilizing small incisions and specialized instruments, it minimizes tissue damage, leading to:

Reduced blood loss: in this study, blood loss was negligible measuring less than 200cc in all surgeries, the specific amount of Blood loss was not reported due to difficulties and inaccuracies in measuring small amounts. The amount is considerably lower than what is typically observed in open procedures. This benefit is particularly valuable for elderly patients or those with pre-existing health conditions. In a systematic review and meta-analysis comparing TLIF and PLIF, (de Kunder et al., 2017) reported that the average blood loss for TLIF across 9 studies, including 450 patients, was 350 ml. This is consistent with what is reported by Phan et al. (Phan et al., 2015) for blood loss, averaging 177 ml for minimally invasive TLIF compared to 461 ml for open surgeries.

Minimal blood loss reduces the risk of perioperative complications such as hemodynamic instability, transfusion-related reactions (Rawn, 2008), and the need for blood products, which are associated with increased morbidity and mortality rates. This is particularly beneficial for vulnerable patient populations, including the elderly or those with pre-existing health conditions, who may have compromised physiological reserves and are more susceptible to the adverse effects of significant blood loss (Mikhail et al., 2020). Additionally, minimal blood loss facilitates clearer visualization of the surgical field, enabling surgeons to perform precise maneuvers and achieve optimal surgical outcomes. Furthermore, it contributes to shorter operative times and reduces the length of hospital stay, thus promoting faster postoperative recovery and overall patient satisfaction.

The reduced blood loss can be attributed to several factors:

- **Minimally Invasive Access:** The small incisions used in pDSS and eTLIF result in significantly less muscle disruption compared to open procedures.
- **Targeted Decompression:** The endoscopic visualization employed in eTLIF allows for precise decompression of the spinal canal and nerve roots, minimizing the need for extensive tissue removal and reducing blood loss.
- **Gentle Tissue Handling:** The specialized instruments used in these procedures are designed for delicate tissue manipulation, further reducing the risk of bleeding.

Less postoperative pain: One of the most significant advantages of minimally invasive Methods like pDSS and eTLIF, which involve smaller cuts and less tissue disruption, observed in this study is the substantial reduction in postoperative pain experienced by patients. This benefit can be directly attributed to the smaller incisions and minimal tissue disruption associated with MIS techniques. As evidenced by the marked decrease in Numerical Rating Scale (NRS) scores. Patients in our study reported a significant decrease in the Numeric Rating Scale (NRS) for pain, with scores falling from 3.61 preoperatively to 1.34 on day 3 postoperatively. This reduction in pain was not only evident in the short term but also persisted over a longer period, with an NRS score of 1.86 reported after 1 year. This reduction in pain translates to several crucial benefits for patient recovery and overall well-being.

Firstly, it significantly lowers the need for analgesic medications, which in turn minimizes the potential for adverse effects associated with these drugs, such as nausea, vomiting, constipation, and respiratory depression. Additionally, reduced reliance on opioids specifically can contribute to a lower risk of dependence and addiction, a growing concern in the medical field(Orosz & Yamout, 2023).

Furthermore, improved pain control leads to enhanced patient comfort, which can positively impact various aspects of the recovery process. Patients experiencing less pain are more likely to ambulate earlier and engage in physiotherapy, leading to faster recovery of mobility and function (Kostic et al., 2024). Additionally, improved comfort can contribute to better sleep, reduced stress and anxiety, and a more positive overall surgical experience.

It is important to acknowledge that individual experiences may vary depending on several factors, including the specific procedure performed, patient characteristics, and pain management protocols. Nevertheless, the overall evidence strongly suggests that the minimally invasive approach offers a significant advantage in terms of postoperative pain control, leading to a more comfortable and potentially faster recovery for patients.

Faster recovery and shorter hospital stays: The average hospital stay of 8.7 days observed in this study points towards a significantly faster recovery trajectory compared to traditional open procedures. Open surgeries often necessitate longer hospitalizations, sometimes exceeding two weeks, due to the extensive tissue trauma and associated complications. This faster recovery translates into numerous benefits for both patients and the healthcare system at large.

For patients, a shorter hospital stay means a quicker return to their daily activities and routines. This is particularly crucial for individuals with demanding jobs, family responsibilities, or those who simply value their independence (Touponse et al., 2023).

Early mobilization also reduces the risk of complications associated with prolonged bed rest, such as muscle weakness, pressure ulcers, and deep vein thrombosis (Solaru et al., 2021). Additionally, shorter hospital stays can alleviate the emotional and psychological stress associated with hospitalization, allowing patients to return to the comfort and familiarity of their homes sooner.

From a healthcare and economical perspective, shorter hospital stays translate into increased bed availability and reduced healthcare costs (Hopkins et al., 2019). This is especially pertinent in countries like Germany, which faces the dual challenge of an aging population and a growing shortage of healthcare personnel (Brücher & Deufert, 2019). With a larger proportion of elderly individuals requiring medical care, efficient utilization of hospital resources becomes paramount. By facilitating faster patient turnover, shorter hospital stays allow healthcare facilities to cater to a greater number of patients, thereby optimizing resource allocation and reducing waiting times for others in need of medical attention.

It is important to note that while 8.7 days might seem lengthy in some contexts, it is considered a relatively short hospital stay within the German healthcare system. This is due to several factors, including the aforementioned aging population. Elderly patients often present with complex medical conditions requiring more intensive treatment and longer recovery periods. Additionally, the decline of multigenerational households in

Germany means that many elderly patients lack the immediate family support necessary for at-home recovery, necessitating longer hospital stays. Other studies reported hospital stay in Germany averaging from 20.8-29.2 days (Abduljawwad et al., 2023)

Lower risk of complications: While the study did report some complications associated with the procedures, such as dural tears and an iliac artery injury, the overall complication rate appears to be lower compared to traditional open procedures. This observation aligns with the growing body of literature suggesting that minimally invasive techniques may offer a safer alternative for patients requiring spinal fusion surgery.

Open TLIF procedures involve a large incision and extensive muscle dissection, which can lead to a higher incidence of complications like: Infection; Open wounds are more susceptible to bacterial contamination, increasing the risk of post-surgical infections. Blood loss; Extensive muscle dissection can result in significant blood loss, sometimes requiring transfusions. Muscle damage and pain; Cutting through muscles can lead to significant post-operative pain and weakness, impacting recovery and mobility. Nerve damage; The manipulation of nerves during open procedures can increase the risk of nerve injury and associated neurological deficits (Joseph et al., 2015; Lau et al., 2013; Tormenti et al., 2012; Wang & Zhou, 2014; Wong et al., 2015).

The combined pDSS and eTLIF, on the other hand, utilizes smaller incisions and specialized instruments to access the spine, minimizing tissue disruption and potentially reducing the risk of these complications.

Recent studies comparing minimally invasive and open TLIF procedures have reported similar findings. A 2015 meta-analysis (Phan et al., 2015) concluded that minimally invasive TLIF was associated with significantly lower rates of blood loss for MI-TLIF compared to open TLIF (median: 177 vs 461 cc). Infection rates were also significantly lower (1.2 vs 4.6). Additionally, the minimally invasive group experienced shorter hospital stays and faster recovery times.

In another retrospective study, by (Yin et al., 2024), it was found that when comparing the TLIF group with the Endo-TLIF group, the latter showed comparable intraoperative blood loss, reduced postoperative CPK elevation, decreased postoperative drainage

volume, and shorter hospital stays after surgery. However, the Endo-TLIF group also experienced longer operative times and incurred higher total costs.

Overall, the available evidence suggests that minimally invasive TLIF offers a promising alternative to open procedures, potentially reducing the risk of complications and facilitating faster recovery for patients. However, further research with larger sample sizes and longer follow-up periods is needed to definitively establish the long-term safety and efficacy of this approach.

While the combined pDSS and eTLIF technique offers numerous advantages, it is important to acknowledge the learning curve associated with mastering these minimally invasive procedures. Surgeons require specialized training and experience to become proficient in using the endoscopic equipment and navigating the confined surgical field. This learning curve can initially translate into longer operative times and potentially higher complication rates (Sharif & Afsar, 2018). However, as surgeons gain experience, operative times decrease and complication rates fall, leading to improved patient outcomes. Therefore, it is crucial to ensure that surgeons performing these procedures have received adequate training and have gained sufficient experience to ensure patient safety and optimal surgical results.

4.3. Feasibility of the combined pDSS and eTLIF technique for treating multi-level degenerative lumbar spinal disorders

The combined percutaneous Deformity Spinal Stabilization (pDSS) and endoscopic Transforaminal Lumbar Interbody Fusion (eTLIF) technique shows considerable promise for the management of multi-level degenerative lumbar spinal disorders. This minimally invasive approach offers several advantages, particularly when addressing multiple affected levels of the spine (Zhai et al., 2024).

Our study indicates that there is no statistically significant difference in surgical duration between patients undergoing treatment for a single level compared to those undergoing multi-level procedures. Specifically, the average surgery time for single-level cases was 164.5 minutes (\pm SD 58.4), whereas multi-level cases averaged 184.7 minutes.

It is important to note that the reported surgery time encompasses the entire process from the initiation of anaesthesia to the patient's transfer to the recovery room, as documented in the SAP-Program. Unfortunately, detailed timing for specific stages of the surgery, such as the incision to wound closure, was not recorded in our SAP system. Consequently, we are unable to provide a breakdown of these stages in this report.

The reduced tissue disruption leads to faster recovery and improved functional outcomes, while minimized cumulative blood loss decreases the need for transfusions and associated complications. Additionally, the smaller incisions and reduced tissue trauma contribute to improved pain control and enhanced patient comfort throughout the recovery process.

For patients with extensive multi-level disease, the minimally invasive nature of the combined technique allows for approach addressing two or more levels at a time, thereby reducing the overall surgical burden and facilitating faster recovery. Furthermore, the combined technique offers a flexible and customizable approach, allowing surgeons to address specific pathologies at each level with precision. However, careful patient selection and surgeon experience are crucial factors for ensuring the success of this technique in multi-level cases. By considering these factors and continuing to refine the technique, the combined pDSS and eTLIF approach has the potential to become a

valuable tool for effectively managing complex multi-level degenerative lumbar spinal disorders.

4.4. Future perspectives and emerging technologies

In today's world, where technology impacts every part of our lives, it's clear that emerging technologies like Artificial Intelligence (AI) and Virtual/Augmented Reality (VR/AR) will have a big effect on medicine as a whole as well as in spine surgery (Benzakour et al., 2023). As minimally invasive techniques, such as percutaneous dorsal spinal stabilization (pDSS) and endoscopic transforaminal lumbar intervertebral fusion (eTLIF), continue to evolve, the integration of cutting-edge technologies is important to advance the field of spinal surgery. These advancements promise to enhance the precision, safety, and overall effectiveness of these novel minimally invasive procedures (Yagi et al., 2023).

AI, as described in a recent review, *Artificial Intelligence and Robotics in Spine Surgery*, by (Rasouli et al., 2021), holds immense potential in revolutionizing comprehensive spine care. Its ability to process vast amounts of data and identify complex patterns makes it an invaluable tool for enhancing various aspects of patient care, research, and surgical practice.

One of the most promising applications of AI in spine surgery lies in its ability to enhance preoperative patient care and outcome prediction. AI algorithms can analyse a patient's clinical data, imaging studies, and other relevant information to assist surgeons in identifying optimal surgical candidates. By weighing multiple factors, including comorbidities, anatomical variations, and potential risk factors, AI can provide personalized insights, enabling surgeons to better select candidates for pDSS and eTLIF. AI-driven algorithms can predict potential complications and optimize surgical strategies, thus improving the safety and success rates of these minimally invasive techniques (Tragaris et al., 2023).

Moreover, by analysing historical patient data and identifying risk factors associated with specific adverse events, AI can alert surgeons to patients at higher risk for complications. This allows for proactive intervention strategies, such as closer monitoring, modification of surgical techniques, or optimization of pre-and postoperative care, ultimately aiming to improve patient safety and surgical outcomes (Lopez et al., 2022).

The integration of VR/AR technologies into minimally invasive spine surgery holds immense potential for enhancing surgical visualization, improving surgical training, and ultimately optimizing patient outcomes. VR/AR systems can create realistic 3D reconstructions of a patient's spine from CT and MRI scans, allowing surgeons to visualize the surgical field with unparalleled detail and plan surgical approaches with greater precision (Y. Liu et al., 2022). This technology allows surgeons to virtually "step inside" the patient's anatomy, identify critical structures, and rehearse complex procedures in a risk-free environment before performing the actual surgery (De Jesus Encarnacion Ramirez et al., 2024).

A review titled "Augmented and virtual reality in spine surgery, current applications and future potentials" by (Ghaednia et al., 2021) explored the use of VR and AR in spine surgery. The article highlights the unique benefits of these technologies, including low cost, easy integration with other technologies, user-friendly features, and their application in navigation systems, making them highly advantageous across various aspects of spine surgery. Head-mounted displays are particularly favoured in both AR and VR systems due to their ease of use. Examples of commercially available head-mounted VR devices include the HTC Vive Cosmos series (Taoyuan City, Taiwan), the Oculus Quest 2 (Irvine, CA, USA), the Oculus Rift (S) (Irvine, CA, USA), and the PlayStation VR (SONY Corp. Nihonbashi, Tokyo, Japan), each varying in cost and requirements. AR and Mixed reality (MR) glasses, such as The Epson Moverio (Los Alamitos, C, USA), Vuzix Blade (West Henrietta, NY, USA), and Google Glass (Menlo Park, CA, USA), are also available, each offering unique features and capabilities.

While head-mounted devices are convenient, they do have limitations. Prolonged use can cause discomfort, headaches, and dizziness. VR systems, in particular, struggle with effectively simulating physical touch, an essential aspect of surgical practice. However, ongoing technological advancements are expected to address these limitations and improve the user experience.

Furthermore, AR systems enable geographically remote surgeons to provide real-time guidance and feedback to trainees in the operating room, overlaying suggestions and instructions onto the trainee's view (Bocanegra-Becerra et al., 2024). AR and VR also facilitate better patient understanding of their conditions and proposed surgical

procedures by providing visually engaging and interactive experiences(Anthony et al., 2021).

Among these, a notable examples include an AR Simulation with Haptic Feedback which reported by (Luciano et al., 2011), they demonstrated the potential of an AR 3D simulator with haptic feedback for training thoracic pedicle screw placement. Using real patient CT data, they created a virtual thoracic spine, allowing fellows and residents to practice drilling and placing virtual pedicle screws, resulting in significant improvements in accuracy and reduced variability.

4.5. Current applications of augmented reality in spine surgery

AR has already found several applications in spine surgery, which are integrated into routine practice, including pedicle screw placement, bone biopsy, and percutaneous intervention. AR-based surgical navigation systems provide real-time guidance for accurate pedicle screw placement, improving surgical accuracy and reducing radiation exposure. Additionally, AR image overlay technology has been employed to enhance accuracy during MR-guided bone biopsies. AR guidance systems, such as the Virtual Protractor with Augmented Reality (VIPAR) developed by (Abe et al., 2013), enhance the visualization of needle trajectory during percutaneous vertebroplasty, improving accuracy and reducing complications.

4.6. Further research and limitations of this study

While the current study provides valuable insights into the efficacy and safety of the combined percutaneous dorsal spinal stabilization (pDSS) and endoscopic transforaminal lumbar intervertebral fusion (eTLIF) technique, its relatively small sample size and limited follow-up duration so that further investigation is necessary. Larger-scale studies involving more diverse patient populations are essential to generalize these findings across various demographics. Additionally, extended follow-up periods will be crucial to understanding the long-term outcomes, particularly concerning the durability of pain relief, functional recovery, and the incidence of late complications such as adjacent segment disease. Such studies would also allow for a stronger assessment of the long-term fusion rates, a critical factor in the success of spinal fusion surgeries.

Furthermore, it is vital to conduct head-to-head comparisons of the combined pDSS and eTLIF technique with other established minimally invasive spinal procedures.

Comparative studies could provide a clearer understanding of the specific advantages and limitations of each technique, enabling surgeons to fit their approach based on patient-specific factors such as anatomy, pathology, and previous surgical history.

Randomized controlled trials (RCTs) could offer the highest level of evidence regarding the efficacy of these techniques in different clinical scenarios if applicable.

In addition to clinical outcomes, evaluating the cost-effectiveness of the combined pDSS and eTLIF technique relative to traditional open procedures and other minimally invasive approaches is crucial. Such analyses should consider not only the direct costs of surgery, including operative time, equipment, and hospital stay, but also the indirect costs, such as recovery time, the need for postoperative rehabilitation, and long-term outcomes. A comprehensive cost-effectiveness study would provide valuable insights for healthcare policymakers, potentially influencing the adoption of minimally invasive techniques over conventional surgeries. These studies could also explore the broader economic impact, including patient productivity and reductions in disability-related costs.

Future research should also explore the integration of advanced imaging modalities and computer-assisted navigation systems in performing pDSS and eTLIF. Technologies such as intraoperative 3D imaging, robotic-assisted surgery, and augmented reality (AR) have the potential to enhance surgical precision, reduce operative times, and improve patient outcomes. Studies focusing on the impact of these technologies on the accuracy of screw placement, the rate of surgical complications, and overall clinical outcomes will be contributory in shaping the future of spinal surgery.

While technical success and clinical outcomes are critical, it is equally important for future studies to emphasize patient-centred outcomes, including quality of life (QoL) assessments, patient satisfaction, and return-to-work rates. Understanding the patient's perspective on pain relief, mobility, and daily functioning is essential for evaluating the true success of surgical interventions.

5. CONCLUSIONS

The combined technique of percutaneous dorsal spinal stabilisation (pDSS) and endoscopic transforaminal lumbar intervertebral fusion (eTLIF) represents a significant advancement in minimally invasive spine surgery, particularly for degenerative lumbar spinal disorders. It addresses the limitations of traditional open surgeries, offering a safer and more efficient alternative.

This novel approach effectively reduces surgical trauma, as evidenced by minimal intraoperative blood loss and reduced postoperative pain. Patients benefit from faster recovery times and shorter hospital stays, enhancing the overall efficiency and appeal of this technique.

The study findings highlight the clinical safety and efficacy of the combined pDSS and eTLIF method, emphasised by a low complication rate and sustained pain relief.

Notably, the technique demonstrated promise in treating multi-level degenerative lumbar spinal disorders, where traditional methods often introduce greater risks due to prolonged operative times and increased tissue trauma. Importantly, the increase in surgical duration for multi-level cases was not statistically significant compared to single-level surgeries, underscoring the efficiency of this approach even in more complex cases.

However, certain limitations must be acknowledged. The follow-up period, though adequate to evaluate short- and mid-term outcomes, does not capture long-term results such as fusion rates and the potential for late-onset complications. The single-institution setting also limits the generalizability of the findings to other clinical environments or populations.

Future research should prioritise expanding the sample size and extending the follow-up duration to assess the long-term efficacy and safety of the combined pDSS and eTLIF technique. Prospective randomised controlled trials comparing this approach directly with traditional open surgeries or other minimally invasive methods would provide robust evidence to guide clinical decision-making and further establish its role in spinal surgery.

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Figures and Tables

Figures:

Figure 1.1 Prevalence of low back pain	1
Figure 1.2 Sagittal MRI for L5/S1 disc prolapse	2
Figure 1.3 Meyerding Grades.....	3
Figure 1.4 Sagittal MRT of lumbar spinal canal stenosis	4
Figure 1.5 Sagittal MRT of Spondylodiscitis.....	5
Figure 1.6 Sagittal sections of a Lumbar-CT scan (L3 Fracture).....	6
Figure 1.7 MRI of tumorous L4	7
Figure 1.8 Approaches for Lumbar Interbody Fusion.....	11
Figure 1.9 Illustration of the TLIF technique.....	13
Figure 1.10 Sequence of steps in percutaneous screw fixation.....	14
Figure 1.11 Illustration of eTLIF	16
Figure 2. 1: Schematic drawing of percutaneous ES2 screws.....	23
Figure 2. 2: A photograph of pezo-T™ PEEK from Ulrich.....	24
Figure 2. 3: A photograph of the EasyGO system.	24
Figure 2. 4: The EasyGO Endoscopic System setup.....	25
Figure 2. 5: Photograph for Patient Positioning and Preparation.....	26
Figure 2. 6: Schematic drawing of the small incisions	26
Figure 2. 7: Photograph of K-wire and ES2 screw	27
Figure 2. 8: Schematic drawing after screws insertion	28
Figure 2. 9: Photograph displays the ES2 screw blades.....	28
Figure 2. 10: Photograph of the holding arm and endoscope camera	29
Figure 2. 11: Bougie dilator system (EasyGo).....	30
Figure 2. 12: Endoscope shaft attached to the holding arm	30
Figure 2. 13: Illustration of minimally invasive posterior approach.....	31
Figure 2. 14: Photograph of the surgical theatre setup.....	32
Figure 2. 15: The Endoscope attached to the optic shaft	32
Figure 2. 16: Endoscopic view of the L5 nerve root.....	33
Figure 2. 17: Intraoperative lateral radiograph.....	34
Figure 4.1 Sagittal MRI and CT scan for Case discussion.....	60
Figure 4.2 X-Ray of the lumbar spine at Day 1 Postop	60
Figure 4.3 X-Ray of the lumbar spine upon follow-up visit	61

Tables:

Table 2.1: Patients’ Demographics and Diagnosis.....400
 Table 2.2 Details of single-level surgery43
 Table 2.3 Details of two-level surgery45
 Table 2.4 Details of three-level surgery46
 Table 3.1: Duration of Surgery segmented by the Level of the Surgery52

Graphs:

Graph 3.1 Stacked Histogram of Age by Gender.....48
 Graph 3.2 Scatter of Duration of Surgery by Age by Gender.....49
 Graph 3.3 Count of single-level surgery50
 Graph 3.4 Count of multiple-level surgery51
 Graph 3.5 Boxplot of Duration of Surgery by Single or Multiple Levels52
 Graph 3.6 Boxplot of Duration of Surgery by Level of Surgery53
 Graph 3.7 Grouped Scatter of Duration of Hospital stay by Age by Gender54
 Graph 3.8 Simple Boxplot Of NRS (Pain Scale) by Time Period55
 Graph 3.9 Related-Samples Wilcoxon Signed Rank Test (NRS D3 - NRSPreop).....56
 Graph 3.10 Related-Samples Wilcoxon Signed Rank Test (NRS 1 Year - NRSPreop).57
 Graph 3.11 Related-Sampies Wilcoxon Signed Rank Test (NRS 1 Year - NRS D3)57

Charts:

Chart 2. 1: Clinical Flowchart21
 Chart 2. 2: Flowchart summary of the surgery.....37

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