

Percutaneous Transforaminal Endoscopic Lumbar Foraminotomy in Stable Degenerative Lumbar Isthmic Spondylolisthesis with Radicular Leg Pain: A Retrospective Study

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Objective: Endoscopic surgery is a minimally invasive option for effectively addressing lumbar degenerative diseases. This study aimed to describe the specific technology of percutaneous transforaminal endoscopic lumbar foraminotomy (PTELF) as a therapeutic intervention for managing radicular leg pain (RLP) resulting from stable degenerative lumbar isthmic spondylolisthesis (DLIS) and to present the associated clinical results.

Methods: From March 2022 and April 2023, 25 patients were diagnosed with single-level stable DLIS with RLP and underwent PTELF. Clinical assessments utilized the visual analog scale (VAS), Oswestry Disability Index (ODI), and modified MacNab criteria. All endoscopic surgery videos were reviewed to interpret the pathology associated with DLIS.

Results: The mean age of the cohort was 65.3 ± 11.0 years. The mean preoperative ODI score, VAS score for low back, and VAS score of the leg were 64.1 ± 8.2 , 7.0 ± 0.7 , and 7.3 ± 0.8 , respectively. These scores significantly improved to 16.3 ± 10.4 , 2.0 ± 0.6 , and 1.7 ± 1.0 at the final follow-up, respectively ($P < 0.01$). The modified MacNab criteria indicated “good” or “excellent” outcomes in 92.0% of cases. Analysis of 23 surgical videos revealed 15 patients with disc herniation, nine with lower vertebral endplate involvement, consistent presence of uneven bone spurs (at the proximal lamina stump and around the foramen), and accumulated scars. Two patients experienced postoperative dysesthesia, and one encountered a recurrence of RLP.

Conclusion: PTELF emerges as a potentially safe and effective procedure for alleviating RLP in patients with stable DLIS. However, additional evidence and extended follow-up periods are imperative to evaluate the feasibility and potential risks associated with PTELF.

Keywords: radicular leg pain, lumbar isthmic spondylolisthesis, transforaminal, foraminotomy, local anesthesia

Introduction

Degenerative Lumbar isthmic spondylolisthesis (DLIS) is a form of lumbar spondylolisthesis, characterized by an abnormal isthmus connection leading to the anterior displacement of one vertebral body relative to the next.^{1,2} This anterior movement primarily occurs in the early stages of the disease and eventually halts, reaching a stable state irrespective of whether the isthmus defect undergoes bone or fibrous healing.^{3,4} At this juncture, conservative measures such as anti-inflammatory drugs and physical therapy may offer relief from DLIS-induced pain. However, a substantial number of patients experience persistent and refractory back or radicular leg pain (RLP) or both, necessitating surgical intervention to alleviate symptoms and restore physical function.⁵ The distinctive pathological features of DLIS encompass four key aspects: fibrocartilage formation or scar accumulation at the isthmus defect, irregular and uneven bone spurs (isthmus bone spurs extending from the proximal lamina stump to the extraforaminal exit zone and bone spurs distributed at the edge of the foramen),⁶ involvement of the lower vertebral endplate (LVE), and disc herniation (DH). These factors, alone or in combination, contribute to foraminal stenosis (FS), exerting pressure on the exiting nerve root

(ENR) and resulting in RLP in patients.^{2,6} Concurrently, vertebral spondylolisthesis and diminished disc height can exacerbate this pathological condition.

Currently, decompression with or without fusion is regarded as a viable surgical option for treating DLIS.⁷ However, the gold standard fusion surgery is conventionally associated with a high incidence of complications and substantial costs.⁸ In adult DLIS cases, the degree of slippage seldom increases, and therefore the need for stabilization and fusion is rarely required to prevent progression of the malalignment.⁹ In cases where patients exhibit stability without evident deformities associated with DLIS, growing evidence supports decompression without fusion as a viable treatment option.¹⁰ Consequently, decompression alone can serve as an effective intervention for younger patients, delaying the need for fusion surgery or as a means of symptomatic relief in older individuals who may not tolerate spinal fusion.⁶

Certain endoscopic surgeries have been employed to address patients with DLIS experiencing RLP with a minimally invasive approach.^{6–9} Endoscopic decompression offers minimal invasiveness, precise treatment, rapid postoperative recovery, minimal tissue damage, and negligible impact on spinal stability.^{6,7,11} Presently, the interlaminar and transforaminal approaches are commonly utilized. Given the unique pathological and chronic characteristics of DLIS, coupled with the thickening and anatomical variation of vertebral lamina and tissues, the posterior approach may necessitate extensive resection of the dorsal area of the foramen, potentially increasing lumbar instability.¹² Considering the FS resulting from DLIS, the transforaminal approach appears more rational due to its natural angle advantage and easier access to pathological structures. Endoscopic decompression techniques through the transforaminal approach have demonstrated safety and efficacy in treating various lumbar degenerative diseases.^{11,13} However, literature on DLIS treatment via the transforaminal approach is currently limited. This study introduced the percutaneous transforaminal endoscopic lumbar foraminotomy (PTELF) technology, detailing its procedure, which effectively enlarges the foramen and removes pathological structures in and around the foramen during decompression.

The objective of this study was to delineate the technical aspects of PTELF and present the preliminary clinical results from 25 cases.

Materials and Methods

Patient Population

A retrospective analysis was conducted on data from 25 patients with single-level DLIS who underwent PTELF between March 2022 and April 2023. The study obtained approval from the institutional review committee, and all participants provided written informed consent. The inclusion criteria were as follows: 1) confirmation of DLIS with FS through clinical manifestations, physical examination, and imaging, including magnetic resonance imaging (MRI) and computed tomography (CT) scan; 2) Grade I–II by Meyerding classification method using standing position lumbar X-ray;¹⁴ 3) verification through imaging studies, nerve examination, and nerve block treatment, that RLP (with or without back pain) was linked to pathological factors of DLIS; and 4) non-responsive to conservative therapies for >3 months. Exclusion criteria included: 1) patients with predominant low back pain; 2) patients with DLIS beyond Grade II according to Meyerding classification;¹³ 3) preoperative segmental instability on the flexion-extension lumbar x-ray of standing position; 4) patients with neurogenic claudication due to central stenosis; 5) patients with lumbar trauma, fracture, tumor, or infection; and 6) those with a history of prior lumbar spine surgery.

Surgical Techniques

All patients underwent PTELF under local anesthesia (50 mL of 0.8% lidocaine). Patients were positioned in the lateral decubitus position, with a soft lumbar pad placed beneath the waist to facilitate puncture. The skin entry point and approach angle were determined using fluoroscopy. PTELF comprised three processes: 1) foraminoplasty, 2) endoscopic lumbar foraminotomy (ELF), and 3) endoscopic soft tissue decompression.

Foraminoplasty

Infiltration anesthesia, using 15–25 mL of lidocaine, was administered layer by layer at the needle entry point and puncture channel. Under fluoroscopic guidance, an 18-G needle was introduced into the foramen area, with 15mL of lidocaine injected, followed by an additional 10mL injected into the superior articular process (SAP) by adjusting the needle direction. After these steps, a guide wire was inserted, and an 8mm incision was made. The TOM Shidi

(MaxMorespine, Hoogland Spine Products GmbH, Germany) needle was then advanced through the SAP along the guide wire, determining the landing point at the posterior edge of the vertebral body under lateral fluoroscopy and reaching the midline of the posterior spine under anteroposterior fluoroscopy (Figure 1A and B). Following the trajectory formed by the TOM Shidi needle, it was progressively substituted with a bone drill (6 and 8 mm; MaxMorespine) to excise sections of the SAP, scar tissue, and hypertrophic ligamentum flavum (LF). As the bone drill advanced, its leading edge closely approached the vertebral body's posterior edge without surpassing the midline of the posterior spine (Figure 1C and D). These maneuvers transformed the distorted foramen into a recognizable endoscopic anatomical setting, ultimately allowing the installation of the working cannula and endoscopic equipment for subsequent procedures (Figure 1E and F).

Endoscopic Lumbar Foraminotomy

Endoscopic lumbar foraminotomy primarily entails the removal of bone around the nerve root. Firstly, anatomical landmarks were established based on marks on the ventral side of the SAP made by the bone drill (Figure 2A). Subsequently, 270° full-length decompression¹⁵ of the traversing nerve root (TNR) was achieved by extracting portions of the SAP (from the base to the body and the tip), hypertrophic LF, and the DH using an endoscopic bone knife or nucleus forceps. Since FS is the primary cause of RLP in patients with DLIS, the subsequent steps focused mainly on the region around the ENR. The anatomical relationship between ENR and intervertebral disc is beneficial for the surgeon to obtain accurate orientation. The removal of the LF and foraminal ligament exposed the ENR, allowing the surgeon to locate the isthmus gap precisely. Soft scar tissue and inflammatory tissue around the isthmus gap were removed, revealing the ENR surrounded by isthmus bone spurs extending from the proximal lamina stump, uneven bone spurs around the foramen, DH, and the LVE (Figure 2B–D). Eliminating these irregular and uneven bone structures constitutes a pivotal aspect of endoscopic lumbar foraminotomy. In cases where bone spurs exhibited a steep growth angle, the flexible use of an endoscopic bone knife facilitated targeted small-scale resection (Figure 2E). Furthermore, removing

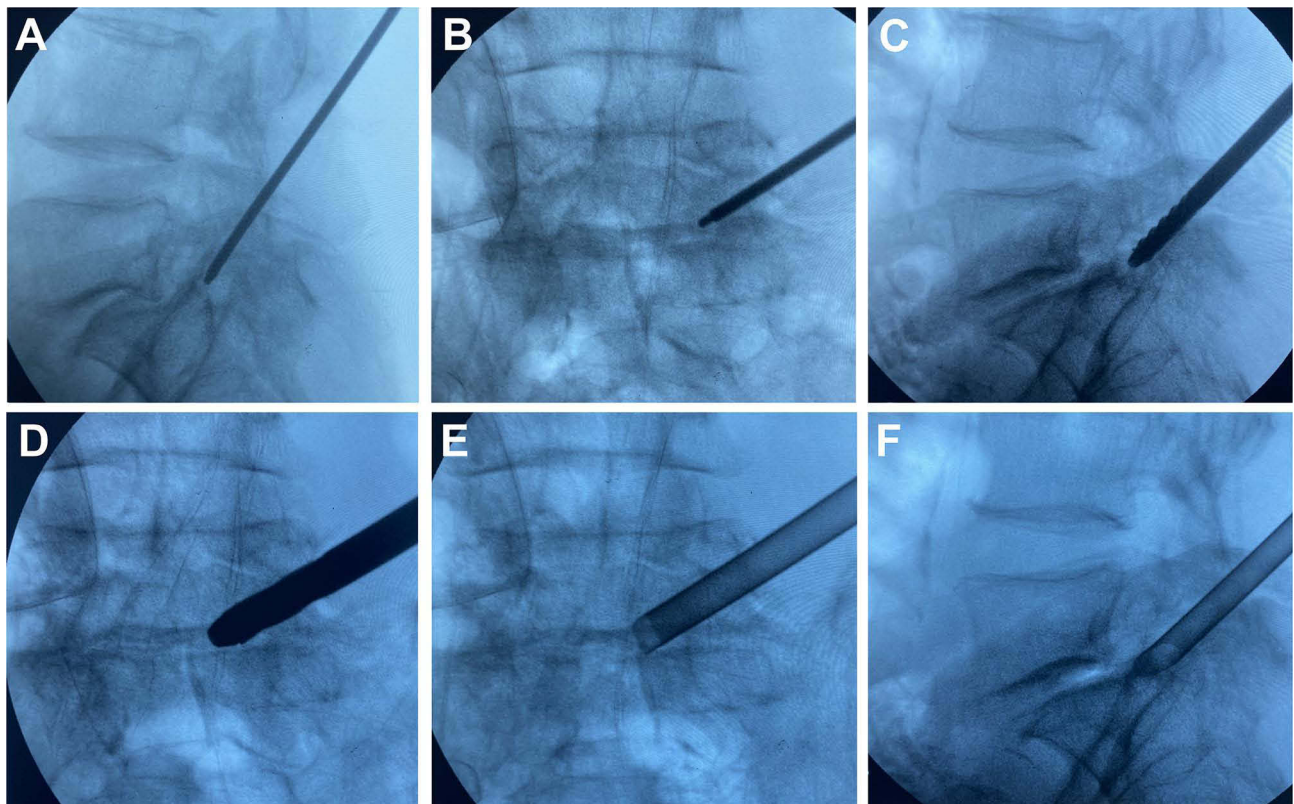


Figure 1 Intraoperative perspective images illustrating the establishment of working channels. Sagittal (A) and anteroposterior (B) fluoroscopic images of the TOM Shidi needle. Employing a 6mm bone drill (C) and 8mm bone drill (D) to remove soft and bony tissues. Anteroposterior (E) and sagittal (F) fluoroscopic images of the working cannula.

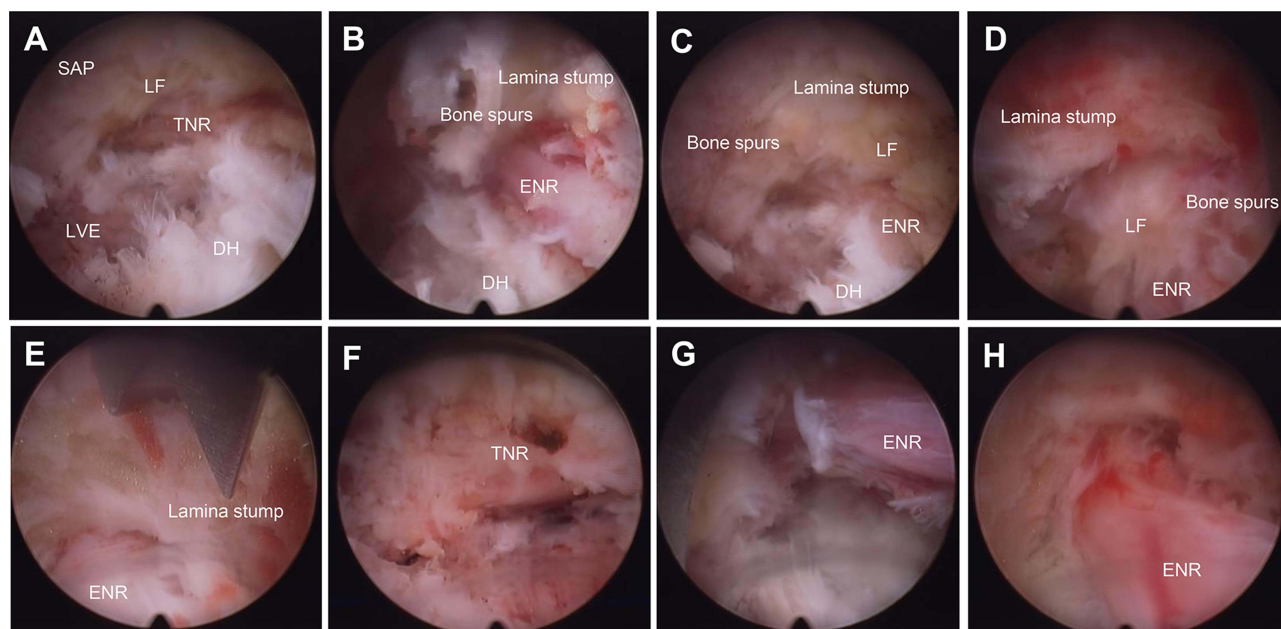


Figure 2 Intraoperative endoscopic views. (A) Identification of the SI TNR. (B–D) Identification of the L5 ENR, showcasing pathology of L5 ENR compression, including bone spurs extending from the proximal lamina stump, bone spurs at the edge of the foramen, LF, and DH. (E) Execution of endoscopic lumbar foraminotomy using an endoscopic bone knife to eliminate pathological bone factors around the ENR. Complete decompression of the TNR (F) and ENR (G and H) and the dural exposure from the starting point to ENR.

Abbreviations: TNR, traversing nerve root; ENR, exiting nerve root; LF, ligamentum flavum; DH, disc herniation; SAP, superior articular process; LVE, lower vertebral endplate.

and grinding a segment of the pedicle is recommended to create supplementary space for the ENR by excising the top of the foramen.

Endoscopic Soft Tissue Decompression

This decompression phase was directed towards the proximal end of ENR, tracing it to the axillary epidural area. Hypertrophic LF and DH (foraminal and extraforaminal) were removed using various forceps to release ENR (Figure 2B–D). Bipolar radiofrequency was employed to reduce the size of the intervertebral disc, separate adhered tissues, and control bleeding. The axillary epidural area is a critical indicator of the successful decompression of the ENR. The dural sac exposure from the starting point to the ENR signified the achievement of foramen decompression. Following the release of the proximal axillary region, a thorough examination of the ENR was conducted from the proximal to the extraforaminal exit zone, and the TNR was observed from the proximal to the distal end by rotating the channel. The decompression endpoint was reached when the free movement of the TNR and ENR was observed during the patient's coughing or breathing (Figure 2F–H).

Subsequently, a drainage tube was inserted, and the wound was sutured. Postoperatively, all patients underwent CT or MRI within 1 week (Figures 3 and 4).

Clinical Assessments

The severity and functional status of pain were assessed using the visual analog scale (VAS) score and Oswestry Disability Index (ODI) index at the preoperative stage and at 1 month, 6 months, and the final follow-up postoperatively. Patient satisfaction was gauged using the modified MacNab criteria at the last follow-up. Throughout the follow-up period, patients underwent reexamination through MRI or CT. The Meyerding classification method was employed to evaluate the grade of spondylolisthesis,¹⁴ and the percentage of spondylolisthesis was measured using standing lumbar lateral X-rays before surgery (Figure 5) and at the final follow-up. The endoscopic surgery video, recorded with specialized equipment, underwent independent review and analysis by two orthopedic doctors, comparing the observed pathological anatomical structures with preoperative imaging.

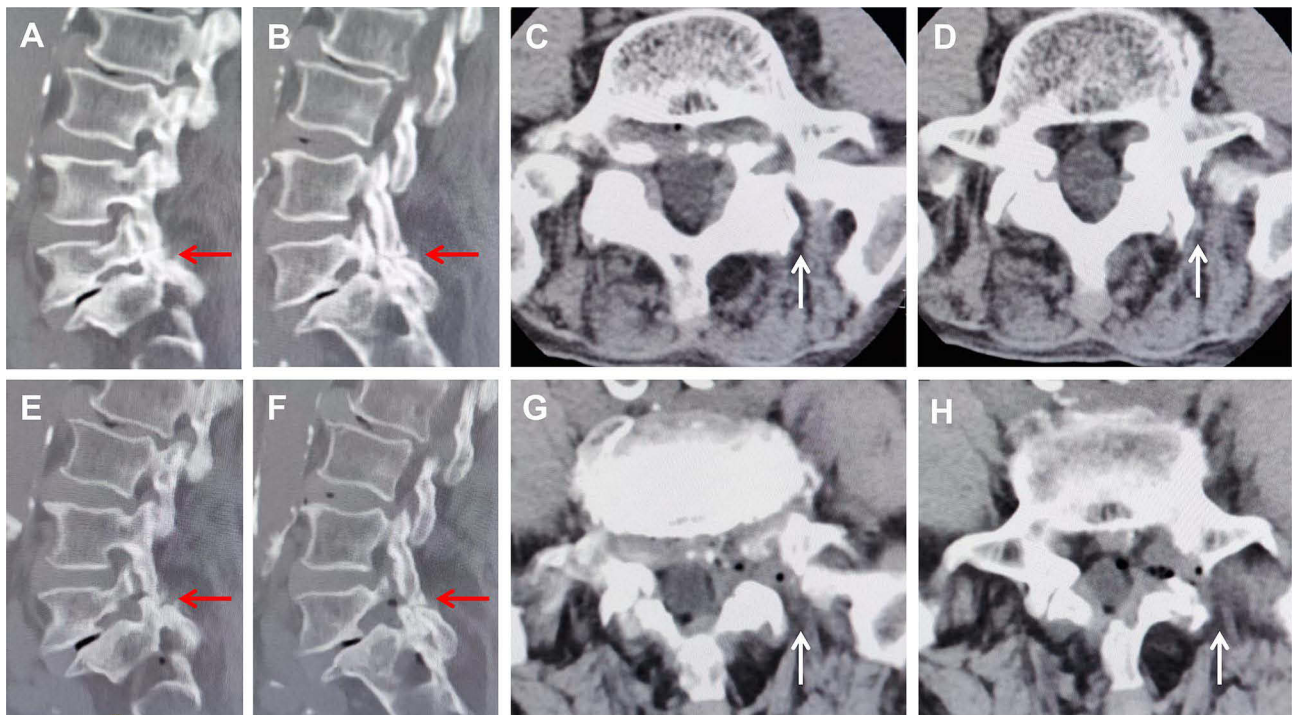


Figure 3 Preoperative and postoperative CT (computed tomography). (A–D) Preoperative CT highlighting the left L5 pars defect (red arrow) and the unique pathology of foramen stenosis caused by lumbar isthmic spondylolisthesis (white arrow), including bone spurs extending from the proximal lamina stump to the extraforaminal exit zone and bone spurs distributed at the edge of the foramen, lower vertebral endplate. (E–H) Postoperative CT demonstrating the removal of the pathological factor compressing the L5 exiting nerve root (red arrow) and enlargement of the foramen (white arrow).

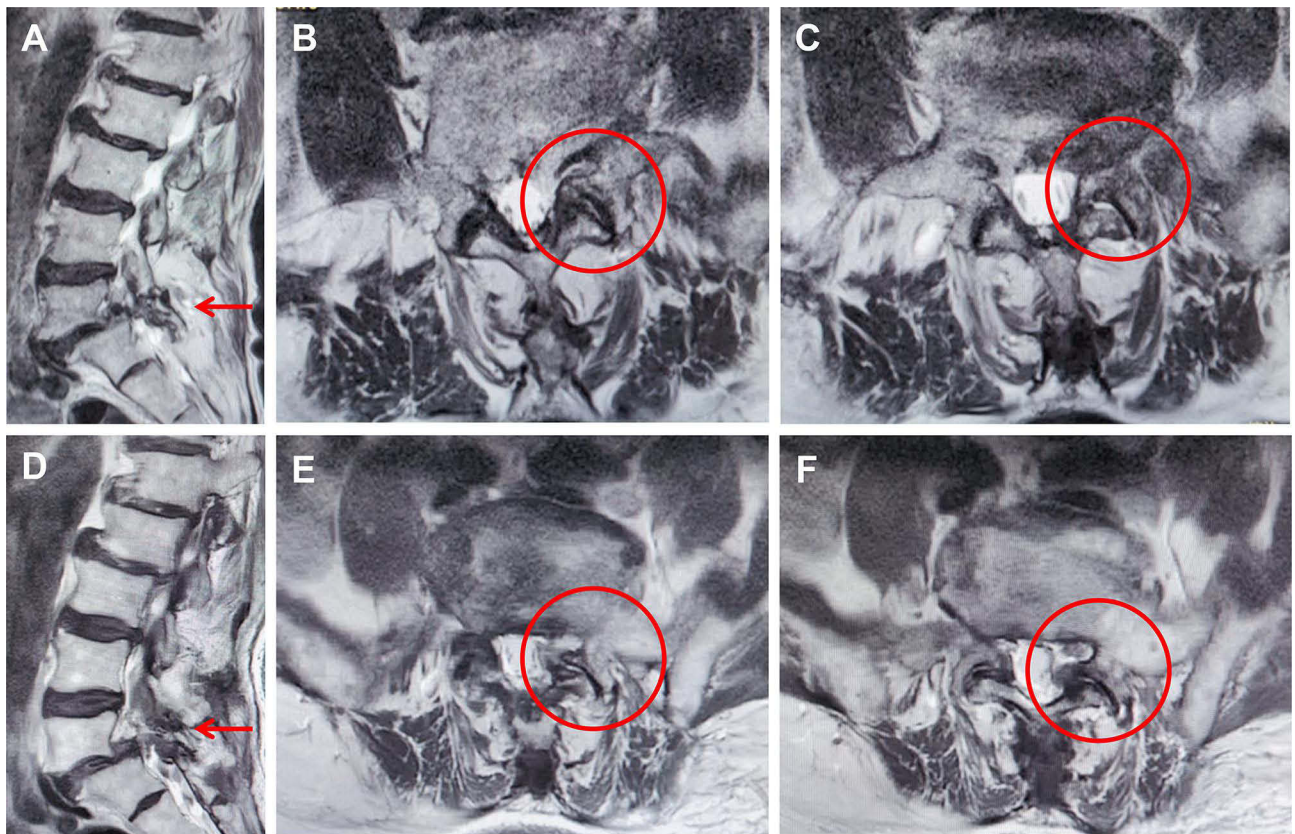


Figure 4 Preoperative and postoperative MRI (magnetic resonance imaging) scans. (A–C) Preoperative MRI indicating the left L5 pars defect (red arrow) and L5-S1 foraminal stenosis (red circle). (D–F) Postoperative MRI revealing foraminal enlargement (red arrow) and liberation of the left L5 exiting nerve root (red circle).

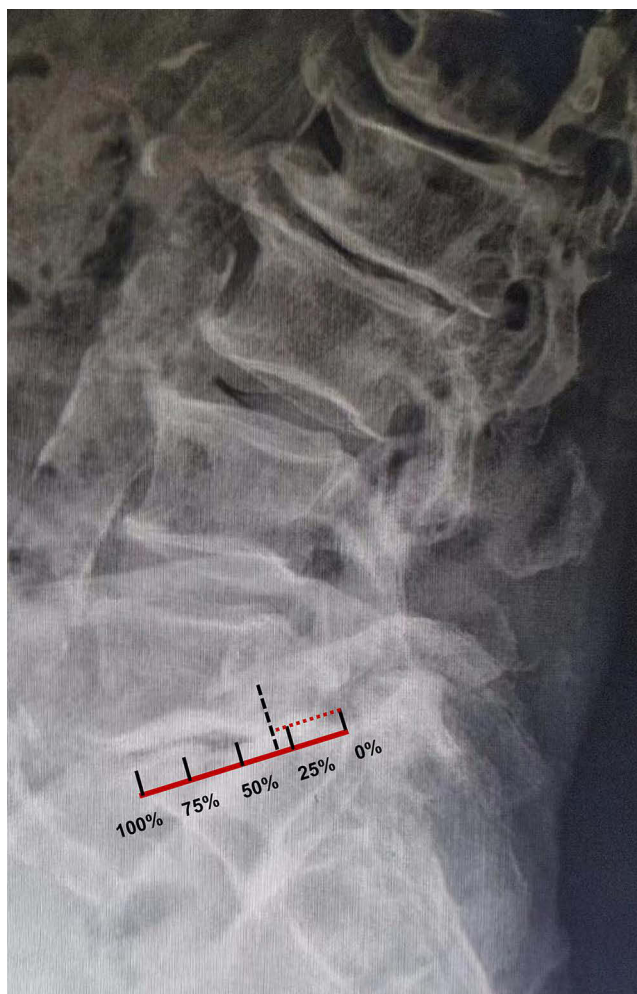


Figure 5 Preoperative Lateral X-ray of the standing lumbar spine illustrating the degenerative lumbar isthmic spondylolisthesis with Meyerding Grade II, along with the measurement of slippage percentage.

Statistical Analysis

Statistical analysis of the clinical results was performed using SPSS 26.0 (IBM, Armonk, USA). Paired *t*-tests or Wilcoxon rank-sum tests were utilized to compare mean outcome scores between pre- and postoperative variables. Statistical significance was set at $P < 0.05$.

Results

Preoperative Demographic Characteristics

Table 1 outlines the preoperative demographic characteristics of the study cohort. The mean age of the 25 patients (13 men and 12 women) was 65.3 years (range: 42–88 years). The symptom duration averaged 46.1 months (range: 5–120 months), and the mean follow-up period was 11.2 months (range: 7–20 months). The surgical interventions targeted L3/4 in one patient (4.0%), L4/5 in three (12.0%), and L5/S1 in 21 (84.0%). Spondylolisthesis was classified as Grade I in 19 cases (76.0%) and Grade II in six (24.0%). The predominant comorbidity was cardiovascular diseases (48.0%), including hypertensive disorders, followed by endocrinology diseases (20%), such as diabetes. Eight patients had no comorbidities (**Table 2**).

Clinical Results

The average operation time and postoperative hospital stay were 73.6 min (range: 50–100 min) and 2.7 days (range: 2–5 days), respectively. The mean preoperative ODI score, VAS score of the low back, and VAS score of the leg were $64.1 \pm$

Table 1 Demographics of Included Patients

Characteristic	Mean \pm SD or Number
Sex (M/F, n)	13/12
Age (years)	65.3 \pm 11.0
Duration of symptoms (months)	46.1 \pm 44.5
Levels involved, L3-4: L4-5: L5-S1	1:3:21
Spondylolisthesis Grade, Grade 1: Grade 2	19:6
Leg pain (unilateral/bilateral)	20:5
Duration of operation (minutes)	73.6 \pm 11.0
Postoperative hospital stay (days)	2.7 \pm 0.7
Follow-up period (months)	11.2 \pm 3.7

Table 2 Comorbidities

Comorbidities	Number of Patients	Percentage
Cardiovascular	12/25	48.0%
Endocrinologic	5/25	20.0%
Cerebrovascular	2/25	8.0%
Urologic	1/25	4.0%
Others	1/25	8.0%

8.2, 7.0 \pm 0.7, and 7.3 \pm 0.8, respectively. These scores improved significantly to 16.3 \pm 10.4, 2.0 \pm 0.6, and 1.7 \pm 1.0 at the final follow-up, respectively (Table 3). The VAS and ODI scores at each postoperative time point (1 month, 6 months, and the final follow-up) were significantly lower than the preoperative scores ($P < 0.01$) (Table 3). Applying the modified MacNab criteria for evaluation at the final follow-up yielded excellent results in 16 patients (64.0%), good in seven (28.0%), and fair in two (8.0%). All patients underwent postoperative dynamic X-rays examination within one week after surgery, and no signs of lumbar instability were found (Figures 6). The average percentage of spondylolisthesis slippage was 19.0% \pm 5.3% preoperatively and 18.8% \pm 5.4% at the final follow-up, with no significant differences ($P > 0.05$). Due to equipment malfunction, the video data for two cases could not be successfully saved. Therefore, 23 video datasets were summarized and analyzed, revealing 15 patients with DH (three extraforaminal, 11 foraminal, and one posterolateral) and nine combined with LVE. Every case exhibited compression of scars and irregular bone spurs (bone spurs extending from the proximal lamina stump to the extraforaminal exit zone and bone spurs distributed at the edge of the foramen).

Complications

Postoperatively, two patients experienced dysesthesia, which was effectively alleviated after the administration of neurotrophic drugs for one week. Another patient initially experienced pain relief postoperatively; however, RLP reappeared in the fourth month. Given the failure of non-surgical interventions and considering the necessity to resume

Table 3 Clinical Outcomes Before and After Endoscopic Decompression at Different Follow-Up Time Points

Time Point	Pre-Op	1-Month Post- Op	6-Months Post- Op	Final Follow-Up
Low back pain VAS	7.0 \pm 0.7	2.8 \pm 0.7*	2.4 \pm 1.2*	2.0 \pm 0.6*
Leg pain VAS	7.3 \pm 0.8	2.6 \pm 0.9*	2.0 \pm 1.3*	1.7 \pm 1.0*
ODI (%)	64.1 \pm 8.2	27.5 \pm 10.0*	21.5 \pm 10.9*	16.3 \pm 10.4*

Note: * $P < 0.01$ versus preoperative data.

Abbreviations: VAS, visual analogue scale; ODI, Oswestry Disability Index; Op, operation.

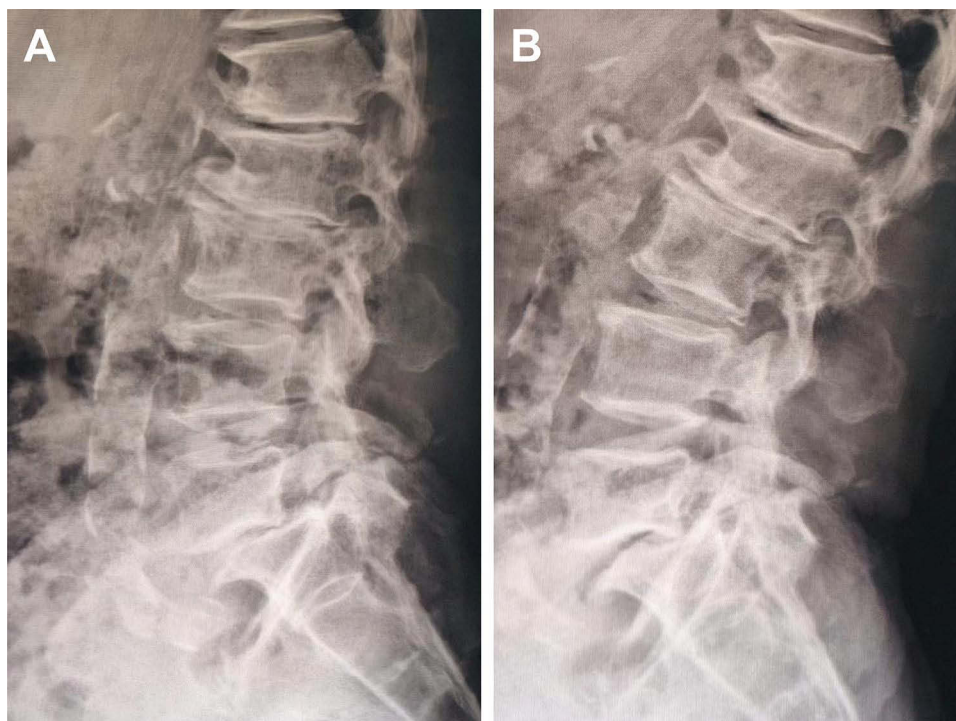


Figure 6 Postoperative flexion (A) and extension (B) lateral view showing degenerative lumbar isthmic spondylolisthesis and stability of L5-S1 (< 3 mm dynamic sagittal translation).

physical labor, this patient opted for transforaminal lumbar interbody fusion combined with pedicle screw fixation. After this surgical intervention, the patient's RLP was alleviated, and sustained relief was observed until the final follow-up.

Discussion

This retrospective study aimed to introduce a novel PTELF technique tailored for patients with DLIS. Despite the overall relief of symptoms in most patients due to the benefits of PTELF, a subset experienced complication. Analyzing the root causes of these complications is essential for surgeons to refine the technology. It is crucial to emphasize that the purpose of PTELF is not to treat spondylolysis itself; it is one of the individualized alternatives to alleviate RLP stemming from FS in patients with DLIS. Preliminary results indicated that PTELF is an effective and safe method for treating stable DLIS.

DLIS exhibits specific pathological features, categorizing cases into three types based on anatomical and clinical variations.^{2,7} The first type involves chronic low back pain primarily caused by abnormal connections between adjacent vertebral bodies (isthmus fracture, facet joint degeneration, intervertebral disc degeneration). The second type is rare central stenosis and neurogenic claudication. Due to the specific pathology of DLIS leading to an abnormal increase in spinal canal diameter, TNR is less compressed.¹⁶ Unlike degenerative spondylolisthesis, which often evolves into neurogenic claudication caused by central spinal canal stenosis. The third type involves radicular pain, typically occurring in the L5/S1 stage of FS,² frequently leading to compression of the L5 nerve root. Our experience indicates that RLP caused by DLIS involves four core pathological factors: fibrocartilage formation or scar accumulation at the isthmus fracture, irregular and uneven bone spurs (hook-shaped bone spurs extending from the proximal lamina stump to the extraforaminal exit zone and bone spurs distributed at the edge of the foramen),⁶ LVE, and DH.

Currently, most experts believe that decompression and fusion are the “gold standard” for treating patients with DLIS.⁷ The logic behind this behavior is that patients with DLIS are not only more likely to experience instability in the affected segment, but also more likely to experience instability in the upper adjacent segment.¹⁷ Therefore, even if there is minimal damage to muscles or joints during surgery, it can lead to instability.⁷ To prevent this uncertainty factor from occurring, fusion is usually increased to enhance lumbar stability. However, some authors have concluded^{3,18} that the relative stability of DLIS can be attributed to the normal development and integrity of the posterior vertebral ligament

complex. The potential for slip progression in patients with DLIS mostly exists in childhood and adolescence, and the likelihood of slip progression is small, and it can gradually reach a stable state during subsequent natural processes. Knight et al⁹ concluded that in adult DLIS, the degree of slippage seldom increases, and fixation and fusion are rarely needed to prevent the progression of slippage. In 1955, Gill¹⁹ first reported the use of decompression without fusion to treat patients with DLIS with radicular symptoms or low back pain, and achieved successful surgical results. In his method, loose vertebral plates and fibrocartilage tissue blocks were removed from the defect in the pars interarticularis, which not only relieved RLP but also alleviated low back pain. Since then, Gill's surgery procedure has been applied and popularized, and some researchers have obtained good nerve root decompression effects by using similar decompression techniques, and have conducted relevant reports.²⁰⁻²² Although patients with unstable DLIS may benefit from fusion, for stable patients who only show RLP, decompression without fusion has many advantages,²³ including less surgical trauma and blood loss, economic advantages, and low complications. In recent years, spinal endoscopic decompression technology has been widely used in lumbar degenerative diseases. Perhaps we can use this minimally invasive and simple endoscopic decompression surgery to relieve pain and improve function.

The PTELF utilized in this study is a minimally invasive surgical technique employing a transforaminal approach. It enables the removal of core pathology with minimal damage to muscles and facet joints, providing comprehensive decompression of the foramen and lateral aspects. PTELF offers several advantages, including minimally invasive procedures, local anesthesia and dual nerve root decompression (ENR and TNR). Surgical data illustrate the minimally invasive nature of PTELF, with an average operation time of 73.6 minutes due to its natural channel and angle advantages, which is shorter than the reported time required for posterior endoscopy.²⁴ After proficient operation, the time can be compressed to 55 minutes. The patient's incision is small, and the average postoperative hospital stay was 2.7 days, contributing to quicker patient recovery and simplified postoperative management. Our study's combined excellent and good rates based on the modified MacNab criteria reached 92.0%. Moreover, the average VAS scores of the leg and lower back decreased by 5.6 and 5.0 at the final follow-up ($P < 0.01$), respectively, and the average ODI improved by 47.8 at the final follow-up ($P < 0.01$). Given that a VAS score reduction of $\geq 50\%$ or ODI score improvement of $> 30\%$ is clinically relevant,^{25,26} our clinical data affirm the effectiveness of PTELF technology for patients with DLIS and its substantial improvement in function.

An additional benefit of PTELF technology is the use of local anesthesia. With an average patient age of 65.2 years, including 14 patients aged ≥ 65 years, and common comorbidities such as cardiovascular diseases in 12 patients (48%), endocrinology diseases (20%) in six, and no comorbidities in eight, PTELF proves advantageous for both young and older patients with comorbidities or those unable to tolerate general anesthesia. Furthermore, PTELF under local anesthesia reduces the risk of nerve injury, as the surgeon can communicate with the patient to judge and assess their condition. Compared to other endoscopic or open surgeries requiring general anesthesia, PTELF under local anesthesia is relatively safe and facilitates fast postoperative recovery.

PTELF technology addresses the bony compression leading to FS and adverse pathology in and around the foramen; it further focuses on restoring the dual nerve root activity. After a comprehensive review and analysis of 23 endoscopic videos, unique patterns were identified in the growth of bone spurs.²⁷ Most of them extended from the proximal lamina stump to the extraforaminal exit zone, constituting the primary bone factors affecting the ENR. Furthermore, small coarse bone spurs were unevenly distributed along the lateral boundary of the lamina to the inner side and the top part of the lamina, covering the foramen around the ENR. As spondylolisthesis progresses, these pathological bones may impact the ENR, especially in the narrowest position between the ENR and the top of the foramen. Furthermore, the accumulation of fibrocartilage and scar tissue around the isthmus fracture gap could occupy the space in the spinal canal and neural foramen, aggravating the spatial compression effect on the nerve. Therefore, a crucial step in PTELF involves the meticulous and alternating use of endoscopic bone knives and forceps to remove various kinds of bone spurs and scars, with a focus on carving around the ENR until the starting point of the ENR (the axillary epidural zone) is exposed. Among the observed cases, 15 involved DH, classified according to Kim's method,²⁸ with 11 being foraminal, three extraforaminal, and one posterolateral. Patients with this pathology typically experience severe RLP. Therefore, although leg pain may be partially relieved after bone decompression, a careful examination is crucial until the nerve roots move freely. Simply exposing the nerve roots is insufficient and may lead to overlooking certain areas of DH. In nine cases, the

main compression was attributed to LVE. As spondylolisthesis progresses and intervertebral disc height is lost, the anatomical structure of the foramen in late DLIS differs from that in typical FS cases. The LVE may become a pathological factor exacerbating FS rather than the SAP.²⁹ The ENR becomes sandwiched between the pedicle and the LVE. Therefore, removing the LVE and grinding off a portion of the upper pedicle is necessary to enlarge the space at the bottom and top of the ENR. This classification is based on the primary compression factors of nerve roots observed in the videos, acknowledging its subjective and inaccurate nature. However, it offers theoretical guidance for decompression, aiding the operator in better judging the endpoint of decompression by addressing each pathology individually and preventing the oversight of specific details.

Some scholars have documented successful cases of the interlaminar approach in treating patients with DLIS,^{6,24} deserving credit as it introduces alternative endoscopic treatment methods. However, based on our surgical experience, the transforaminal approach may be better suited for the unique pathology of DLIS, providing an optimal angle for comprehensive foramen and lateral decompression. Furthermore, the chronic accumulation of hyperplasia in patients with DLIS results in thicker vertebral lamina; the pathological changes of isthmus fractures and spondylolisthesis distort typical anatomical structures. These can potentially lead to intraoperative confusion for surgeons, and extensive osteotomy work may result in iatrogenic fractures or instability.¹²

Attention must be given to the potential risk of injuring the ENR while establishing the working channel. When DLIS occurs at the L5-S1 level with late spondylolisthesis above grade I, it frequently manifests as the narrowing of intervertebral space and foramen height. The invasion of bone drill may stimulate the ENR, causing patient discomfort. In such cases, the bone drill is not recommended to reach the midline of the posterior spine. When the patient's pain is unbearable, withdrawing the bone drill and directly placing the dilator and working channel for full-endoscopic foraminoplasty is recommended. Moreover, some patients may present a high iliac crest and large L5 transverse process, making it challenging to establish a working pathway. Our approach involves using a lumbar pad to open the intervertebral space and foramen, facilitating complete puncture. Familiar tools are employed during the surgical procedure to remove the bottom and ventral sides of the SAP selectively and the LVE as necessary to create an unrestricted workspace to minimize damage to the facet joint.

Our patients' average slip rate at the last follow-up ($18.8\% \pm 5.4\%$) showed no significant progression compared to preoperative measurements ($19.0\% \pm 5.3\%$). This finding implies that PTELF does not affect the short-term slip progression of DLIS, aligning with conclusions from other endoscopic studies.^{8,9} By avoiding excessive facet joint resection and laminectomy, the transforaminal approach enables the resection of pathological bone structures under endoscopy as needed and in a controlled manner. This approach allows for planned preservation of facet joints, suggesting that PTELF may not lead to significant iatrogenic postoperative spinal instability.

In this study, two patients experienced postoperative abnormalities, both with severe bony FS and nearly a decade-long history of leg pain. Given that they were early surgical patients, technical inexperience was hypothesized to have resulted in excessive operation, instrument squeezing, or stimulation when removing bone spurs around the nerve, leading to mild nerve edema.¹⁵ This hypothesis underscores the importance of maintaining a clear vision, mastering the appropriate visual angle for accurate operation, and minimizing unnecessary intraoperative procedures as much as possible. Another patient experienced recurrent ipsilateral radicular neuralgia in the fourth month after the procedure. Despite unsuccessful conservative treatment, endoscopic revision surgery was performed to enlarge and clean the periphery of nerve roots again. Considering the patient's physical work, fusion and pedicle screw fixation were performed. The recurrence was attributed to the patient working too early without proper lumbar support, highlighting the need to extend postoperative bed rest and ensure consistent use of waistline support to prevent recurrence. Furthermore, rehabilitation education and postoperative follow-up supervision for patients are crucial.

MIS-TLIF is a reliable minimally invasive decompression fusion technology, which can not only remove osteophyte and fibrous scar tissue in isthmus through minimally invasive channels, but also fix or correct the spondylolisthesis through screw implantation. It can effectively avoid the complications caused by traditional open surgery³⁰ and is favored by many orthopedic surgeons. Therefore, this technology should be given priority for patients with unstable DLIS. However, some patients may experience residual low back pain, adjacent segment degeneration, or positional cage migration after instrument implantation.^{31,32} In addition, MIS-TLIF is more invasive than transforaminal endoscopic

decompression and lacks direct nerve decompression.³³ Some recent studies have shown that additional fusion may not bring significant clinical improvement compared to using decompression alone, especially in the case of minimally invasive decompression.^{23,34} The choice of surgical method may depend on the patient's spinal stability, neurological function, primary medical needs, and overall health status. For patients with stable DLIS, which mainly presents with RLP, PTELF may be a more suitable technique for nerve root decompression and effective pain relief with minimal damage to muscles and small joints.

According to some authors^{7,35} and our experience, patients who meet the following criteria may get unsatisfactory surgical results and have a higher risk of postoperative instability, while fusion decompression may be a better choice: 1) dynamic translation > 3 mm on the flexibility-extension radiology of standing position or angular displacement > 10°; 2) significant lumbar degenerative scoliosis (Cobb angle greater than 20° in the coronal plane), kyphosis; 3) Meyerding Grade III or higher; 4) the main symptom is low back pain; 5) severe central canal stenosis. In our study, the primary indications of PTELF were single level stable DLIS patients who primarily exhibited RLP and did not meet the above criteria.

Individualized treatment is crucial for patients with DLIS. Spinal fusion may be premature for young patients, and employing PTELF as an intermediate surgical option before considering fusion is a reasonable and beneficial approach. For older patients presenting solely with RLP, it is essential to consider the necessity of fusion and hospitalization costs. Simple and minimally invasive PTELF may be a more favorable recommendation for this demographic. While this study has demonstrated numerous benefits associated with PTELF, it is crucial to acknowledge that its initial implementation gives patients a choice during the disease course and does not preclude the possibility of subsequent surgeries. In essence, PTELF serves as an effective complement to traditional DLIS decompression.

Considering the unique pathology of DLIS, the shortcomings of PTELF include a steep learning curve and challenging technical operations. The surgeon's skill level and the severity of the patient's condition determine the clinical success rate of PTELF. Therefore, it is recommended that this technique be gradually mastered by accumulating experience in endoscopic decompression for other degenerative diseases, such as lumbar spondylolisthesis. Initially, cases with mild spondylolisthesis and no significant reduction in the height of the foramen should be selected. Unilateral PTELF can alleviate ipsilateral FS, lateral recess stenosis, or bilateral ventral stenosis. However, for patients with severe bilateral symptoms, bilateral PTELF should be considered, even though it may prolong the operation time. Furthermore, fusion combined with percutaneous pedicle screw fixation for relative decompression of contralateral nerve roots is a viable option.³⁶

Several limitations characterize this study: 1) Strict inclusion criteria and a limited number of patients with stable DLIS result in a relatively small sample size and shorter follow-up duration. Extensive cases and long-term follow-up are imperative to validate the effectiveness of PTELF and monitor the stability of isthmic spondylolisthesis over an extended period. 2) Being a retrospective study without a control group, a prospective randomized trial or comparative cohort study is necessary to thoroughly assess the efficacy of PTELF in comparison to other endoscopic or open fusion surgeries for treating patients with DLIS.

Conclusion

For patients experiencing stable DLIS accompanied by RLP, PTELF technology emerges as a safe and minimally invasive alternative. However, continuous vigilance for potential risks is warranted, necessitating long-term follow-up and attention to monitor lumbar stability changes and overall outcomes.

Abbreviations

RLP, radicular leg pain; PTELF, percutaneous transforaminal endoscopic lumbar foraminotomy; CT, computed tomography; MRI, magnetic resonance imaging; VAS, visual analog scale; ODI, Oswestry Disability Index; LF, ligamentum flavum; SAP, superior articular process; DLIS, degenerative lumbar isthmic spondylolisthesis; LVE, lower vertebral endplate; DH, disc herniation; FS, foraminal stenosis; ENR, exiting nerve root; TNR, traversing nerve root; ELF, endoscopic lumbar foraminotomy.

Data Sharing Statement

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy reasons.

Ethics Approval and Informed Consent

The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of Chengde Medical University Affiliated Hospital (protocol code CYFYLL2023238, approval date 18 April 2023). All patients included in the study signed written informed consent.

Consent for Publication

All authors have confirmed that the details of any images, videos, recordings, etc can be published, and that the person(s) providing consent have been shown the article contents to be published.

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Disclosure

The authors declare no conflicts of interest in this work.

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