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Endoscopic spine surgery: New concepts and advancements

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Endoscopic spine surgery: New concepts and advancements

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Editorial: Endoscopic spine surgery

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Editorial on the Research Topic
Endoscopic spine surgery

Endoscopic surgery has been widely accepted in the whole surgical field, as well as in the field of spinal surgery. The characteristic of endoscopic surgery is to puts the camera eye in the target area for close observation and projects the magnified high-definition image onto the screen. The surgeons look at the screen and perform the operation under the "indirect" visualization, which needs the training of hand-eye coordination. This feature is different from traditional surgery through loupe magnification or microscopic magnification (1). However, more and more surgeons, encouraged by the incomparable high-definition images, have devoted themselves to endoscopic surgery. I would like to make an analogy that an excellent endoscopic surgeon is like a master who is directing a high-definition blockbuster movie in the operating room.

Endoscopic spine surgery was initially used for lumbar disc lesions (2). However, it has evolved dramatically in recent years with the rapid development of endoscopic armamentaria and technological innovations, as well as a better understanding of endoscopic anatomy and approaches. As a result, the indications of endoscopic spine surgery are ever-expanding, from the initial lumbar disc degeneration to other types of pathologies located from craniovertebral junction to sacral vertebrae (3, 4).

In this research topic of Frontiers in Surgery, in the field of percutaneous single-channel endoscopic spine surgery, some attempts and efforts have been made to solve different pathologies. Ye et al. reported that they decompressed the medulla oblongata successfully using full-endoscopic uniportal retropharyngeal odontoidectomy (https://doi:%2010.3389/fsurg.2022.973064). There have been several papers focusing on this technique since Rutten first reported it in 2018 (5–7). As we all know, craniocervical junction pathologies are complex and challenging. In recent years, with the rapid development of posterior internal fixation and reduction technology, some patients do not need to undergo anterior odontoidectomy (8, 9). Therefore, the role of this technique in the whole treatment strategy to the craniocervical junction pathologies should be carefully considered and evaluated. Yu et al. reported a case with lumbar spinal epidural lipomatosis (SEL) who was treated with a percutaneous full-endoscopic uniportal decompression surgery successfully (https://doi.org/10.3389/

fsurg.2022.894662). Percutaneous endoscopic surgery provides another option for SEL which has similar clinical symptoms to lumbar spinal stenosis. In addition, in terms of lumbar degenerative pathologies, Ahn et al. described a new surgical technique of endoscopic lumbar foraminotomy (ELF) for radiculopathy due to foraminal stenosis in patients with stable advanced spondylolisthesis, which the exiting nerve root be decompressed by resecting upper pedicle, lower vertebral endplates and SAP (https://doi.org/10.3389/fsurg.2022.1042184). This is a challenging technique, and the authors have obtained good results. It will be of interest to the readership of our topic research because of innovative thinking and technology, although there are some limitations such as lack of the control group, without long time follow-up and relative high complication rate.

Altogether twenty-two papers have been accepted due to its highlights in this topic research. It is worth noting that the number of papers focusing on Unilateral Biportal Endoscopy (UBE) technology is increasing. UBE technology has better freedom and compatibility with traditional surgery due to the separation of operation channel and observation channel. Some techniques are very interesting. Zhu et al. introduced a novel suture anchor techniques for cervical laminoplasty using UBE (https://doi.org/10.3389/fsurg.2022.913456), which shows in this "endoscopic dream factory" where everything is possible, even beyond all imagination. Of course, if a kind of technique can be popularized, it also needs other necessary conditions, such as definite safety, effectiveness, easy to learn and convenient tools.

Whether uniportal or biportal, literatures on endoscopic lumbar interbody fusion have grown tremendously in the last several years (10–12). Not surprisingly, the same is true of our research topic. there were five articles discussing this issue. This phenomenon indicates that the interest of endoscopic spine surgeons seems to have transited from simple decompression to further fusion after 20 years of full development. Lin et al. retrospectively compared the surgical outcomes between percutaneous endoscopic lumbar interbody fusion (PE-LIF) and minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) for the treatment of lumbar spinal stenosis. They concluded that both PE-LIF and MIS-TLIF are safe and effective for LSS. PE-LIF has a definite short-term curative effect with less trauma (https://doi.org/10.3389/fsurg.2022.916087). Endoscopic LIF may be the preferred options for select patients, such as the elderly. Techniques and instruments for endoscopic LIF have evolved over the past decade, leading to clinical and radiologic outcomes have improved, with particular benefits seen within ERAS pathways. However, just like any new technology, spine surgeons should be aware of the learning curve necessary before achieving operative mastery to minimize unique complications that can occur. At the same time, the fusion rate under water irrigation environment seems to need more convincing evidence.

Although endoscopic spine surgery has abundant merits that need not be detailed here, some obstacles make the learning curve steep and the surgical outcome is strongly dependent on the surgeon's practice of personal cultivation. These obstacles include confusing anatomical orientation, difficult to manipulate in a narrow space and so on. As a result, grafting new technologies such as navigation or robotics into endoscopic spine surgery has emerged (13). Ye et al. reported two cases of successfully treated lumber pyogenic spondylodiscitis using Da Vinci robot-assisted laparoscopic retroperitoneal approach (https://doi.org/10.3389/fsurg.2022.930536). The robot system provides high-definition images of three-dimensional vision and endo-wrist of the robot exceeds the limit of human hands which can perform precise movements continuously without fatigue and error during the procedure. There is no doubt that in the future, more new technologies, such as robots and intelligent navigation, will be integrated into endoscopic spinal surgery, which can bring revolutionary changes to spinal surgery.

Author contributions

YY, Z-ZL and YN have made equal contributions to this article. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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CASE REPORT
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Unilateral Biportal Endoscopic Tumor Removal and Percutaneous Stabilization for Extradural Tumors: Technical Case Report and Literature Review

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Background: Extradural spinal tumors arise from soft or bony tissues in the spine and account for majority of spinal tumors. Interest in the unilateral biportal endoscopic (UBE) technique is rising, because it can easily decompress the bony spinal canal and accommodate all open surgical instruments under endoscopic guidance. However, reports of this technique have been limited to certain diseases. This study first demonstrates the UBE technique for extradural tumor biopsy and removal, and percutaneous stabilization in a 72-year-old female patient with dramatic symptom improvement.

Methods: We used the UBE technique for decompression and the percutaneous screw fixation technique for stabilization in a patient with an extradural mass compressing the thecal sac and destroying the posterior element. Under endoscopic guidance, a unilateral approach was used, and decompression and flavectomy were performed bilaterally. After decompression, tumor removal and biopsy were performed using various forceps and biopsy needles. After confirming sufficient spinal canal decompression, the screw was placed percutaneously. We evaluated the technical process of the procedure, the patient's pre- and postoperative pain (using the visual analog scale), and operative radiology and pathologic results.

Results: Postoperative pain and disability improved clinically, and spinal alignment stabilized radiologically. As the pathology findings confirmed an aneurysmal bone cyst, the treatment was completed without adjuvant therapy.

Conclusions: We treated an unstable spine due to an extradural tumor with the UBE and percutaneous screw techniques.

Keywords: biportal endoscopic spine surgery, endoscopic spine surgery, spinal cord tumor, tumor biopsy, unilateral biportal endoscopy

INTRODUCTION

Extradural spinal tumors arise from soft or bony tissues in the spine, and account for 60% of all spinal tumors (1). Extradural tumors can cause clinical symptoms related to axial destruction of the bony structure, as well as myelopathy and radiculopathy caused by spinal cord and nerve compression (2). To manage this disease entity, physicians should achieve three goals for diagnosis and treatment: pathologic confirmation, neural decompression, and structural reconstruction (3). With the development of endoscopic techniques and instruments, interest in the unilateral biportal endoscopic (UBE) technique is also growing, because it can easily decompress the bony spinal canal and accommodate all open surgical instruments under endoscopic guidance. However, indications and reports of this technique have been limited to degenerative (4) and infectious diseases (5). In this technical note, we describe a step-by-step procedure of how we biopsied the affected tissue and performed tumor removal, spinal canal decompression, and stabilization using the UBE and percutaneous screw placement techniques in a 72-year-old female patient with dramatic symptom improvement.

MATERIALS AND METHODS

Ethics Statement and Case Presentation

We obtained study approval from our institutional review board (approval no.: UHS-HERC-051-10032022), and written consent was obtained from the patient for publication of the report and any accompanying images. The 72-year-old woman visited the outpatient clinic for progressive leg weakness and back pain for the past 3 years. Her back pain was scored as five according to the visual analog scale (VAS), and pain radiating from the buttock to leg was scored as seven on both sides. Bilateral front thigh numbness had started 3 months prior. The patient's knee jerk was 3+, and the hip motor power of both legs decreased subjectively to a grade of four. Preoperative magnetic resonance imaging showed a vertebral body mass with retropulsion into the spinal canal (**Figure 1A**) and bilateral spinal canal compression caused by an extradural mass (**Figure 1B**). A homogeneous solitary mass, suspected to be a primary extradural tumor, was noted on radiology. The middle and posterior columns involved the facet and spinous processes. Chest and abdominopelvic computed tomography findings were normal, and blood tumor markers were negative. The Tomita morphological classification (6) was type 4 (extra-compartmental extradural tumor), and the spine instability neoplastic score (7) was 14 (junctional lesion with pain, lysis, bilateral bone collapse, and kyphosis on radiology), indicating an unstable spine. Preoperative radiographs showed decreased vertebral height (**Figure 1C**) and heterogeneous bone density (**Figure 1D**). Before the procedure, we explained the possibility of secondary tumor removal if pathology results showed malignancy.

Abbreviations: H & E, hematoxylin and eosin; UBE, unilateral biportal endoscopic; VAS, visual analog scale.

Procedure

Position and Instruments

Under general anesthesia, the patient was placed on the spine table (**Supplementary Video 1**). A surgical drape was placed aseptically, covering the area from the lower thoracic spine to the lumbar spine in a water-tight fashion. For zero-degree endoscopy, a high-definition imaging system, a 3,000-cc sodium chloride irrigation system, and a standard laminectomy set were used (**Figure 2A**). After the T12–L1 interlaminar space was identified, a scope portal was placed into the interlaminar space cranially, and an instrumental portal was placed caudally (**Figure 2B**).

Unilateral Approach and Bilateral Decompression

Using a radiofrequency coagulator, we identified the lower end of the upper lamina and interlaminar space as

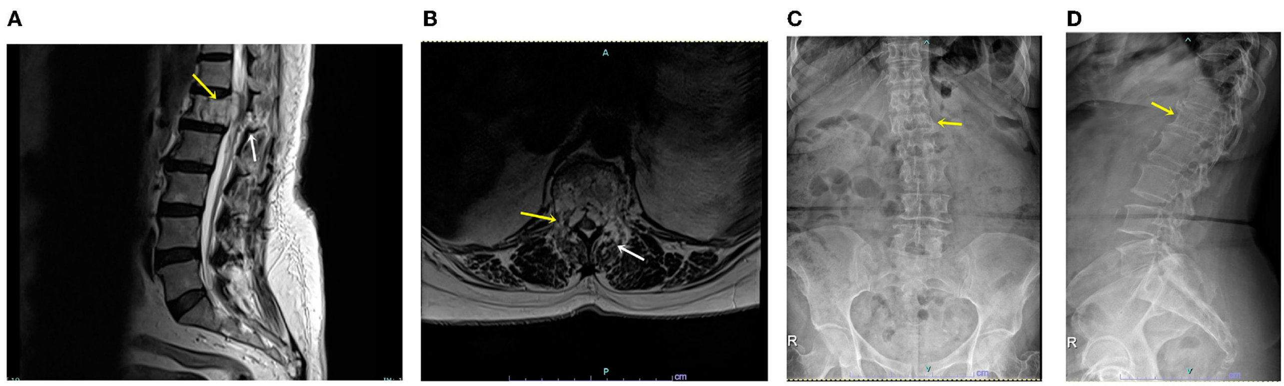

FIGURE 1 | (A) Sagittal T2-weighted magnetic resonance image showing a lytic mass (yellow arrow) with spinal canal and posterior involvement (white arrow). **(B)** Axial T2-weighted magnetic resonance image showing the vertebral body, pedicle, and spinal mass (yellow arrow), as well as facet and laminar-mass extension (white arrow). **(C)** Plain anteroposterior radiograph showing decreased vertebral body height (yellow arrow). **(D)** Plain lateral radiograph showing heterogeneous density and decreased vertebral body height (yellow arrow).

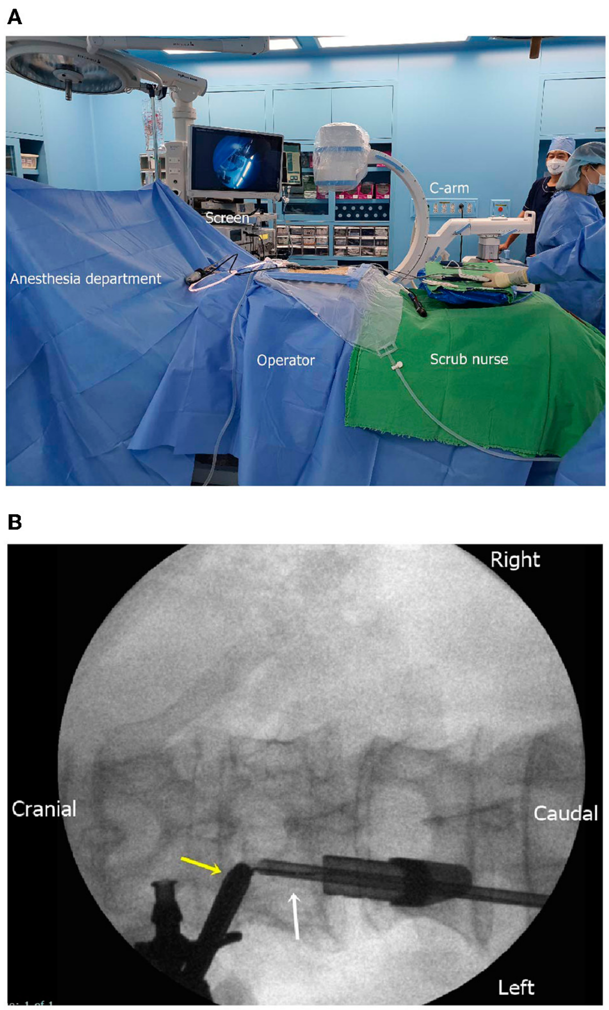

FIGURE 2 | (A) Intraoperative setting for biportal endoscopic surgery of the extradural tumor. The C-arm, monitor, continuous irrigation system, and aseptic dressing are prepared. **(B)** Intraoperative fluoroscopic placement of the endoscope (yellow arrow) and instrument (white arrow).

landmarks for laminectomy (**Figure 3A**). Laminectomy was performed using an automated drill (**Figure 3B**), and bilateral flavectomy was performed using pituitary forceps and Kerrison punches (**Figure 3C**). After bilateral interlaminar decompression was performed, the thecal sac and extradural mass under the pedicle were identified (**Figure 3D**).

Tumor Biopsy and Removal

We performed needle biopsy under endoscopic guidance (**Figures 3E,F**). The depth and location of the tumor were confirmed by fluoroscopy, and a tissue was obtained (**Figure 3G**). The tumor mass was removed with pituitary forceps and a curette (**Figure 3H**), and it was suspected that hemostasis was required. Bilateral thecal sac decompression was performed after tumor removal and bleeding control (**Figure 3I**).

Percutaneous Screw Fixation

Using a previous endoscopic incision, an instrumental portal, and additional incisions, percutaneous pedicle screws were inserted into T11, T12, L2, and L3 using a percutaneous screw system (CD Horizon Solera Voyager Spinal System; Medtronic, Memphis, TN, United States). After bilateral screw placement, the rod was connected bilaterally (**Figures 4A,B**). A drainage bag was inserted into the tumor removal site, and the skin was sutured with 3-0 nylon (**Figure 4C**). After all procedures were completed, radiography was performed to confirm stabilization (**Figure 4D**). Postoperatively, pain was managed with acetaminophen (100 mg, thrice daily, intravenous), and third-generation cephalosporin antibiotics were administered for 3 days.

RESULTS

After the surgery, imaging showed that the thecal sac was decompressed bilaterally (**Figure 5A**), and that the retropulsed tumor was subtotally removed (**Figure 5B**). The patient's bilateral leg numbness improved to a VAS score of 1, and weakness improved on postoperative day 1. The biopsy results showed chondroid material with a blood clot, and the final diagnosis was aneurysmal bone cyst (**Figures 5C,D**). Following the oncologist's opinion, treatment was completed without adjuvant radiotherapy or chemotherapy. Follow-up radiographs were obtained after 1, 3, 6, and 12 months, and computed tomography (**Figure 5E**) and magnetic resonance imaging were performed 12 months postoperatively. At the 12-month follow-up, the tumor had not recurred, the spinal alignment was stable, and the patient was asymptomatic.

DISCUSSION

To the best of our knowledge, this study was the first to apply the UBE and percutaneous screw fixation techniques for extradural tumor treatment. Our goals were pathologic confirmation, spinal cord decompression, and stabilization of the spinal column; all of which were achieved. The patient was satisfied with her dramatically improved clinical symptoms.

A solitary spinal mass with or without symptoms is usually suspected as a primary spinal tumor or metastasis from another organ. Primary non-lymphoproliferative spinal tumors account for <5% of all bony tumors; therefore, spinal metastases are more frequent [60% of all spinal tumors (8)] than primary masses. However, pathologic confirmation is necessary for a solitary mass in the spine without symptoms related to other organs, and surgical treatment should be chosen based on clinical and radiologic findings.

Fine-needle biopsy is recommended for pathologic confirmation when diagnosing a solitary spinal mass without instability (9). However, for a symptomatic spinal canal mass, treatment should be based on clinical symptoms and radiologic instability. For a solitary mass with possible malignancy, total

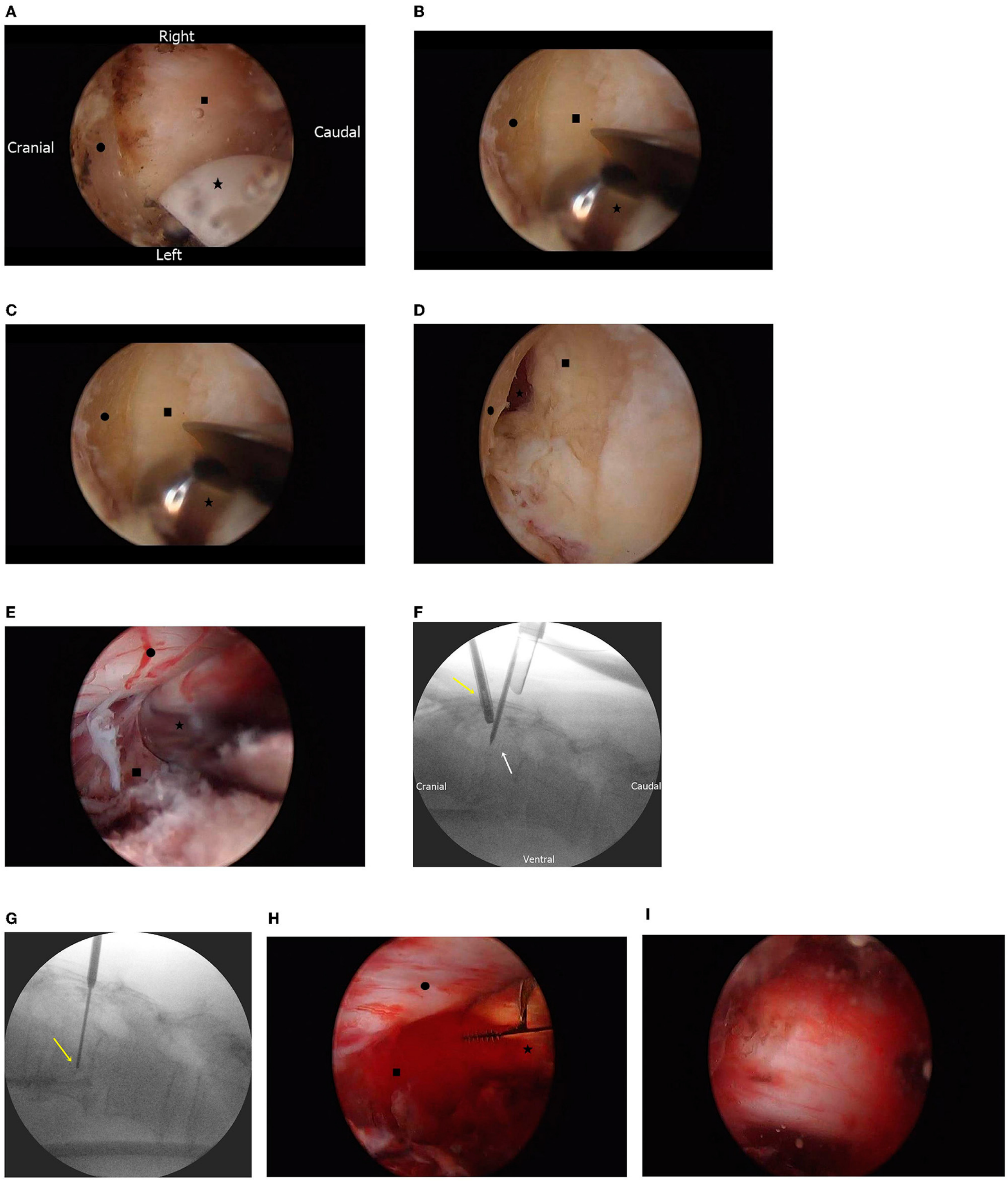

FIGURE 3 | (A) Endoscopic findings of the prepared working space. The lower border of the lamina (•) and interlaminar space (■) are identified using the radiofrequency electrode (★). **(B)** Endoscopic findings of laminectomy. The upper lamina (•) and ligamentum flavum (■) are identified, and bone is drilled with an automated drill (★). **(C)** Endoscopic findings of flavectomy. Under the middle of the partially removed lamina (•), both the ligamentum flava (■) and epidural space are identified (★) under the top of the ligamentum flavum. **(D)** Endoscopic findings after removal of the ligamentum flavum. Under the thecal sac and nerve root (•), the hypervascular mass is identified (■). **(E)** Endoscopic-guided needle biopsy. By needle biopsy (★), the tumor (■) tissue is obtained without causing nerve injury (•).

(Continued)

FIGURE 3 | (F) Fluoroscopic image of the endoscopic-guided tumor biopsy. Under endoscopic guidance (yellow arrow), the biopsy needle is inserted (white arrow). **(G)** Fluoroscopic image of the needle biopsy. The biopsy needle (yellow arrow) is adjusted; the amount of tissue obtained is dependent on vertebral body depth. **(H)** Endoscopic finding of tumor removal with an instrument. The vascular mass (■) is removed with pituitary forceps (★) without causing nerve injury (•). **(I)** After tumor removal and bilateral decompression, the spine is decompressed and pulsated.

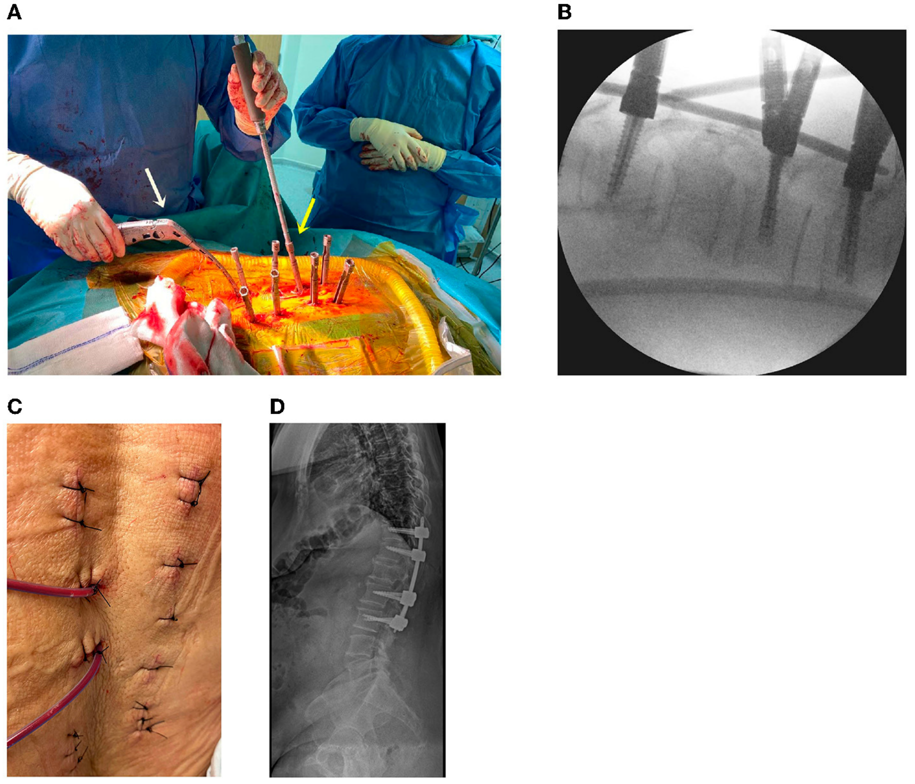

FIGURE 4 | (A) Operative setting using the percutaneous screw fixation procedure. Screw capping (yellow arrow) and rod placement (white arrow) are performed. **(B)** Intraoperative fluoroscopy for screw and rod application. **(C)** The skin is sutured after the surgery. **(D)** Plain radiograph after the surgery.

removal with *en bloc* resection is recommended (10). Because of the invasiveness of this operation, other surgical options such as subtotal resection, intracystic injection, and embolization are recommended in cases of benign pathology, especially for aneurysmal bone cysts (11). Intracystic injection and embolization cannot decompress the spinal canal and may lead to leakage, and symptoms can consequently worsen. Therefore, less invasive procedures with spinal decompression should be pursued for benign masses involving the spinal canal.

The literature on the biportal technique is still limited to treatments for degenerative disease entities, including spinal stenosis decompression, herniated disc removal, and interbody fusion for instability (12). The advantages of the biportal technique compared with other techniques include shorter hospital stay and less postoperative back pain based on preservation of the back muscle (13). This technique has strengths in bilateral decompressive laminotomy and flavectomy, because free movement of the scope is easy and possible on the contralateral side of the thecal sac. Compared with the uniportal technique, the biportal technique allows for insertion of various surgical instruments without limitations of the cannula, and bone and tissue removal is easy. With extradural tumors, the UBE technique allows for decompression of the spinal canal with various surgical instruments and safe removal of a tumor by utilizing a high-definition imaging system.

Percutaneous screw stabilization for metastatic spinal tumors involves a short operative time, minor intraoperative bleeding, and a short hospital stay (14). Without muscle dissection, accurate placement of the pedicular screw is possible with a small incision. A recent system can insert rods without needing additional incisions; therefore, this technique has become easier. Placement is not limited to tumors and areas of trauma in degenerative spinal diseases (15). Extradural tumors or trauma injuries with spinal cord compression are possible indications for this procedure. Hospital stay was only 2 days with both endoscopic techniques, and postoperative opioids were not administered. Accordingly, medical costs can also decrease. However, there are reports of percutaneous screw fixation without fusion material showing low fusion rate compared with the fusion technique (16). Therefore, indications for percutaneous screw fixation should be considered elderly and short level involvement only (17).

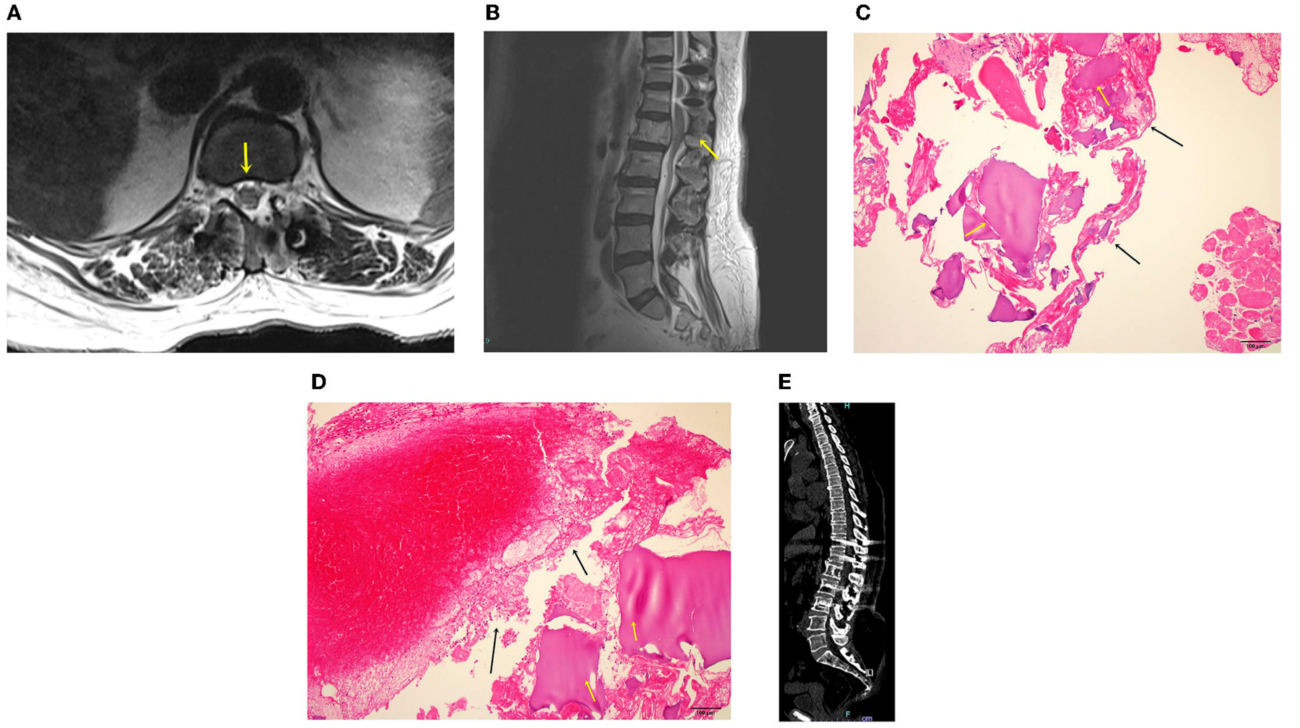

FIGURE 5 | (A) Magnetic resonance image after bilateral decompression. Spinal canal widening is complete, and the thecal sac is decompressed (yellow arrow). **(B)** Sagittal magnetic resonance image after the procedure. The spinal canal is decompressed, and the screw is placed. **(C)** Hematoxylin and eosin (H & E) staining of the surgical biopsy specimen. A chondroid material (black arrows) and a blood clot (yellow arrows) are identified. **(D)** H & E staining of the surgical biopsy specimen. The chondroid material (black arrows) and blood clot (yellow arrows) are shown. The 12-month postoperative computed tomography showed no more extension and removed tumor **(E)**.

There are certain points that surgeons should consider. The incision should be wider than that in degenerative surgery. The authors recommend that each hole be 1 cm and that the rod insertion site be at least 2 cm. A relatively larger incision can help surgeons identify bleeding and allow for more efficient tumor removal and screw and rod insertion. Unclear vision can prolong the operation time and water retention in the soft tissue. If bleeding occurs during the procedure, bone bleeding should be controlled using an RF coagulator or bone wax. If bleeding focus is not clear, prothrombin hemostatic matrix and compression are useful options for solving the problem (18).

Our technique has some limitations in terms of its broader application. First, a mass suspected to be malignant in radiology should be totally removed. Second, the endoscopic technique cannot expose a wide range like the microscopic technique, and tissues can be lost due to continuous water irrigation. More case evaluations involving this technique are needed, even with its limited indications. Additionally, prospective, multicenter case studies are essential for evaluating outcomes associated with this technique. With the continuous development of new techniques and comparisons with other techniques, it is necessary to evaluate outcomes further.

In conclusion, we described a biportal technique for spinal canal decompression, tumor removal, and biopsy, as well as a percutaneous stabilization technique. With the development of instruments and surgical techniques, our combined technique will play a role in spinal oncology.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary material**, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University Hospital Sharjah Institutional Review Board. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

S-kK: conceptualization, resources, writing (original draft preparation), writing (review and editing), visualization, and project administration. H-aK: methodology. E-jH: software and investigation. RB, S-kK, and S-cL: validation. MA: formal analysis. S-cL: data curation and supervision. All authors have read and agreed to the published version of the manuscript. All authors contributed to the article and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsurg.2022.863931/full#supplementary-material

Supplementary Video 1 | The entire operative procedure including endoscopic tumor removal, tumor biopsy, and percutaneous screw fixation.

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Learning Curve and Initial Outcomes of Full-Endoscopic Posterior Lumbar Interbody Fusion

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Study Design: This was a retrospective cohort study.

Objective: We evaluated the feasibility, safety, and accuracy of full-endoscopic posterior lumbar interbody fusion (FE-PLIF) by assessing the learning curve and initial clinical outcomes.

Summary of Background Data: Low back pain is one of the crucial medical conditions worldwide. FE-PLIF has been reported to be a minimally invasive method to treat mechanical low back pain, but there lacks a thorough evaluation on this new technique.

Methods: The patients were divided into three groups in the order of operating date, implying that Group A consisted of the initial 12 cases, Group B the subsequent 12 cases, and Group C the last 12 cases. The data of patients were reviewed for gender, age, preoperative symptoms, satisfaction, as well as clinical outcomes demonstrated by visual analog scale (VAS). The operative time and intraoperative fluoroscopy were recorded to demonstrate the learning curve and the extent of radiographic exposure. Statistical significance was set at a $p < 0.05$ (two-sided).

Results: The patients enrolled in this study were followed up at an average of 1.41 ± 0.24 years. Overall, patients were satisfied with the surgery. The average number of intraoperative fluoroscopy was 6.97 ± 0.74. A significant improvement was observed in the VAS of both lumbar pain and leg pain. The overall fusion rate was 77.7%. Complications were reported in two patients in Group A, one in Group B, and none in Group C. The average operative time showed a trend of gradual decline. The learning curve was characterized using a cubic regression analysis as $y = -27.07x + 1.42x^2 - 0.24x^3 + 521.84$ ($R^2 = 0.617$, $p = 0.000$).

Conclusions: FE-PLIF is an effective and safe method for treating low back pain caused by short-segmental degenerative diseases. The learning curve of this technique is steep at the initial stage but acceptable and shows great potential for improvement.

Keywords: full-endoscopic, posterior approach, interbody fusion, minimally invasive surgery, learning curve

INTRODUCTION

Low back pain is one of the crucial medical problems worldwide, especially in low- and middle-income countries that lack enough resources to treat it (1). Mechanical lower back pain intrinsically arises from changes in human body structures such as the spine, intervertebral disc, and the surrounding soft tissue (2). In the case of ineffective conservative treatment, the mainstay treatment of mechanical lower back pain caused by degenerative lumbar diseases involves lumbar discectomy together with interbody fusion. Posterior lumbar interbody fusion (PLIF) has been widely used for significantly reducing the pain, restoring sagittal profile, decreasing complications, as well as gaining good fusion rates and long-term stability (3–5). However, conventional open posterior surgery is associated with the risk of nerve root injury and dural tear, as well as longer operation time, more blood loss, and extensive scar formation within the spinal canal (6). Therefore, several new techniques have been developed to achieve better clinical outcomes, easier process and less trauma.

The past few years have witnessed a trend toward minimally invasive, accurate, and intelligent procedures for the surgical therapy of low back pain caused by degenerative lumbar diseases. As a minimally invasive surgery, the newly reported technique of full-endoscopic posterior lumbar interbody fusion (FE-PLIF) has been recognized as a safe and reliable method for its clear visualization and minimal damage as it uses a rigid rod-shaped endoscope, which integrates the working channel together with lighting, camera and irrigation system (7). In addition, good decompression and accurate intervertebral cage insertion are obtained with the assistance of the endoscope. The percutaneous pedicle screw implantation provides local stability similar to that endowed by traditional procedures. However, full-endoscopic surgery requires effective hand-eye cooperation and identification of under-endoscopic anatomic structures that may lead to a steep learning curve, limiting its applications (8). In this study, we systematically evaluated the learning curve of FE-PLIF and reported the initial clinical outcomes together with our preliminary experience to further provide a thorough assessment of the safety, accuracy, and feasibility of FE-PLIF.

MATERIALS AND METHODS

Patients

The study retrospectively enrolled the first 36 patients who underwent FE-PLIF surgery consecutively in our hospital. The diagnosis was confirmed by two clinical professors based on a combination of clinical symptoms and imaging evidence including X-ray, computed tomography (CT), and magnetic resonance imaging (MRI). The patients were divided into three groups in the order of operation date, implying that Group A consisted of the initial 12 cases, Group B the subsequent 12 cases, and Group C the last 12 cases. The operations were performed by two fellowship-trained spine surgeons. The clinical demographic features and radiographic features of the patients are shown in **Tables 1, 2**.

The inclusion criteria were (1) discogenic low back pain, (2) single or double segmental degenerative lumbar stenosis mainly caused by lumbar disc herniation, facet joint hyperplasia, or hypertrophy of the ligamentum flavum, (3) degenerative lumbar spondylolisthesis up to Grade I according to the Meyerding standard, and (4) other single or double segmental degenerative lumbar diseases requiring stability and fusion. The exclusion criteria of this study were (1) the presence of a significant spinal deformity, (2) developmental or multi-segmental (over two) lumbar spinal stenosis, (3) severe spondylolisthesis hard to restore without an open procedure, (4) unclear location of the responsible segment or imaging data inconsistent with the patient's symptoms, and (5) intolerance to FE-PLIF for other reasons such as severe cardiopulmonary disease and previous lumbar surgery.

Surgical Technique

All patients enrolled in our study were operated on using the iLESSYS Delta Endoscopic System (Joimax GmbH, Karlsruhe, Germany) for visualization. Under general anesthesia and neuromonitoring, the patient was placed in the prone position on a radiolucent table with the abdominal suspension to reduce abdominal pressure and therefore decrease bleeding. Routine disinfection, sterile towel sheet spread, and incision protective film affixation were performed. After confirming the surgical position and angle by "C-arm" (**Figure 1A**), a longitudinal incision of about 1.2 cm in length was made above the responsible segment with a No. 11 blade. Serial dilators were advanced step-by-step until palpating the lamina. A working cannula with an outer diameter of 13.7 mm and an inner diameter of 10.2 mm was inserted through the dilator. Next, the dilaters were removed, and the "C-arm" fluoroscopy was performed to confirm the location of the cannula.

TABLE 1 | Clinical demographic data of three groups that underwent FE-PLIF.

Parameters	Group A	Group B	Group C	*p* value
Sex ratio (female/male)	6/6	6/6	7/5	0.895
Age (years, mean ± SD)	50.92 ± 11.16*	49.42 ± 9.08	50.00 ± 7.26	0.528
Duration of symptoms (days, mean ± SD)	78.83 ± 34.92	75.00 ± 49.41	92.50 ± 42.88	0.580

TABLE 2 | Clinical radiographic data of three groups that underwent FE-PLIF.

Variable	Group A	Group B	Group C
L4/5 disc herniation	6	5	4
L5/S1 disc herniation	2	5	5
L4/5 spinal canal stenosis	3	1	1
L4/5 spondylolisthesis	–	–	1
L5/S1 spondylolisthesis	1	1	1

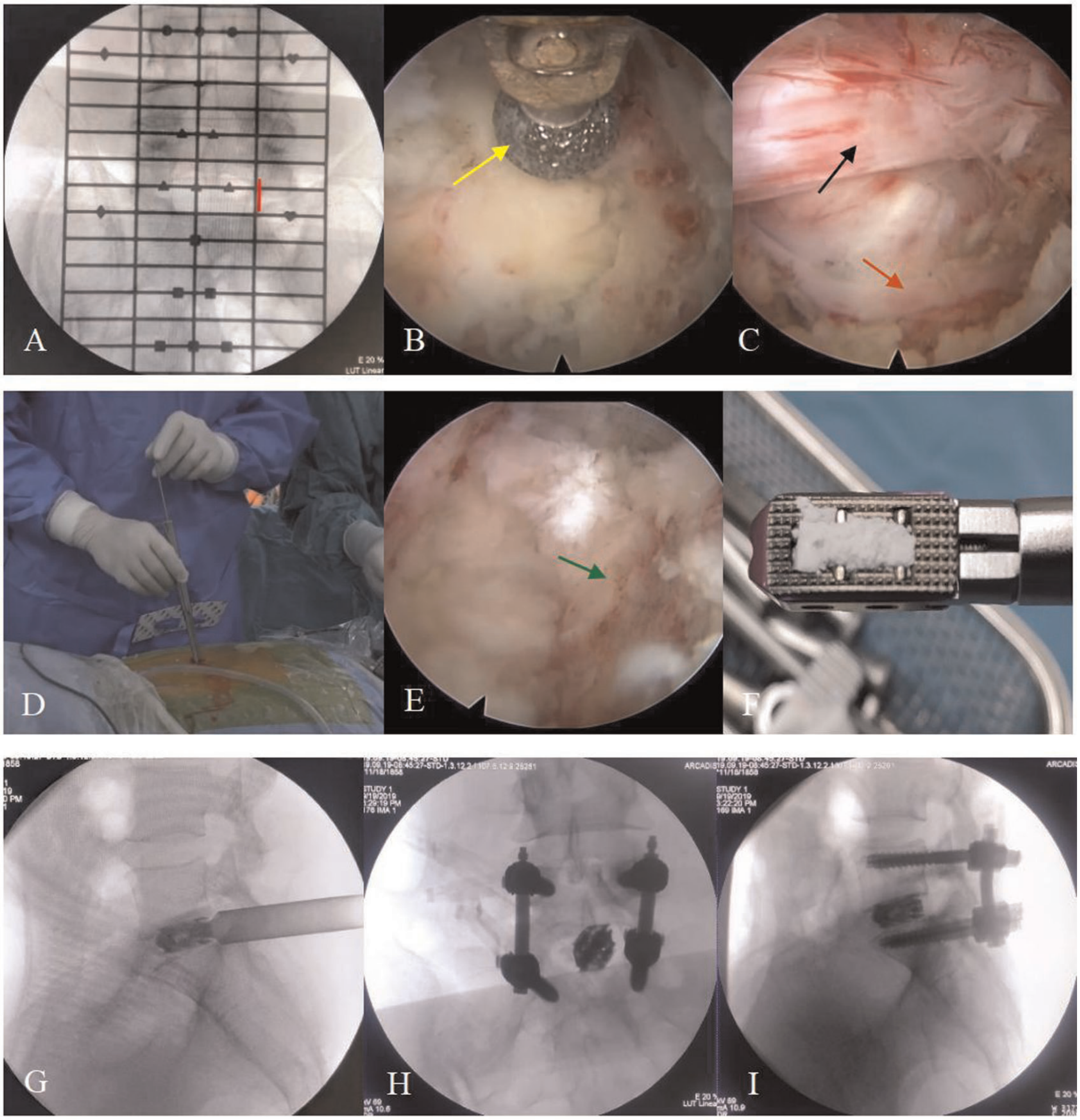

FIGURE 1 | The surgical steps. (**A**) The positioning device is used to identify the responsible segment and decide the location of the incision (red line). (**B**) The articular process (yellow arrow) is polished by endoscopic burrs. (**C**) The vessel (red arrow) and nerve root (black arrow) are exposed before entering into the spinal canal. (**D**) The working channel is replaced before placing the expandable cage. (**E**) The cartilaginous endplate is removed and the bony endplate (green arrow) is exposed. (**F**) The cage is grafted with the bone before implantation. (**G–I**) The position of the cage and percutaneous pedicle screws is confirmed by "C-arm" fluoroscopy when placed.

Afterward, an endoscopic system with an irrigating channel, which had an outer diameter of 10 mm, an inner diameter of 6 mm and a view angle of 15-degree, was connected and placed into the working cannula. The ipsilateral laminectomy, removal of the ligamentum flavum and medial facetectomy were performed by endoscopic burrs, Kerrison punches and osteotomes (**Figure 1B**), and the nerve root inside the spinal canal was exposed layer by layer during this process (**Figure 1C**). With the nerve root carefully protected, a standard full-endoscopic discectomy was performed using endoscopic forceps.

The working channel was then replaced by a dedicated fork-shaped cannula with an inner diameter of 11.5 mm (**Figure 1D**) for cage implantation. The intervertebral space was further treated with serial reamers, curettes, and rasps until the cartilage endplate was completely peeled off and the bony endplate was entirely exposed for better fusion. Harvested local bones from laminectomy and arthrotomy performed earlier were inserted into the anterior disc space, and an expandable titanium cage (Shanghai Reach Medical Instrument Co., Ltd., Shanghai, China) was placed into the intervertebral space along the working channel. Its location was confirmed by "C-arm" fluoroscopy. The cage location, nerve root relaxation, residual nucleus tissue, and active bleeding inside and outside the spinal canal were rechecked under the endoscopic view. Next, the endoscope and working channel were withdrawn. Bilateral percutaneous pedicle screws and connecting rods with appropriate length were placed on the upper and lower vertebral bodies and fixed (Zina; Sanyou, Shanghai, China). If the patient was diagnosed with lumbar spondylolisthesis, the reduction was required simultaneously. The "C-arm" fluoroscopy was performed again to confirm the position of the internal fixation device. Next, the incision was sutured layer by layer. No drainage was required.

Outcome Measures

We used VAS which rages from 0 to 10 to evaluate the pre- and post-operative clinical results. Operative time, blood loss, times of intraoperative X-ray fluoroscopy, length of hospital stay, complications, and rate of conversion to an open procedure were recorded. The satisfaction of patients was scored using the Macnab criteria. The fusion rates were evaluated by using Bridwell's fusion grading system on computer tomography scans or radiographs at the last follow-up. All radiographs in this study were assessed by two independent researchers. Through the discussion with another independent expert, different opinions on fusion healing were reconciled and reached a consensus.

Statistical Analysis

SPSS version 22.0 (SPSS 109 Inc., Chicago, IL) was used to conduct statistical analysis. The data were analyzed using independent sample *t*-test, paired *t*-test, chi-square test, one-way analysis of variance, and regression analysis. Statistical significance was set at a $p < 0.05$ (two-sided).

RESULTS

Clinical Outcomes

All of the 36 patients enrolled in this study had undergone FE-PLIF between 2019 and 2021. The radiological measurement data revealed 27 cases of lumbar disc herniation, 5 cases of lumbar spinal canal stenosis, and 4 cases of lumbar spondylolisthesis. All patients underwent FE-PLIF successfully without conversion to open surgery. The blood loss was less than 70 mL in all patients; one patient required postoperative drainage in Group A due to intraoperative dural tear. The average number of intraoperative fluoroscopy performed was 6.97 ± 0.74. The patients enrolled in this study were followed up at an average of 1.41 ± 0.24 years (range: 1–2 years). The majority of patients had immediate relief in pain and dysesthesia. The incidence of complications was 8.3%. One case of dural tear and one case of incomplete reduction requiring open-access revision after 3-month follow-up in group A, one case of postoperative nerve root symptom in group B, and no complications in group C were reported. Patient satisfaction measured using the Macnab criteria showed the surgical outcomes were excellent in 27 (75%) patients, good in 8 (22.2%) patients, and fair in 1 (2.7%) patient with no poor assessment. There was no recurrence of clinical symptoms until the final follow-up (**Figures 2** and **3**).

The quantified clinical outcomes are shown in **Table 3**, **Figure 4A**,**B**. In Group A, the average postoperative hospitalization stay was 5.62 ± 1.69 days (range: 3–9 days). Case 1 stayed in the hospital after surgery for an especially longer duration than other patients because the complete observation was needed for the first case to ensure safety. The hospitalization duration of Case 5 was extended for the removal of the drainage tube and the recovery of dural tear. A significant improvement in the VAS of lumbar pain at day 1 after the surgery was recorded compared with preoperative VAS ($p < 0.001$). However, no statistical difference was found between day 1 after the surgery and the final follow-up ($p = 0.137$). As for the VAS of leg pain, the outcome at the final follow-up was significantly improved compared with that at day 1 after the surgery (*p*-value between preoperative and postoperative VAS was less than 0.001, and was 0.009 between postoperative and final follow-up VAS). In Group B, the average hospitalization stay was 5.50 ± 2.07 days (range: 3–8 days). The VAS of lumbar pain and leg pain were both significantly improved at day 1 after the surgery compared with the preoperative VAS ($p < 0.001$, both) and improved tremendously at the final follow-up compared with day 1 after the surgery ($p = 0.008$ and 0.026, respectively). Case 20 stayed in the hospital for a long time because she felt pain in the right leg that increased while walking. The pain did not subside immediately after the surgery and turned worse, which was believed to be related to the intraoperative traction for the nerve root. After hormone and dehydration therapy to relieve neuro edema, the pain reduced slightly 7 days after the surgery. In Group C, the average hospitalization stay was 4.38 ± 2.07 days (range: 2–9 days). There was a significant improvement on day 1 after the surgery in both VAS of lumbar and leg pain ($p < 0.001$, both). Statistical difference was only found in VAS of leg pain between day 1 after the surgery and the final follow-up ($p = 0.003$), but there was no significant difference in those of lumbar pain ($p = 0.615$). As shown in **Figure 4**, no statistical difference was found in the VAS of leg pain among all the three groups in each period. Furthermore, no statistical difference was found among them in the VAS of preoperative and final follow-up lumbar pain. The VAS of postoperative lumbar pain showed a different status; the VAS of postoperative lumbar pain in Group B was slightly higher than that of Groups A ($p = 0.017$) and C ($p = 0.004$).

According to Bridwell's fusion grading system, there were 9 cases of definite fusion and 2 case of probable fusion in group A, 11 cases of definite fusion and 1 case of probable fusion in group B, and 8 cases of definite fusion in group C. At 1-year follow-up, the overall fusion rate with definite grade reached 77.7%. The fusion rate with definite grade reached 75% in group A, 91.6% in group B and 66.6% in group C (**Table 3**). No significant difference was observed in fusion rate among three groups at 1-year follow-up ($p = 0.345$).

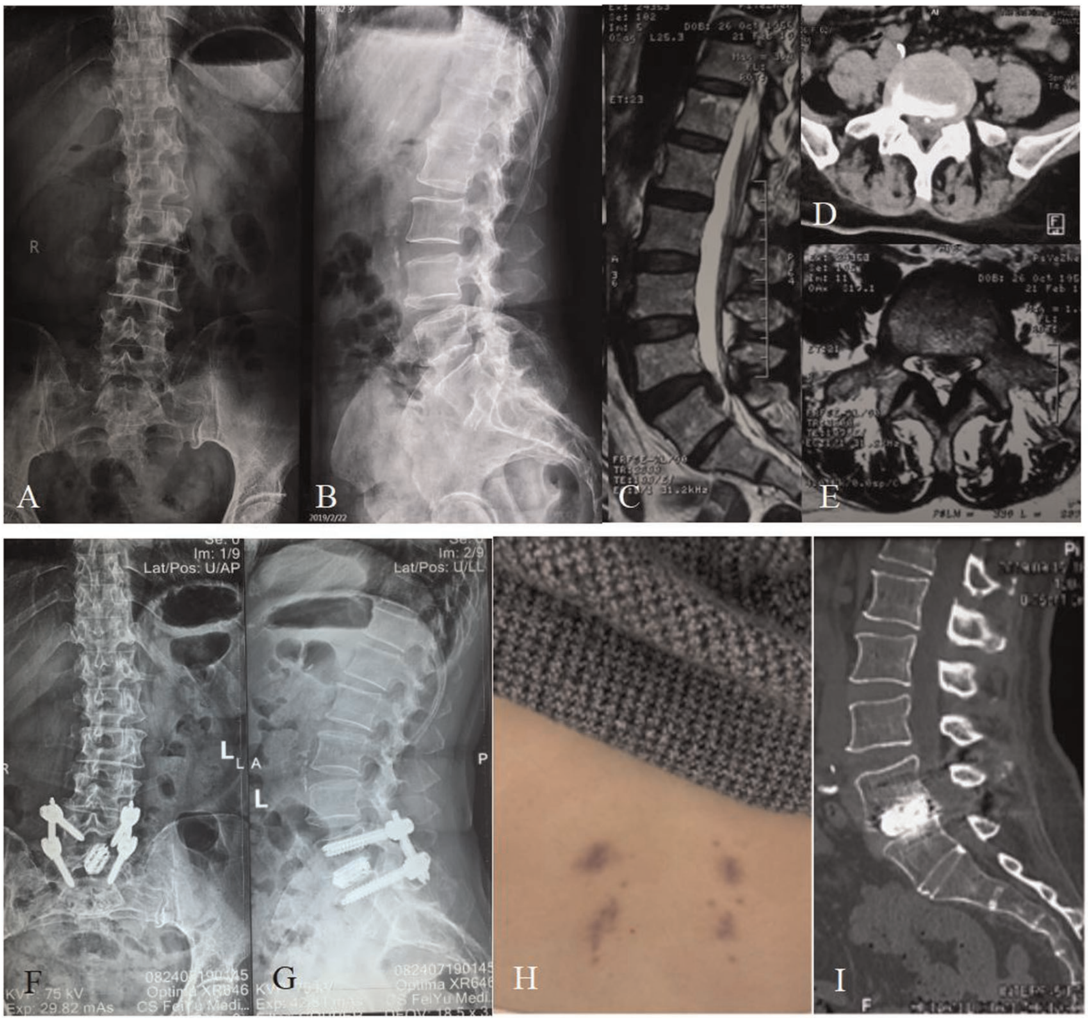

FIGURE 2 | Sixty-two-year-old female with over 10-year lumbar pain and 1-week leg pain. (**A**,**B**) Preoperative X-ray showing the patient had a slightly degenerative lumbar scoliosis and had no lumbar spondylolisthesis or apparent lumbar instability. (**C**) Preoperative sagittal MRI showing the patient had an L5/S1 disc herniation with downward prolapse. (**D**,**E**) Preoperative cross-sectional CT and MRI showing that the herniated disc with calcification oppressed the left nerve root of S1. (**F**,**G**) The postoperative X-ray showing that the cage and pedicle screws were complete and in position. (**H**) There was a very small incision scar that healed well at the follow-up of 3 months after surgery. (**I**) The postoperative CT showing a sign of probable fusion within the interbody of L5/S1 at the follow-up of 6 months after surgery.

Results for the Learning Curve

The operative time was recorded to evaluate the learning curve of FE-PLIF. The average operative time was 410.00 ± 58.13 min in Group A (range: 305–535 min), 364.42 ± 37.42 min in Group B (range: 300–420 min), and 319.17 ± 42.90 min in Group C (range: 270–420 min). A statistical difference was found among the three groups ($p < 0.001$). Further analysis found that statistically significant differences existed not only between Group A and Group B ($p = 0.032$), but also between Group B and Group C ($p = 0.012$). The median of operative time appeared in Case 11. Case 1 in Group A experienced the longest operative time among all patients in that group. In Group B, Case 20 experienced a longer operative time than other patients because her herniated disc was extremely large, making it difficult to perform complete decompression. In Group C, Case 29 experienced the longest operative time in this group because the spondylolisthesis had lasted a few years and thus was hard to reduce. No statistical difference was present among the operative time of different diseases ($p = 0.337$). The learning curve shown in **Figure 5** was characterized using a cubic regression analysis ($y = -27.07x + 1.42x^2 - 0.24x^3 + 521.84$, $R^2 = 0.617$, $p = 0.000$).

DISCUSSION

Methods to achieve better clinical outcomes and fewer complications have always drawn the attention of surgeons

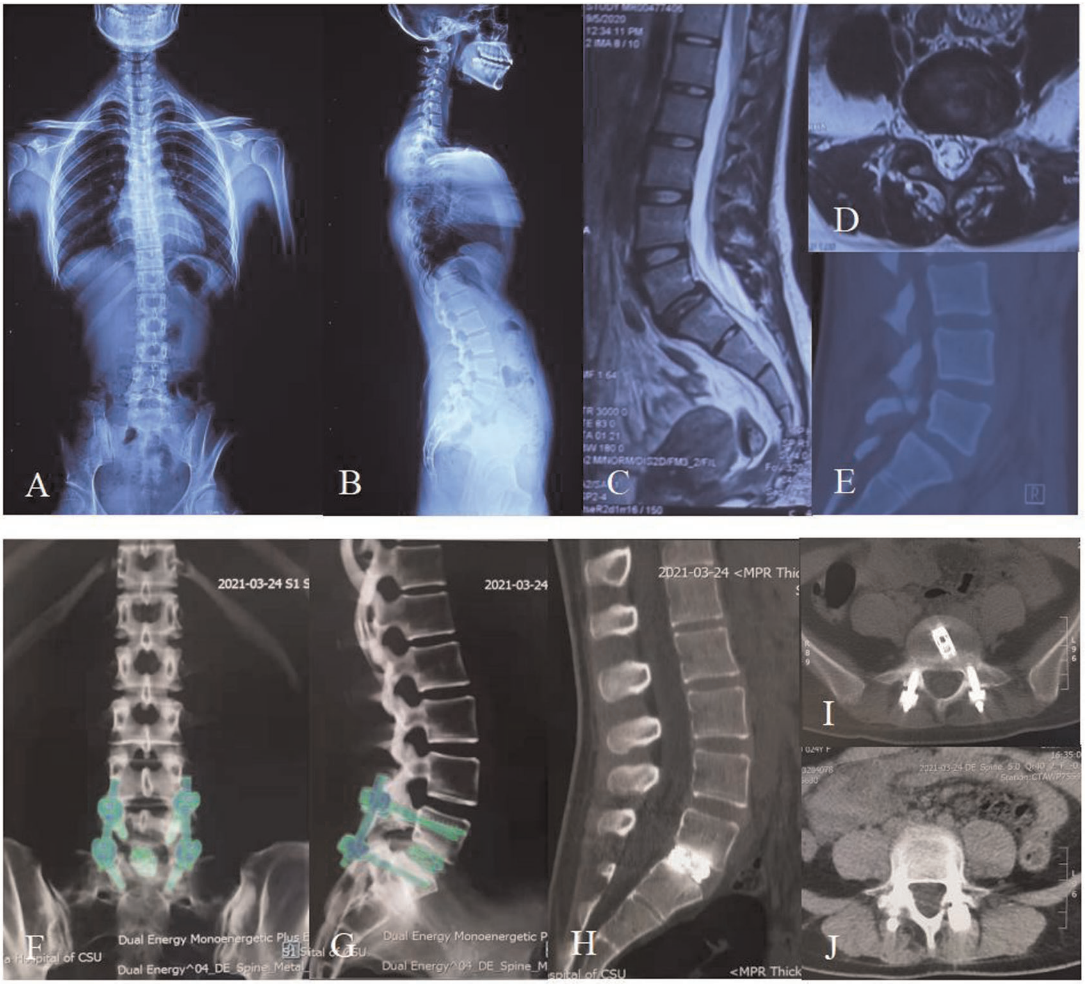

FIGURE 3 | Twenty-four-year-old female with 10-month lumbar pain and half-month left leg pain. (**A**,**B**) Preoperative X-ray showing the patient had a degenerative L5/S1 spondylolisthesis up to Grade I according to the Meyerding standard and had a slightly degenerative lumbar scoliosis. (**C**) Preoperative sagittal MRI showing the patient had an L5/S1 spondylolisthesis and multi-level disc degeneration. (**D**) Preoperative cross-sectional MRI showing that the spondylolisthesis in L5/S1 led to a stenosis of left lateral recess. (**E**) Preoperative sagittal CT showing an isthmus fissure in L5 and spondylolisthesis in L5/S1. (**F**,**G**) The postoperative dual energy CT showing that the cage and pedicle screws were complete and in position at the follow-up of 6 months after surgery. (**H–J**) The postoperative CT showing a sign of fusion within the interbody of L5/S1 at the follow-up of 9 months after surgery, and the fixation instruments were complete and in position.

since spinal fusion was first described in 1911(9). Although several surgical approaches have been developed, the best choice remains controversial, especially after the introduction of the endoscopic lumbar discectomy technique in 1988 that brought surgical spine into the minimally invasive era (10–15). Both posterior interlaminar and lateral transforaminal approaches are frequently used procedures. Previous studies have reported similar efficacy of these two established techniques (16). Compared with PLIF, the transforaminal approach was invented to reduce the chance of damaging the nerve root, which was achieved by unilateral exposure during decompression, unilateral cage interference during insertion, as well as less traction due to lateral approach (17). However, this technique requires expanded foraminal and thus has its limitations, such as the trauma caused by resection of ventral articular process, potential risk of injuring exiting nerve root, and difficulty in access caused by the high iliac spine (18–20). The posterior approach is superior in bilateral decompression, familiar overlooking angle of view, good visualization, as well as the ability to deal with several types of herniations such as huge herniation and herniation with calcification (21–23). However, this technique suffered from high invasiveness. The FE-PLIF used in our study provides a modified method. The application of a working channel with an inner diameter of over 10 mm ensured a rapid and convenient decompression due to a large operative space. Moreover, the interlaminar approach reduced the damage of the articular process by arthroplasty as well as avoided the exit of the nerve root necessary for the transforaminal approach (24). In addition, the large fork-shaped cannula enabled the use of an expandable cage, which benefitted in restoring disc height and rebuilding lumbar lordosis (25). A combination with

TABLE 3 | Clinical outcomes of three groups that underwent FE-PLIF.

Parameters		Variable			*p* value
		Group A	Group B	Group C	
VAS of lumbar pain	Preoperative	6.83 ± 1.95	7.58 ± 1.08	7.08 ± 1.98	0.559
	Postoperative	1.42 ± 0.67	2.41 ± 1.16	1.00 ± 0.95	0.003*
	Final follow-up	1.00 ± 0.74	1.08 ± 1.00	0.83 ± 0.72	0.754
VAS of leg pain	Preoperative	7.42 ± 0.90	6.75 ± 1.36	7.17 ± 1.11	0.362
	Postoperative	1.58 ± 0.90	1.50 ± 1.00	1.83 ± 1.19	0.718
	Final follow-up	0.67 ± 0.65	0.50 ± 0.67	0.58 ± 0.67	0.829
Postoperative hospitalization duration (days)		5.62 ± 1.69	5.50 ± 2.07	4.38 ± 2.07	0.385
Cases of complications		2	1	0	–
Fusion rate (%)		75	91.6	66.6	0.345
Definite fusion		9	11	8	–
Probable fusion		2	1	0	–
Non-union		1	0	4	–

VAS, visual analogue score.
**p < 0.05, the difference between groups was statistically significant.*

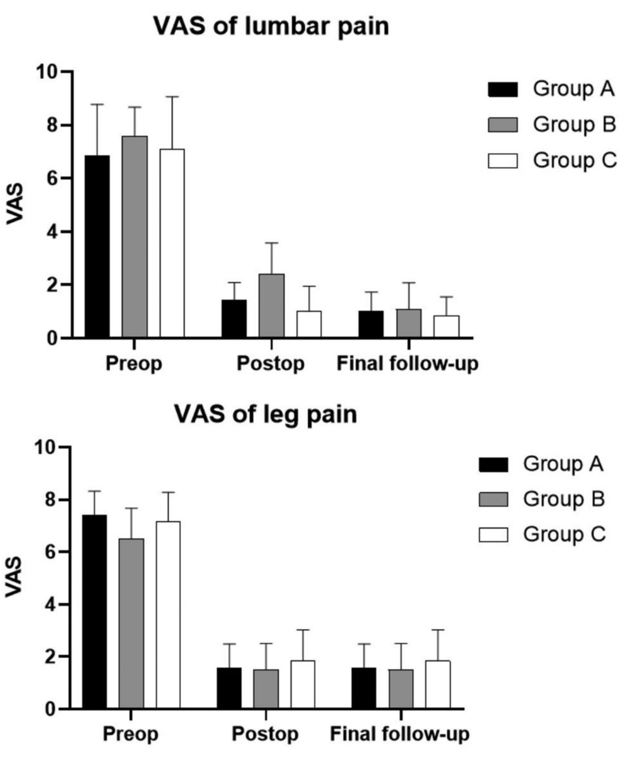

FIGURE 4 | Mean values and standard errors of visual analog scores (VAS) in three groups. (**A**) VAS of lumbar pain in three groups. (**B**) VAS of leg pain in three groups. Abbreviations: Preop, preoperative; postop, postoperative; VAS, visual analog score.

percutaneous pedicle screw, which has been widely applied and studied in spine trauma (26–28), helped in achieving stability similar to that of open instrumentation. Overall, the technique of FE-PLIF realized excellent decompression using endoscopy and a large working channel, achieved outstanding stabilization through an expandable cage and pedicle screw fixation in a minimally invasive manner. In this way, FE-PLIF has the strength of wide application in treating lower lumbar vertebrae with symptomatic bilateral recess stenosis, high iliac crest, large L5 transverse process, large articular process, narrow intervertebral disc space and spondylolisthesis lower than grade II (29). In our study, the VAS of lumbar pain and leg pain significantly decreased after surgery in all groups, which affirmed the curative effect of FE-PLIF. Partial patients in showed a better improvement in VAS at the follow-up compared with postoperative VAS. Previous studies showed that different ways of exercising, habits, and physical therapy after the surgery could differently benefit recovery (30, 31). Therefore, more detailed studies are required to identify the reason for this difference. The VAS of postoperative lumbar pain in Groups A and C was significantly better than that of Group B. Considering there was no statistically significant difference between the preoperative lumbar pain, the different postoperative effects could be ascribed to increased skilled operations and nursing with time. Complications including nerve root symptoms resulting from excessive intraoperative traction, incomplete decompression requiring open-access revision, and dural tear were reported in Groups A and B. In our study, patients underwent FE-PLIF reached a difinite fusion of 77.7% at 1-year follow-up, which was similar to previous study (32). The complications showed a decreasing trend with increased experience, suggesting that FE-PLIF is generally an effective, safe, and reliable method for decompression and stabilization. However, the endoscopic and percutaneous procedures require repeated fluoroscopy during operation to confirm the position of instruments such as the working channel, cage, and pedicle screws, which may increase radiographic exposure of both surgeons and patients. Radiation exposure is known to harm the human body, especially in early life (33, 34). As per our experience, minimally invasive spinal surgery is more popular among

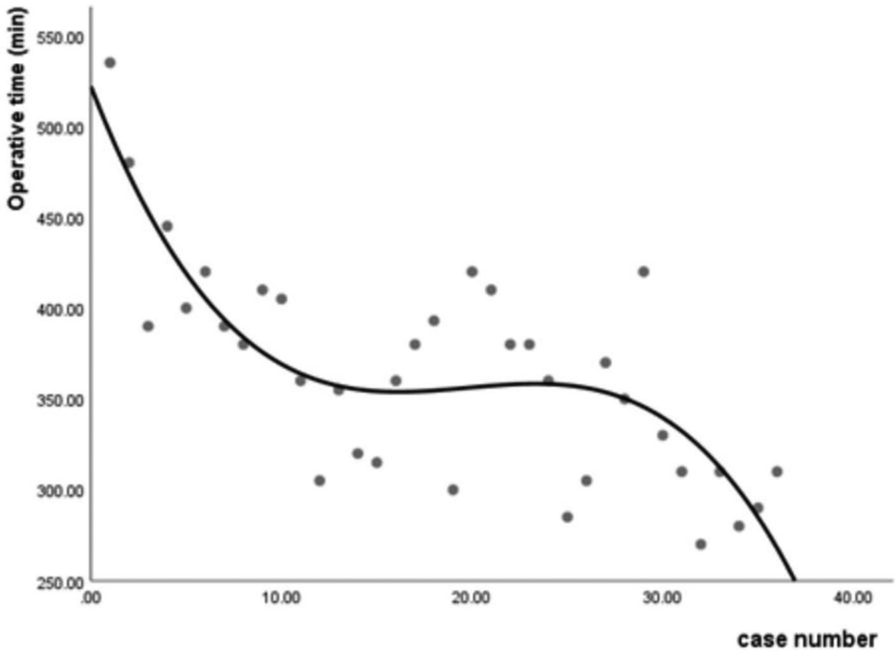

FIGURE 5 | The learning curve of FE-PLIF.

young patients. Therefore, the control of radiation exposure should be seriously considered. The indication of FE-PLIF should be strictly controlled, and various techniques including navigations could be combined with FE-PLIF to reduce fluoroscopy frequency (35–37). Certain other improvements could also be made. The expandable cage used in our study was made of titanium, which may probably bring out the problems including settlement related to metal particles, controversial fusion rates, and the need for a large amount of bone graft. Several new materials have been developed to reduce such shortcomings such as polyether ether ketone (38). In addition, similar to other surgical techniques with pedicle screw implantation, when the patient suffers from osteoporosis, strengthening methods such as a screw with bone cement should be considered (39, 40).

To the best of our knowledge, this is the first study focusing on the learning curve of FE-PLIF. Our study suggested that the learning curve of FE-PLIF was steep at the initial stage. The overall operative time of FE-PLIF appeared a little long, which may increase the risk of hidden blood loss and anesthetic accident—play an important role in perioperative rehabilitation (41, 42). The reason may be related to repeated fluoroscopy, lack of experience, as well as the addition of cage and percutaneous screw insertion. The significant difference in the operative time among groups showed there was a trend of gradual decline along with the increasing number of operations. The learning curve shown in **Figure 5** suggested that after the initial ten-time practices, the skills could be well mastered, and the downward trend of the learning curve shows a great potential to complete the operations in a shorter time before reaching a stable performance. It could be inferred that the operative time may be controlled within 3 h with increased experience. To increase safety and efficiency, more advanced training in endoscopic procedures for surgeons is advocated. Furthermore, the development of endoscopic instruments could benefit the improvement in the learning curve of FE-PLIF.

An unneglected limitation of this study is the limited number of cases enrolled. Compared with the outcome reported by Kim et al, in which the technique of bi-portal endoscopy-assisted lumbar interbody fusion required approximately 34 cases to reach an adequate performance level (43), the limited number of cases may increase the statistical error and decrease the accuracy of the evaluation of the learning curve in our study. Considering the difficulty for beginners to adapt to both endoscopic lumbar operation and percutaneous pedicle screw implantation simultaneously, more cases and surgeons should be enrolled into studies for a better evaluation. In addition, our study was based on a short-term follow-up, which is not as reliable as long-term clinical outcomes, given that certain complications, such as mechanical complications for internal fixation, chronic low back pain, and failed fusion can appear at a long time after the surgery. Further studies are expected to include larger samples, report outcomes with longer terms, and use more indicators to better evaluate the safety and efficacy of FE-PLIF.

CONCLUSION

According to our results, FE-PLIF is a safe and effective method to treat low back pain caused by short-segment degenerative diseases. The learning curve was initially steep, turned stable after 10 times of practice and showed great potential in shortening the operation time into lower than 3 h.

DATA AVAILABILITY STATEMENT

This was a retrospective study based on the true follow-up materials of cases undergone surgeries. All the data for patients' relevant information were available in the system of our hospital.

ETHICS STATEMENT

This study was approved by the Ethics Committee of the 2nd Xiangya Hospital, Central South University.

AUTHOR CONTRIBUTIONS

RT and XL made substantial contributions to the conception or design of the work, together with the acquisition, analysis, and interpretation of data for the work; RT, XL and BR drafted the work. Pengfei Wu, Bin Jiang and Yuliang Dai revised it critically for important intellectual content; YL and GL provided final approval of the version to be published; BW provided agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All authors contributed to the article and approved the submitted version.

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ORIGINAL RESEARCH
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Treatment of Upper Lumbar Disc Herniation with a Transforaminal Endoscopic Technique

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Background: To investigate the clinical efficacy of percutaneous endoscopic transforaminal discectomy (PETD) in the treatment of upper lumbar disc herniation (LDH).

Methods: Twenty-two patients, 14 males and 8 females with ages ranging from 23 to 76 years, who had upper LDH and were treated with PETD from April 2015 to April 2020 in the Department of Neurosurgery of Xuanwu Hospital, were selected to evaluate the surgical efficacy by the visual analog scale (VAS) and Oswestry Disability Index (ODI).

Results: All patients underwent successful completion of PETD surgery. The operation time was 80.4 ± 18.0 min; intraoperative fluoroscopy was used 17.1 ± 8.7 times; and the hospital stay was 3.2 ± 0.6 days. The VAS scores were 7.9 ± 1.2, 2.3 ± 1.5, 2.2 ± 1.3, and 2.1 ± 1.0 before the operation, 1 day and 3 months after the operation, and during the last follow-up, respectively. The postoperative VAS score was significantly lower than that before the operation ($P < 0.01$). The ODI scores before and 3 months after the operation were 59.8 ± 16.8 and 15.3 ± 8.2, respectively; thus, the postoperative score was decreased ($P < 0.01$).

Conclusion: Upper lumbar discs have unique anatomical structures, and PETD is a safe and effective surgical method for the treatment of upper LDH.

Keywords: high level, upper lumbar disc herniation, Minimally invasive, endoscope, percutaneous endoscopic transforaminal discectomy

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INTRODUCTION

Upper lumbar disc herniation (LDH) refers to an annulus fibrosus rupture or a herniated nucleus pulposus at or above L3–L4, and some scholars suggest that upper LDH refers to the L1–L2 and L2–L3 levels (1, 2). The incidence of upper LDH is low, accounting for approximately 5% of all LDH cases (3). Compared with lower LDH, upper LDH has unique anatomical characteristics, including a narrow spinal canal volume, narrow distance between the nerve roots and dura mater, shorter nerve roots in the intervertebral foramen area, and close proximity to the conus medullaris. Therefore, upper lumbar intervertebral disc surgery carries a higher risk, and the surgical results are not satisfactory (4).

With the improvement in spinal endoscopic technology, the efficacy of percutaneous endoscopic transforaminal discectomy (PETD) in the treatment of LDH has become comparable to that of open surgery. In addition, this technique involves less surgical trauma, faster postoperative recovery, and no adverse effects on spinal stability and has been widely used (5). At present, some clinicians use spinal endoscopy for upper discectomy. Due to the unique properties of upper LDH, its endoscopic treatment has different characteristics from those of lower LDH (6). In this study, we summarized and analyzed the clinical data of patients with upper LDH treated with PETD to explore the operating skills and clinical efficacy of the surgery.

MATERIALS AND METHODS

General Data

Twenty-two patients with upper LDH (3 L1–L2 cases, 6 L2–L3 cases, and 13 L3–L4 cases) treated with PETD from April 2015 to April 2020 in the Department of Neurosurgery of Xuanwu Hospital, China, were selected, including 14 males and 8 females; the age ranged from 23 to 76 years, with an average of 44.3 years; the disease course ranged from 1 to 23 months, with an average of 5.2 months.

Clinical manifestations: radiating pain in the lower extremities in 21 cases, lumbosacral pain in 11 cases, numbness in the area where affected nerves were distributed in 9 cases, lower extremity weakness in 3 cases, perineal pain in 3 cases, perineal numbness in 2 cases, and hip pain in 2 cases.

Inclusion criteria: (1) First time surgery; (2) single-segment LDH at L1–L2, L2–L3, or L3–L4 or LDH combined with spinal stenosis; (3) radicular pain and low back pain associated with disc herniation; (4) poor results or frequent relapse after conservative treatment for more than 4 weeks.

Exclusion criteria: patients undergoing reoperation, and cases involving severe disc calcification, severe significant lumbar degenerative deformity, segmental instability, bony spinal stenosis, or cauda equina syndrome.

Imaging Data

All patients underwent routine preoperative examinations by lumbar computed tomography (CT), magnetic resonance imaging (MRI), and lumbar anteroposterior, lateral, hyperextension, and hyperflexion X-ray. The imaging examinations were used to confirm the diagnosis and type of LDH, shape and size of the intervertebral foramen, height of the iliac crest, and shape of the spine and to determine lumbar spine stability.

Classification according to the site of protrusion: 5 cases of central protrusion and 17 cases of paramedian protrusion. Classification according to pathology: 18 cases of protrusion type, 3 cases of prolapse type, and 1 case of sequestered type.

Surgical Methods and Perioperative Management

(1) Surgical methods: Combined local anesthesia and intravenous anesthesia was used. The patient was placed in the lateral decubitus position. According to the patient's body size and the operation segment, the puncture site was approximately 6–10 cm from the midline, and the puncture direction was caudally inclined by 5–30°. The subcutaneous tissue, deep fascia, and facet joints were anesthetized by local infiltration of lidocaine and ropivacaine. After the target disc was positioned under fluoroscopy, the positioning needle was inserted into the base of the superior articular process of the lower vertebral body. The soft tissue expansion cannula and working catheter were inserted sequentially along the guide wire (if necessary, intervertebral foramen formation was performed under the visualization channel, and part of the inner wall of the superior facet was removed with a trephine) (**Figure 1**).

After the successful placement of a working channel, a foraminoscope (SPINENDOS, Germany) was inserted. The herniated, prolapsed, or sequestered intervertebral disc tissue was removed using grasping forceps under direct vision through the foraminoscope, and part of the hypertrophic or calcified ligamentum flavum was removed or trimmed. Finally, the ruptured annulus fibrosus was ablated and shrunken using bipolar radiofrequency. When the nerve root was fully decompressed, the endoscope and working cannula were removed. The subcutaneous tissue and the wound were sutured.

(2) Perioperative management: Broad spectrum antibiotics were used once during surgery. Patients were allowed to get out of bed after 4 to 18 h of bed rest following the surgery. Patients wore a soft waist brace for 3 weeks after the surgery and avoided excessive physical activity and strenuous physical exercise for 3 months.

Efficacy Evaluation

Evaluation with the visual analog scale (VAS) was performed before the operation, 1 day and 3 months after the operation, and during the last follow-up (7). Evaluation with the Oswestry Disability Index (ODI) was performed before the operation and 3 months after the operation to assess the improvement in pain after the operation. The improvement rate = (preoperative ODI score−last follow-up ODI score)/preoperative ODI score × 100%. An improvement rate of 75%–100% was considered excellent, 50%–75% was considered good, 25%–49% was considered fair, and <24% was considered poor. An improvement rate of >25% was considered effective. Lumbar MRI was reexamined one day after the operation, and lumbar MRI, CT, and X-ray results were reexamined 3 months and 1 year after the operation to observe the presence or absence of residual nucleus pulposus or LDH recurrence and the stability of the spine.

Statistical Methods

The data were analyzed using SPSS version 23.0 (SPSS Inc., Chicago, IL, USA), and are represented by $\bar{x} \pm s$. The preoperative and postoperative VAS and ODI scores were compared using a paired t-test, and $P < 0.05$ was considered statistically significant.

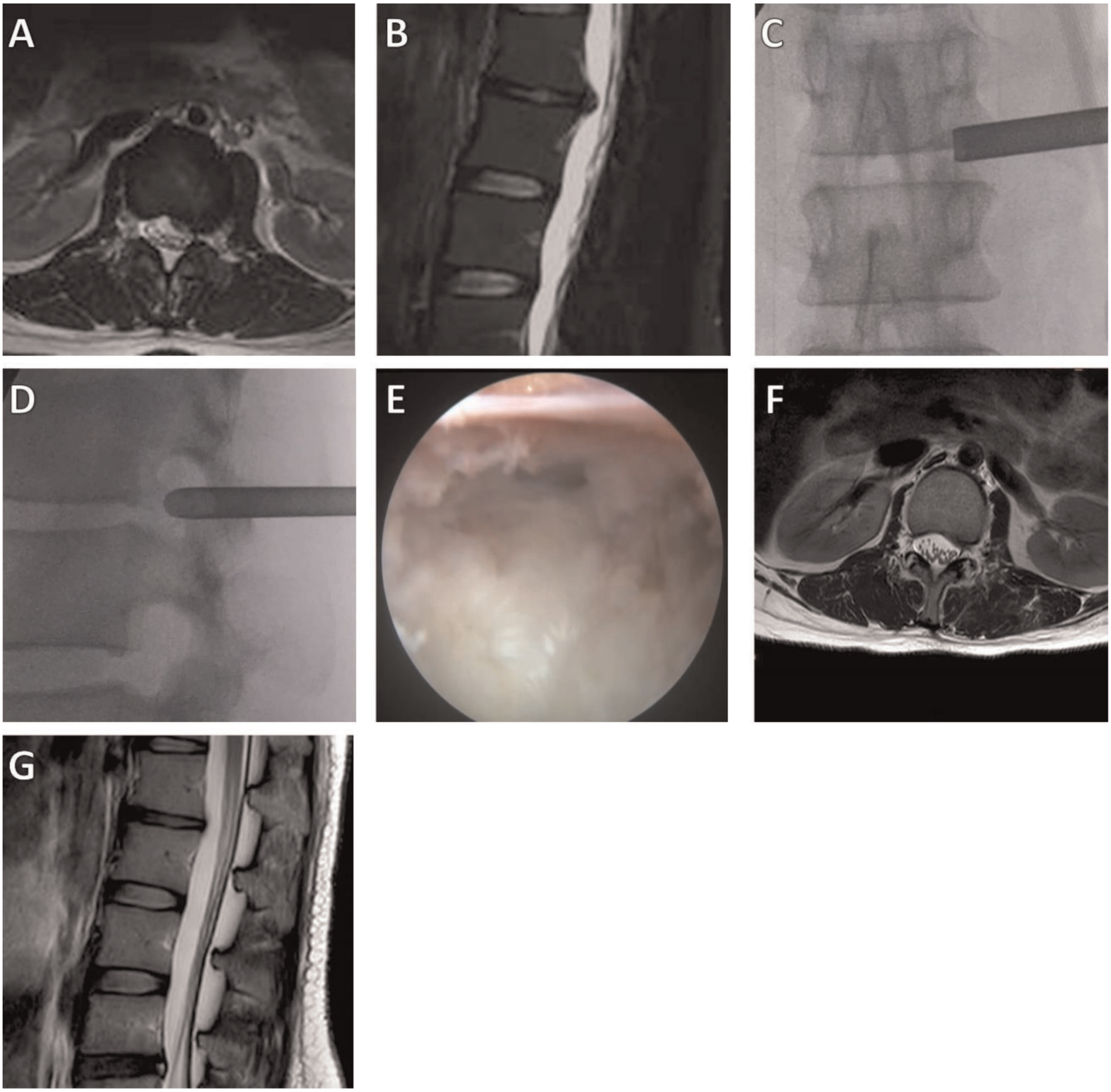

FIGURE 1 | A 28-year-old female patient had radiating pain in the left lower extremity. (**A**,**B**) Preoperative axial and sagittal MRI results showed L1–2 LDH, with compression of the dural sac; (**C**,**D**) Intraoperative anteroposterior and lateral X-rays show the position of the working cannula; (**E**) The herniated intervertebral disc was removed, and the nerve root decompression was satisfactory; (**F,G**) Postoperative MRI showed that the herniated intervertebral disc resection was satisfactory.

RESULTS

All 22 patients completed surgical treatment with PETD, and the results were as follows.

1. Surgical results: The operation time was 50–125 min, with an average of 80.4 ± 18.0 min; the intraoperative blood loss was minimal; therefore, it was not evaluated; intraoperative fluoroscopy was used 11–45 times, with an average of 17.1 ± 8.7 times; the postoperative hospital stay was 2–5 days, with an average of 3.2 ± 0.6 days.
2. Complications: One patient had decreased thigh flexion muscle strength on the affected side after the operation, resulting in a decrease from the preoperative grade of 5 to 2. The patient underwent rehabilitation exercise therapy, and the strength recovered to grade 4 after 1 month and to grade 5 after 3

TABLE 1 | Difference between pre- and postoperative scores ($\bar{x} \pm s$) for patients with lumbar disc herniation.

Date	VAS score (points)	ODI score (points)
Before surgery	7.9 ± 1.2	59.8 ± 16.8
1 day after surgery	2.3 ± 1.5[a]	
3 months after surgery	2.2 ± 1.3[a]	15.3 ± 8.2[a]
Final follow-up	2.1 ± 1.0[a]	

Note: [a]Compared with preoperative VAS and ODI, P = 0.000.
VAS, visual analog scale; ODI, Oswestry disability index.

months. One patient had postoperative numbness of the lower extremity on the diseased side and recovered after 3 weeks. No surgical complications such as intervertebral space infection occurred.

3. Follow-up results (**Table 1**): All 22 patients had preoperative and postoperative VAS and ODI scores. Twenty-one patients (95.5%) were effectively followed up for more than 12 months, and the follow-up time ranged from 12 to 47 months, with an average of 19.7 months. The VAS scores were 7.9 ± 1.2, 2.3 ± 1.5, 2.2 ± 1.3, and 2.1 ± 1.0 before the operation, 1 day and 3 months after the operation, and during the last follow-up, respectively. The postoperative VAS score was significantly reduced compared to the preoperative value (all $P < 0.01$). The ODI scores before the operation and 3 months after the operation were 59.8 ± 16.8 and 15.3 ± 8.2, respectively; therefore, the postoperative value was lower than the preoperative value ($P < 0.01$). Evaluation of the efficacy according to the improvement rate: excellent in 18 cases (81.8%), good in 2 cases (9.0%), fair in 1 case (4.5%), and poor in 1 case (4.5%), with an excellent and good rate of 90.9% and an effective rate of 95.5%. There were no cases of recurrence.

DISCUSSION

Compared with the lower lumbar spine (L4–L5 and L5–S1), the incidence of upper LDH is lower, accounting for approximately 5% of LDH, with herniation occurring at L3 to L4 accounting for approximately 70%–83% of cases (1). The lower incidence of upper LDH may be due to the upper lumbar spine having less movement, and the relative stability of the lumbar spine reduces lumbar disc degeneration, thus reducing LDH (8, 9).

The anatomical structure of the upper lumbar vertebral body and accessories is quite different from that of the lower lumbar spine. The vertebral bodies and intervertebral discs of the upper lumbar vertebra are relatively small, and the spinal canal mainly has an oval shape, with no or a very shallow lateral recess. The epidural space is small, and the fat content of the epidural space is very low. The surrounding anatomical environment lacks buffer space. Additionally, there are more nerve tissues in the dura, and the nerve roots are short and tend to run horizontally (5, 10). Therefore, once disc herniation occurs, even if the degree is very mild, it can still cause significant compression of the spinal cord and result in corresponding symptoms. Disc herniation does not directly compress a single nerve root but compresses the dural tissue, causing complex and diverse clinical manifestations. Few patients exhibit upper LDH; therefore, misdiagnosis and missed diagnosis can easily occur. The patients in this study had radiating pain in the lower extremities, lumbosacral pain, limb numbness, lower limb weakness, perineal pain, perineal numbness, hip pain, and other symptoms. The locations of their pain were extensive, and most of the patients had more severe low back pain symptoms. There were few typical signs of nerve root localization similar to lower LDH, while many patients showed symptoms of cauda equina compression. Among the patients in this study, 5 had bilateral symptoms without the intermittent claudication symptoms of spinal stenosis. Upper LDH is easily confused with other diseases, and it requires the attention of clinicians.

When upper LDH occurs, there is little buffer space after the nerve and spinal cord are compressed, and the symptoms often cannot be relieved by themselves. For patients that fail to respond to conservative treatment, surgical treatment should be carried out. Traditional surgical methods include lumbar microdiscectomy and lumbar discectomy combined with intervertebral fusion (11). Open surgery for the treatment of upper LDH has a satisfactory clinical effect, but the operation requires extensive traction and dissection of paravertebral soft tissues, which tends to impair the stability of intervertebral joints and ligaments and results in increased surgical trauma (5). With improvements in spinal endoscopic techniques, the PETD technique has been widely used in the treatment of LDH, and the surgical efficacy has become comparable to that of open surgery. In addition, the surgical trauma is reduced and the postoperative recovery time is decreased (12). At present, PETD has been studied for the treatment of upper LDH (6, 13, 14). The upper lumbar lamina space is relatively narrow and the foramina is relatively large, so PETD is superior to percutaneous endoscopic interlaminar discectomy (PEID). In this study, PETD was used to treat upper LDH, and good results were obtained. The excellent and good rate was 90.9%, and the effective rate was 95.5%. Except for one patient with decreased muscle strength after the surgery, the operation was successfully completed in the remaining patients. Compared with traditional open surgery, PETD has a shorter operation time, less blood loss, fewer wound complications, and less postoperative instability. This is because endoscopic surgery reduces paravertebral muscle injury and preserves the posterior ligament and bone structure, thereby reducing iatrogenic tissue trauma. The operation was completed in all patients under local anesthesia, and patients were allowed to get out of bed 4 h after the operation. The degree of postoperative pain relief and wound healing in patients were faster than those in patients undergoing open surgery, and the patients could return to normal work after 3 weeks of rest.

Because the upper lumbar spine has different anatomical characteristics from those of the lower lumbar spine, the key points in performing endoscopic surgery are also different from those of the lower lumbar spine. Compared with the lower lumbar, the foramina of the upper lumbar vertebrae is larger. Thus the placement of the working channel is relatively simple and foraminoplasty is not required. As a result, the operation time of the upper lumbar TELD is shorter and the operation is easier. The upper lumbar spinal canal is small, there is less epidural fat, and the nerve roots emanate from the dural sac at the level of the middle and lower 1/3 of the vertebral body, leaving the intervertebral foramen below the corresponding pedicle. In addition, there are more nerve tissues in the dura mater at this site, the buffer space in the spinal canal is small, and the risk of damaging the dural sac and nerve roots during surgery is increased (6, 15). To prevent nerve damage, in this study, when performing a puncture to establish a working channel, the puncture point was located closer to the posterior midline. Skin puncture was performed 6–8 cm from the posterior midline, and the angle of the puncture reached approximately 40°. The puncture point for the L1–L2 segment was closer to the midline than those for the L2–L3 and L3–L4 segments. With this puncture method, nerve roots and the dural sac can be avoided, and the internal organs are not easily injured. There are many neurovascular variations in the upper lumbar spine, and it is necessary to adjust to the patient's response during surgery. If the patient has radiating pain or weakness in the lower extremities, the puncture direction must be changed in a timely manner to prevent permanent nerve injury. When an even larger puncture angle is used, the established working channel is usually positioned more to the outside, and the surgeon does not operate directly in the spinal canal. First, part of the intervertebral disc is removed, and with progression of the surgery, a larger space is obtained; then, the operation is performed in the spinal canal. When upper lumbar discectomy is performed, it is more likely to damage the blood vessels accompanying the nerve roots, thus causing increased blood loss. Therefore, it is necessary to operate as close to the lower edge and the ventral side of the intervertebral foramen as possible. When larger blood vessels obscure the surgical field, they should be cauterized in advance.

Compared with the lower lumbar spine, upper lumbar is more stable and the discectomy recurrence rate is low. In addition to resecting the nucleus pulposus protruding into the spinal canal, further removal of the nucleus pulposus tissue in the intervertebral disc is not needed. However, the loose nucleus pulposus in the intervertebral disc should be removed. Allowing the patients to cough or hold their breath can help further distinguish the potential protruding nucleus pulposus. There were no cases of recurrence in this study.

Due to the low incidence rate, only 22 patients were included in this study, which is a limitation of the study. More patients should be included in future studies, and long-term follow-up should be performed.

CONCLUSION

Because of the unique anatomical structure of the upper lumbar spine, patients with upper LDH have unique clinical manifestations, and surgical treatment also has unique characteristics. PETD is an effective method for the treatment of upper LDH.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

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Clinical Efficacy of Endoscopic-Assisted Resection of Single-Segment Ossification of the Posterior Longitudinal Ligament in the Treatment of Thoracic Spinal Stenosis

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Objective: To explore the clinical efficacy, characteristics and safety of endoscopic-assisted resection of single-segment posterior longitudinal ligament ossification in the treatment of thoracic spinal stenosis (TSS).

Method: Fifteen TSS patients, including 6 males and 9 females aged 43–70 years treated with endoscopic-assisted resection of single-segment posterior longitudinal ligament ossification through the transfacet joint approach by our team from November 2016 to June 2020 were retrospectively analyzed. The operation time, intraoperative blood loss, and postoperative complications were recorded. The VAS score, ODI and JOA score (full score, 11 points) were recorded before the operation, after the operation and at the last follow-up to evaluate the clinical efficacy and calculate the improvement rate.

Results: The ventral side of the spinal cord was decompressed in all patients, providing improvements in neurological symptoms and significant pain relief. The mean follow-up time was 20.27 ± 3.87 months. Mean operation time, intraoperative blood loss, and hospitalization time were found to be 84.80 ± 13.23 min, 36.33 ± 7.41 mL, 5.13 ± 1.02 days; respectively.The JOA score at the last follow-up was 8.6 ± 1.25, which was significantly better than the preoperative (5.53 ± 1.20) and postoperative (6.87 ± 1.31) scores ($p < 0.05$). The mean JOA score improvement rate was 56.5 ± 18.00%. The JOA score improvement rate classification at the last follow-up was excellent in 3 cases, good in 8 cases, effective in 3 cases, and no change in 1 case; for an effective rate of 93.33%. The VAS score significantly decreased from 6.67 ± 1.01 preoperatively to 3.47 ± 0.88 postoperatively and 1.73 ± 0.67 at the last follow-up ($p < 0.05$). The ODI significantly decreased from 72.07 ± 6.08 preoperatively to 45.93 ± 5.01 postoperatively and 12.53 ± 2.33 at the last follow-up ($p < 0.05$). Dural rupture occurred in 2 patients during the operation; 1 patient experienced neck discomfort during the operation, which was considered to be caused by high fluid pressure and was relieved by massage and by lowering the height of the irrigation fluid. No cases of cerebrospinal fluid leakage, wound infection or other complications occurred.

Conclusion: Endoscopic-assisted resection of posterior longitudinal ligament ossification through the facet joint approach is a safe and effective method for the treatment of TSS.

Keywords: minimally invasive, spinal endoscopy, posterior longitudinal ligament ossification, thoracic spinal stenosis, TSS, OPLL (ossification of the posterior longitudinal ligament)

INTRODUCTION

Thoracic spinal stenosis (TSS) is a degenerative disease that progresses slowly and can remain asymptomatic for a long time, but the delay in diagnosis results in irreversible damage to the nervous system at the time of diagnosis (1–4). The pain caused by TSS also seriously affects the work and life of patients. Therefore, the treatment of TSS is extremely important. Although there is no unified principle or standard for the treatment of TSS, relevant scholars generally believe that the clinical effect of conservative treatment for TSS is poor. As a result, patients with TSS should undergo surgery soon after diagnosis (5).

In patients with TSS, ossification of the posterior longitudinal ligament (OPLL) is the main cause of ventral spinal cord compression (6–8). A large number of scholars have reported that the traditional open surgical treatment method has disadvantages, including the severe trauma, many potential complications, and unstable efficacy (9), and this surgical method is becoming increasingly unsuitable for many patients. With the development of minimally invasive techniques, endoscopic spinal surgery has been widely used in the treatment of diseases affecting the cervical and lumbar spine, with good clinical results (10, 11). At the same time, some scholars have applied endoscopic techniques in the treatment of OPLL of the thoracic spine and have also achieved good surgical results (12). Therefore, endoscopic-assisted resection of OPLL in the thoracic spine for the treatment of TSS has gradually become a research focus.

However, there have been few reports on the treatment of TSS by an endoscopic-assisted transfacet joint approach. We used an endoscopic-assisted transfacet joint approach for the resection of OPLL and discussed the characteristics, clinical efficacy and safety of this operation in the treatment of TSS.

MATERIALS AND METHODS

Patients

Fifteen patients with TSS treated by endoscopic-assisted resection of single-segment posterior longitudinal ligament ossification through the transfacet joint approach by our team from November 2016 to June 2020 were retrospectively analyzed. Common clinical manifestations were chest and back pain, girdle sensation, numbness in the saddle area, bowel and bladder dysfunction, numbness and weakness of both lower extremities, unsteady walking, sensation of stepping on cotton while walking, increased muscle tone, and tendon hyperreflexia.

Inclusion and Exclusion Criteria

The inclusion criteria were as follows: 1. diagnosis of single-segment TSS caused by OPLL made according to the patient's medical history, clinical manifestations and imaging findings; 2. dysfunction at and below the affected segment, with a serious impact on quality of life; 3. persistence or progression of symptoms during conservative treatment at regular institutions; and 4. complete follow-up data.

The exclusion criteria were as follows: 1. TSS caused by a tumor, infection, fracture or deformity of the spine; 2. history of thoracic spine surgery or thoracic spine instability; 3. paraplegia or other underlying disease precluding surgery; 4. TSS of two or more segments or cervical or lumbar spine disease; or 5. TSS was caused by intervertebral disc herniation and ossification of the ligamentum flavum.

Preprocedural Imaging

Several imaging examinations were performed before the operation. 1. Frontal and lateral X-rays of the thoracic spine and double oblique X-rays were obtained, if necessary. 2. Thin-slice computed tomography (CT) of thoracic vertebral lesions was performed to determine the position, extent, and severity of compression, as well as to identify the presence of dural sac adhesion or ossification to prepare for dural sac rupture and cerebrospinal fluid leakage in advance. 3. Magnetic resonance imaging (MRI) of the thoracic spine was performed to examine the compression site for a high signal intensity on T2-weighted imaging (T2WI) (13, 14) and to predict the clinical efficacy and prognosis. Based on the clinical manifestations combined with the preoperative imaging results, the surgical approach was designed. The thickness, length and bypass distance of the compression site were measured in advance, and an individualized surgical plan was formulated for each patient.

Choice of Surgical Approach

The surgical approach was determined preoperatively based on the CT and MRI findings of each patient. Patients with OPLL that deviated to one side and did not extend beyond the midline underwent surgery with a unilateral approach for decompression. Patients who had OPLL that was central, wide-based and extend beyond the midline underwent surgery with a bilateral approach for decompression.

Surgical Procedure

The patient was placed such that the lesion was facing upward, with pillows placed under the waist and armpits. Oxygen was inhaled, and electrocardiography, blood pressure, and blood oxygen saturation monitoring were performed. To relieve pain and keep the patient awake, the anesthesiologist administered dexmedetomidine (0.2–0.7 μg/kg/min) and sufentanil (0.1 μg/kg). C-arm X-ray was used to locate the surgical segment. After accurate positioning, the needle insertion point was marked on the body's surface, usually 5–8 cm lateral to the midline of the spinous process. Lidocaine was infiltrated layer by layer to establish anesthesia to the posterior aspect of the facet joint. Under fluoroscopic guidance, an 18-gauge puncture needle was inserted. After the guide wire was inserted, the puncture needle was removed, and a skin incision of approximately 1 cm with the needle insertion point as the midpoint was created. In turn, the dilation catheter was inserted along the guide wire, which was placed close to the lateral edge of the lamina or the bone at the facet joint, the endoscopic working channel was inserted along the dilation catheter, and the dilation catheter was pulled out. Fluoroscopy was performed again to ensure correct positioning of the channel. The guide wire was observed to be at an angle of 50° to 70° with respect to the sagittal plane of the spine. The endoscope was then inserted through the working channel, and blunt dissection of the soft tissue at the facet joint was performed. The tissue was separated along the lateral edge of the facet joint, the facet joint and the upper edge of the pedicle of the lower vertebral body were separated, and an external serrated trephine was placed on the selected facet joint. After removing the lateral edge of the tip of the inferior articular process, the exposed articular cartilage could be observed; the cartilage was circumscribed, the dorsal side of the superior articular process was exposed, the superior articular process was trephined, and the dorsal lateral edge of the ligamentum flavum or the pedicle was exposed. Then, the dura mater and the intercostal nerve root were separated from the ventral side, using an inclined working cannula to protect the nerve root, and the intervertebral disc and ossified posterior longitudinal ligament were exposed. Biopsy forceps were used to cut the annulus fibrosus. Then, the connection between the edge of the ossified posterior longitudinal ligament and the posterior edge of the vertebral body was severed, and the ossified posterior longitudinal ligament was polished from the ventral side of the posterior longitudinal ligament to a thin and translucent state with a diamond drill; a nerve dissector was placed in the space between the ossified posterior longitudinal ligament and the dura and used to press toward the ventral side until the ossified posterior longitudinal ligament was completely removed (**Figure 1**). After the compressive material was removed, the dural sac was inflated, good pulsation was confirmed, and the nerve root was fully released. Postoperative

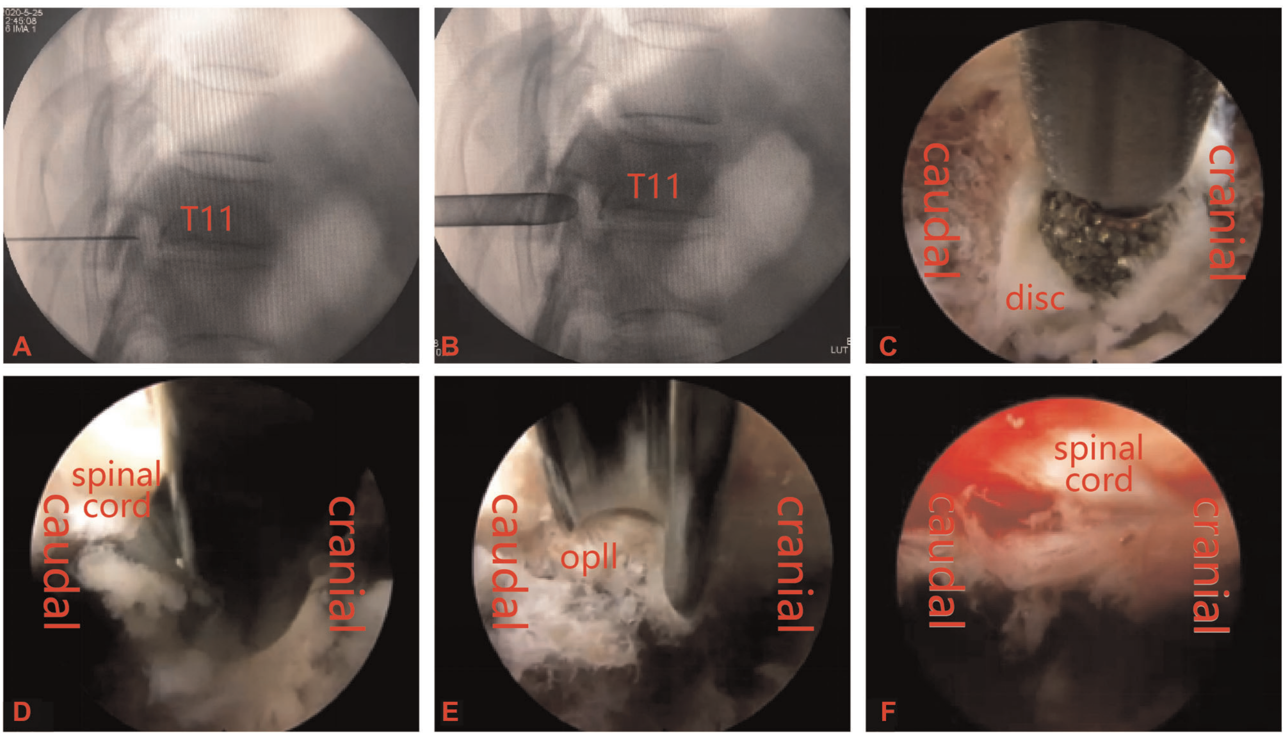

FIGURE 1 | (**A**,**B**) Percutaneous puncture to the dorsal side of the facet joint, followed by insertion of a working cannula. (**C**–**E**) Removal of the ossified posterior longitudinal ligament by decompression using a power drill system, blue forceps and osteotome. (**F**) Complete removal of ossified tissue and full decompression of the meninges after the operation.

radiofrequency coagulation was used to stop bleeding. The working cannula was removed, and the incision was sutured (**Figure 2**).

Postoperative Management

No drain was placed after the operation. The pillows were removed for 8 h, and the patient was placed in a supine position. The vital signs and sensory and motor conditions of the limbs were closely observed. Patients were encouraged to ambulate the day after surgery; wear thoracic and lumbar supports for 3 months after surgery to facilitate wound repair; and avoid prolonged sitting, bent-over weight-bearing, twisting and other strenuous activities. Antibiotics were routinely administered for 3 days. CT and MRI reexaminations were performed 3 days after the operation.

Clinical Evaluation

The visual analog scale (VAS) pain score, Oswestry Disability Index (ODI) and modified Japanese Orthopedic Association (JOA) score (full score, 11 points) (**Table 1**) were used to evaluate the patients preoperatively, 3 days after the operation and at the final follow-up. After the evaluation was performed, the JOA score improvement rate was calculated using the following formula: RR = (postoperative score - preoperative score)/(11 - preoperative score) × 100%. The JOA score improvement rate was then classified as excellent (75%–100%), good (50%–74%), effective (25%–49%), and no change or deterioration (0%–24%) (15). Perioperative data, including the operation time, intraoperative blood loss and postoperative complications, were recorded.

Statistical Analysis

Statistical analysis was performed using SPSS 21.0. Statistical data conforming to a normal distribution are expressed as $\bar{x} \pm s$. The preoperative and postoperative ODIs were analyzed by paired-samples *t*-test, and the VAS and JOA scores were analyzed by rank-sum test. $p < 0.05$ was considered statistically significant.

RESULTS

All operations were successfully completed. Among the 15 patients, there were 6 males and 9 females; the age ranged from 43 to 70 years, with an average of 56.7 ± 8.4 years. The follow-up time ranged from 13–27 months, with an average of 20.27 ± 3.87 months. The ventral spinal cord was decompressed in all patients with the aid of spinal endoscopy. Postoperative imaging showed full spinal decompression and ossified posterior longitudinal ligament removal in all patients. Twelve patients underwent surgery with a unilateral approach, and 3 patients underwent surgery with a bilateral approach (**Figure 3**).

TABLE 1 | Summary of the JOA scoring system for the assessment of thoracic myelopathy.

Neurological status	Score
Lower-limb motor dysfunction	
No dysfunction	4
Lack of stability and smooth reciprocation of gait	3
Able to walk on flat floor with walking aid	2
Able to walk up/downstairs with handrail	1
Unable to walk	0
Lower-limb sensory deficit	
No deficit	2
Mild sensory deficit	1
Severe sensory loss or pain	0
Trunk sensory deficit	
No deficit	2
Mild sensory deficit	1
Severe sensory loss or pain	0
Sphincter dysfunction	
No dysfunction	3
Minor difficulty in micturition	2
Marked difficulty in micturition	1
Unable to void	0

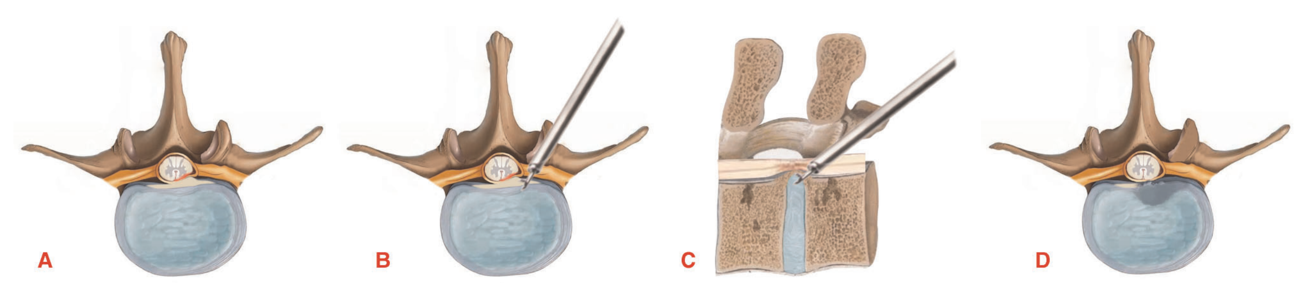

FIGURE 2 | Diagram of the surgical procedure. (**A**) The spinal cord is compressed by the ossified posterior longitudinal ligament. (**B**,**C**) Removal of the ossified posterior longitudinal ligament through the facet joint approach. (**D**) The ossified posterior longitudinal ligament was completely removed and the ventral side of the spinal cord was completely decompressed.

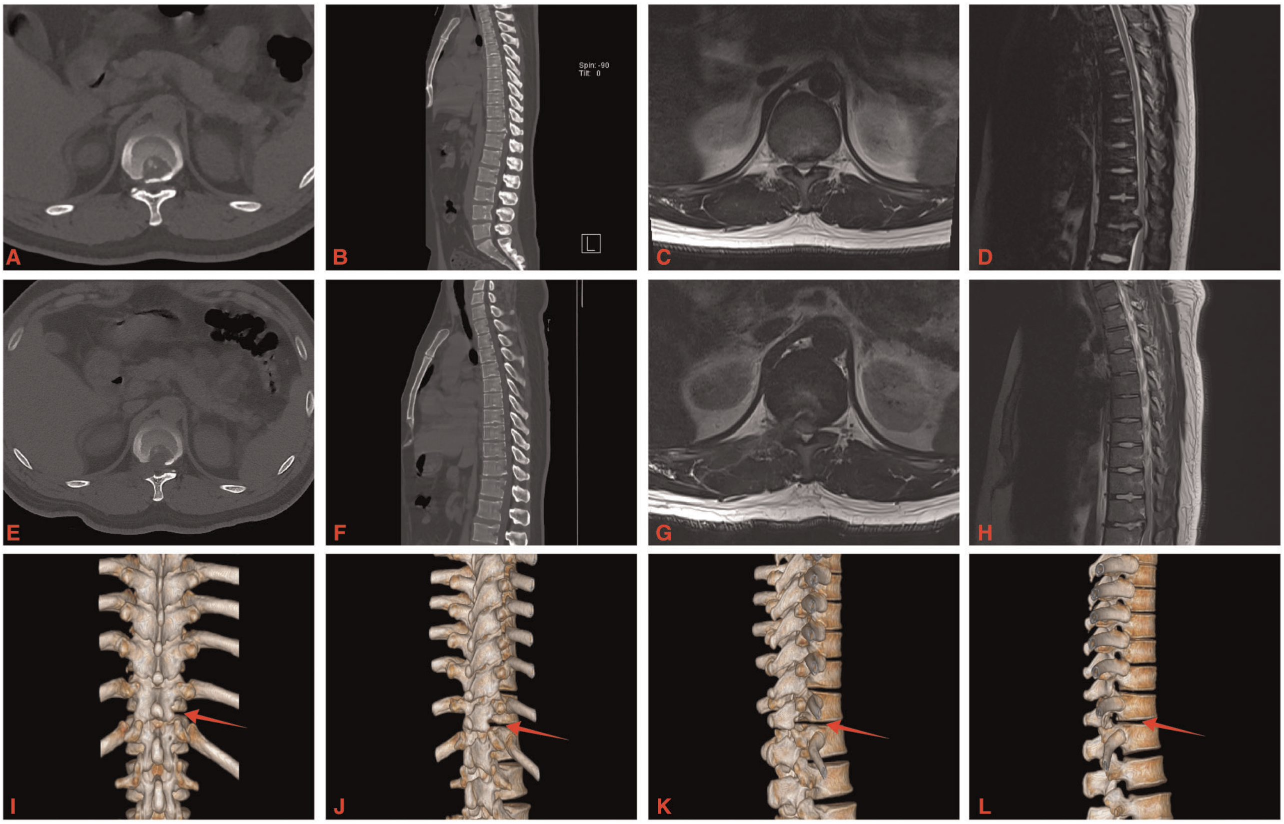

FIGURE 3 | A 46-year-old male with OPLL at T11-12. (**A–D**) Preoperative CT and MRI showed T11-12 posterior longitudinal ligament ossification and spinal cord was compressed. (**E–H**) Postoperative CT and MRI showed that the ossified posterior longitudinal ligament was removed and the ventral side of the spinal cord was completely decompressed. (**I–L**) The three-dimensional reconstruction of the CT images showed right side facet joint of T11-12 was resected (red arrow).

The mean operation time was 84.80 ± 13.23 min (range: 61–105 min), and the mean intraoperative blood loss was 36.33 ± 7.41 mL (range: 20–50 mL). The mean hospitalization time was 5.13 ± 1.02 days (range3–7 days) (**Table 2**).

The neurological symptoms of all patients improved after the operation, and their pain was significantly relieved. There were no cases of cerebrospinal fluid leakage, wound infection, or symptom progression. The mean follow-up time was 20.27 ± 3.87 months (range: 13–27 months). The mean JOA scores of patients improved from 5.53 ± 1.20 before the operation to 6.87 ± 1.31 after the operation and to 8.6 ± 1.25 at the last follow-up, with an average JOA improvement rate of 56.5 ± 18.00% and a significant difference between the preoperative and postoperative scores ($Z = -3.437$, $p = 0.001$). The JOA score improvement rate classification at the last follow-up was excellent in 3 cases, good in 8 cases, effective in 3 cases, and no change in 1 case, for an effective rate of 93.33%. The VAS score significantly improved from 6.67 ± 1.01 preoperatively to 3.47 ± 0.88 postoperatively and 1.73 ± 0.67 at the last follow-up, with an improvement rate of 74.38 ± 7.71% ($Z = -3.497$, $p = 0.000$). Additionally, the ODI significantly improved from 72.07 ± 6.08 preoperatively to 45.93 ± 5.01 postoperatively and 12.53 ± 2.33 at the last follow-up, with an improvement rate of 82.67 ± 2.38% ($t = 46.398$, $p = 0.000$) (**Table 3**).

The ossified posterior longitudinal ligament was completely removed in 13 patients, the dura was ruptured during the operation in 2 patients (patients 5 and 10), and neck discomfort occurred in 1 patient (patient 5), which was considered to be caused by high fluid pressure. Spinal cord hypertension was relieved by massage and by lowering the height of the irrigation fluid. The neurological symptoms of all patients improved after the operation, and their pain was significantly relieved. There were no cases of cerebrospinal fluid leakage, wound infection, or symptom progression.

DISCUSSION

The incidence of OPLL of the thoracic spine is low, at approximately 0%−1.9% (16), and it mainly occurs in the midthoracic region, which is poorly vascularized. Severe irreversible damage to the spinal cord can occur. Surgical removal of the ossified posterior longitudinal ligament and decompression of the ventral side of the spinal cord to restore spinal cord function are the main goals of its treatment (17, 18). The indications for spinal endoscopic technology are continuously expanding, and with this technology, diseased tissue can be excised accurately under direct endoscopic vision with relatively little damage to normal structures and

TABLE 2 | Patient characteristics and surgical outcomes.

NO	Age (years)	Sex	Segment	F-up (months)	Approach	Operation time (min)	Blood loss (mL)	Hospitalization time (days)	Complication
1	47	M	T9/10	13	Single	65	30	6	None
2	50	F	T9/10	23	Single	76	40	5	None
3	57	F	T8/9	19	Single	70	30	3	None
4	62	F	T11/12	17	Single	74	40	5	None
5	68	F	T4/5	20	Double	101	45	7	Dura rupture
6	46	M	T11/12	25	Double	87	40	6	None
7	66	M	T10/11	22	Single	86	35	4	None
8	43	M	T8/9	18	Single	99	40	5	None
9	49	M	T7/8	26	Single	90	35	4	None
10	63	F	T10/11	22	Single	86	30	6	Dura rupture
11	51	F	T10/11	17	Single	78	30	5	None
12	60	F	T7/8	27	Single	96	35	6	None
13	70	M	T5/6	19	Single	98	45	5	None
14	55	F	T6/7	15	Double	105	50	6	None
15	64	F	T11/12	21	Single	61	20	4	None

TABLE 3 | Preoperative and postoperative JOA, VAS and ODI scores.

NO	JOA			RR (%)	VAS			Improvement rate (%)	ODI			Improvement rate (%)
	Preop	Postop	Last		Preop	Postop	Last		Preop	Post	Last	
1	4	4	5	14.29	8	5	3	62.50	84	56	18	78.57
2	6	7	8	40.00	7	4	2	71.43	80	47	13	83.75
3	6	8	10	80.00	7	3	2	71.43	78	50	15	80.77
4	8	8	9	33.33	4	3	1	75.00	60	42	11	81.67
5	7	8	10	75.00	5	2	1	80.00	65	38	10	84.62
6	6	7	9	60.00	7	3	2	71.43	70	48	12	82.86
7	6	8	9	60.00	7	4	2	71.43	72	50	14	80.56
8	6	8	9	60.00	6	4	1	83.33	69	48	10	85.51
9	6	7	8	40.00	7	3	1	85.71	74	40	9	87.84
10	5	7	8	50.00	6	4	2	66.67	70	47	12	82.86
11	5	6	9	66.67	7	3	1	85.71	66	41	13	80.30
12	6	8	10	80.00	7	4	2	71.43	72	46	12	83.33
13	3	4	7	50.00	8	5	3	62.50	78	53	16	79.49
14	4	6	9	71.43	7	2	1	85.71	68	40	11	83.82
15	5	7	9	66.67	7	3	2	71.43	75	43	12	84.00
p-value		0.001	0.001			0.001	0.000			0.000	0.000	

satisfactory clinical efficacy. Many scholars have begun to try endoscopic-assisted retropleural approaches and transforaminal approaches for ventral spinal cord decompression in the treatment of TSS (19). In 2018, Ruetten et al. (20) first reported the application of an endoscopic-assisted retropleural approach in the treatment of TSS with ventral decompression of the thoracic spinal canal in adult cadavers. The results from the cadaveric study demonstrate that the transthoracic retropleural approach can provide easy access to the lesion site and allow adequate decompression of the prethoracic epidural space. This approach was applied in nine patients to decompress the ventral side of the spinal cord; while one of the eight patients who completed follow-up had a dural tear and two patients showed neurological deterioration at different times, the condition of all patients improved. Gao (21) and others described endoscopic-assisted transforaminal decompression of the ventral spinal cord, with improvements in the symptoms of all patients after surgery. The concept of a "safety triangle" has also been proposed; operating within the "safety triangle" can further improve the efficacy and safety of surgery. Adequate decompression of the ventral side of the spinal cord and reduced stimulation of the spinal cord are keys to ensuring surgical efficacy and safety. In this study, the clinical symptoms of the 15 patients were improved after surgery, and the imaging results showed adequate decompression of the spinal cord. The final JOA score of the patients was significantly improved compared with the preoperative score, and the effective rate was 93.33%. The final VAS score and ODI were significantly lower than those before surgery, and these results are similar to those of the other two surgical methods. However, the operative time in this study was 84.80 ± 13.23 min (range: 61–105 min), the mean intraoperative blood loss was 36.33 ± 7.41 mL (range: 20–50 mL), and the mean hospital stay was 5.13 ± 1.02 days. Compared with the traditional open surgery results reported by Masahiko et al. (22), all variables showed great improvement with this method. The follow-up results showed that the clinical efficacy of the transfacet joint approach was the same as that of the retropleural and transforaminal approaches and that satisfactory outcomes could be achieved. Therefore, the transfacet joint approach is safe and effective and can be used in the treatment of TSS caused by ventral spinal cord compression.

The classic surgical method for decompression of the ventral spinal cord in cases of compression caused by OPLL is the "box resection" method, in which anterior decompression is achieved without stimulating the spinal cord. However, anatomically, the thoracic cavity is immediately adjacent to the spinal canal, and the thoracic intervertebral foramen is largely occupied by the intercostal nerves. Thus, the conventional surgical approach for ventral spinal cord decompression may cause complications, such as pneumothorax or intercostal nerve stimulation or even injury, potentially affecting the surgical operation and even the therapeutic efficacy (23). The thoracic facet joint is located between the thoracic cavity and the spinal canal. During the operation, the endoscopic channel was placed on the dorsal side of the inferior articular facet, and then the upper and lower facet joints were trephined to access the ventral side of the spinal cord. There is a certain safe distance from the thoracic cavity that was maintained throughout the operation, and the intercostal nerve was basically not touched. Therefore, the transfacet joint approach can largely avoid the occurrence of such complications as those mentioned above. Zhao et al. (24) performed ventral spinal cord decompression in 14 patients through the transfacet joint approach. The only intraoperative complication was a dural tear, and no other complications, such as chest and nerve root injuries, occurred, which is consistent with the findings of this study. During decompression through the transfacet joint approach, part of the lamina on the dorsal side of the spinal cord can be removed first to achieve indirect decompression and further ensure the safety of ventral decompression operations. With the help of the 30° field of view of the spinal endoscope, approximately 180° of decompression can be achieved on the ventral side of the spinal cord; this scope of decompression is comparable to that of the transforaminal approach.

Intraoperative dural rupture has long been a common complication of spinal surgery. Cho et al. (25) reported that the incidence of cerebrospinal fluid leakage due to dural rupture is as high as 37.7%. The incidence of dural rupture is related to dural ossification. Yu et al. (26) reported that the incidence of cerebrospinal fluid leakage was 63.6% and 3.5% in those with and without dural ossification, respectively, and that gelatin foam can be applied for dural rupture repair during the operation. The dural rupture rate in the present study was 13.3%, which is similar to that reported in the literature and may be due to the small sample size of our study. It is also possible that our use of a drill to fully remove the ossified tissue by grinding contributed to this result. Mazur (27) and others believe that although direct dural repair is the preferred treatment for cerebrospinal fluid leakage, conservative measures are also feasible when the dura cannot be directly repaired. Due to their small size, dural ruptures that occur during endoscopic surgery are difficult to repair. Therefore, in patients with a dural rupture, we applied a dural repair material or gelatin foam and did not place a drainage tube after surgery; no symptoms of low intracranial pressure (such as headache and vomiting) were observed.

Endoscopic-assisted ventral decompression of the thoracic spinal cord has high risks and is difficult, and reducing surgical complications and improving surgical efficacy remain continuous pursuits. Therefore, many new technologies continue to be applied in surgery. In 2019, Zhang et al. (28) applied a new flexible burr system under endoscopy to treat 11 patients with calcified thoracic disc herniation, and no postoperative complications were observed. Alcachupas (29) described the use of a 3D intraoperative imaging system in surgery for patients with thoracic disc herniation. New technologies, such as intraoperative ultrasound technology, have also been used (30). The use of visualization technologies and other new technologies in the treatment of TSS overcomes the limitations of thoracic spinal surgery, improves surgical safety while improving surgical efficacy, and facilitates ventral thoracic spinal cord decompression by decreasing the difficulty and complexity of the involved surgical procedures.

CONCLUSION

The classic surgical method for ventral spinal cord decompression in cases of compression caused by OPLL is the "box resection" method, in which anterior decompression is achieved without stimulating the spinal cord. The new minimally invasive procedure for resecting the OPLL described herein yielded excellent postoperative outcomes with few complications, demonstrating its safety and effectiveness. However, the sample size of this study was small, the follow-up time was short, and the long-term efficacy of the method requires verification by long-term follow-up observation.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the First Affiliated Hospital of Zhengzhou University. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

XL and HH performed the statistical analyses and drafted the manuscript. ZZ revised the manuscript. YL collected the data. GW, XC and YX carried out the studies and revised the manuscript. All authors contributed to the article and approved the submitted version.

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Can the Full-Percutaneous Endoscopic Lumbar Discectomy in Day Surgery Mode Achieve Better Outcomes Following Enhanced Recovery after Surgery Protocol? A Retrospective Comparative Study

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Background: Full-percutaneous endoscopic lumbar discectomy (F-PELD) is a popular operation for the treatment of lumbar disc herniation (LDH). Some studies have reported that F-PELD in day surgery mode produced favorable outcomes for LDH. At the same time, minimally invasive spinal surgery following enhanced recovery after surgery (ERAS) presents a rising trend in recent years, but few studies reported whether F-PELD will produce better outcomes in the day surgery (DS) mode combined with ERAS.

Objective: To analyze whether F-PELD in day surgery mode following ERAS can produce better clinical outcomes than in traditional surgery mode.

Methods: The patients who underwent F-PELD between January 2019 and October 2020 were retrospectively analyzed, and the patients who met the inclusive criteria were followed up. The patients were divided into day surgery (DS) group ($n = 152$) that combined with ERAS and traditional surgery (TS) group ($n = 123$) without ERAS. The length of hospital stays (LOS), visual analogue scale (VAS), and Oswestry Disability Index (ODI) of two groups were compared before surgery, immediately after surgery, one month after surgery, and one year after surgery.

Results: A total of 298 patients who underwent F-PELD were reviewed. 290 patients were included in the study and followed up, and 275 patients who had completed the follow-up were available for analysis. There were no statistically significant differences between the two groups in terms of age, gender, preoperative VAS, and ODI. There were significant statistical differences in the VAS and ODI immediately after surgery (VAS for back pain: DS group 1.4 ± 1.1, TS group 2.0 ± 1.2, $p < 0.001$; VAS for leg pain: DS group 0.8 ± 0.8, TS group 1.1 ± 1.1, $p = 0.010$; ODI: DS group 5.8 ± 4.3, TS group 7.6 ± 7.4, $p = 0.010$) and one month after surgery (VAS for back pain: DS group 0.8 ± 0.9, TS group 1.1 ± 1.0, $p = 0.035$; ODI: DS group 3.2 ± 3.5, TS group 4.5 ± 6.5, $p = 0.036$). At one year after surgery, the VAS (back pain: DS group 0.3 ± 0.6, TS group 0.3 ± 0.7, $p = 0.798$; leg pain: DS group 0.2 ± 0.4, TS group 0.1 ± 0.4, $p = 0.485$) and ODI (DS group 0.8 ± 1.2, TS group 0.7 ± 1.7, $p = 0.729$) were further improved, but no statistically significant difference was observed between two groups. LOS of DS group (1.38 ± 0.49 days) was significantly shorter than the TS group (5.83 ± 2.24 days, $p < 0.001$), and some postoperative complications occurred in the TS group, including throat discomfort ($n = 5$, 4.1%), discomfort after catheterization ($n = 7$, 5.7%), abdominal distention ($n = 3$, 2.4%), and nausea ($n = 5$, 4.1%). None of the above complications resulted in serious consequences.

Conclusion: The F-PELD in day surgery mode following ERAS produced a better short-term clinical effect and reduced the LOS, which is worthy of promotion.

Keywords: percutaneous endoscopic lumbar discectomy, day surgery, enhanced recovery after surgery, lumbar disc herniation, endoscopy

INTRODUCTION

Lumbar disc herniation (LDH) is one of the most common lumbar intervertebral disc degenerative diseases. Patients with the LDH often seek medical attention for discogenic low back pain or radiating pain, most of which are caused by herniated discs pressing on nerves (1, 2). Percutaneous endoscopic lumbar discectomy (PELD) has recently become popular in the treatment of LDH due to the smaller skin incision, light tissue damage, shorter operation time, rapid recovery, and earlier return to work (3–5). At present, most studies show that the average length of stay of PELD as a traditional model is 2 to 5 days (6–8). However, some studies have shown that PELD in day surgery mode has also produced good clinical outcomes, and these researchers believe that day surgery is feasible for PELD (9). Therefore, the comparison of these two procedures has great clinical significance.

Enhanced recovery after surgery (ERAS) is a clinical concept based on evidence-based medicine, optimizes clinical pathways of perioperative management through multidisciplinary collaboration in surgery, anesthesia, nursing, and nutrition to reduce postoperative complications, shorten hospital stay, and promote recovery (10, 11). ERAS has been widely used in colorectal, joint surgery (12, 13). In recent years, some studies have reported that the application of ERAS in spinal surgery also produced obvious advantages (14–16). However, the use of ERAS in F-PELD has rarely been reported, and the specific protocol of ERAS has not been formulated. It is not clear whether F-PELD following the day surgery (DS) mode, which combined with ERAS, will produce better effects. Therefore, this study aims to evaluate the clinical outcomes of F-PELD in day surgery mode following ERAS and to provide some relevant clinical evidence for the treatment of LDH.

MATERIALS AND METHODS

General Information

From January 2019 to October 2020, 298 patients with LDH were treated with F-PELD at the Spinal Surgery department of Tianjin Hospital, and the patients who met the criteria for inclusion and exclusion were included in the follow-up. They were divided into the day surgery (DS) group, combined with ERAS and traditional surgery (TS) groups. All surgeries were performed by the same surgeon. The length of hospital stay (LOS), low back and leg pain visual analogue scale (VAS), and Oswestry Disability Index (ODI) were compared between two groups.

The inclusion criteria are as follows:

(a) The diagnosis is consistent with the clinical and imaging examinations,
(b) The primary spinal endoscopic surgery,
(c) Patients who have been ineffective for more than three months after receiving conservative treatment.

The following exclusion criteria are applied:

(a) Previous lumbar spine surgery,
(b) Mental illness or cognitive dysfunction,
(c) Other comorbidities or severe systemic diseases such as tumors, gout, and infections.

The study was approved by the hospital ethics committee.

Surgery Procedure

All operations were performed by the same surgeon who had many years of experience in the PELD technique.

(a) For the patients who underwent F-PELD in day surgery mode, we provided the preoperative education in order to alleviate the scared and anxious feelings of them. Patients were given a nonsteroidal anti-inflammatory analgesic (celecoxib 100 mg) and pain threshold raising drugs (pregabalin 75 mg) two hours before surgery. And Midazolam (0.5–1 mL) was injected intramuscularly right before operation. patients with L5/S1 disc herniation were positioned prone, while patients with L3/4 and L4/5 disc herniation were positioned laterally. We used a C-arm x-ray to define the entry spot before puncturing. The surgical area was disinfected, and local anesthesia was performed at the entry point. Then, an 18-G needle was used to anesthetize the path with 1% lidocaine. A small number of patients undergoing surgery with local anesthesia may experience unbearable intraoperative pain, which can be increased by adding ropivacaine to increase the anesthetic effect. If we found foraminal stenosis under endoscopy, we could remove part of the bone on the ventral side of the superior articular process by using a trephine. If the patient is in severe pain, lateral access nerve block anesthesia should be used in addition to the anesthetic methods described above. And then, the following procedure was surgery. During the operation, straight leg raising test was performed to detect the surgical effect because patient who underwent the individual local anesthesia was in a conscious state. At the end of the surgery, the dural sac and nerve-root were freely mobilized. Betamethasone (4 mg) was administered to the local nerves before the wound was closed. After the surgery, patients took celecoxib and pregabalin orally to prevent the occurrence of pain, while topical analgesic plaster around the surgical area were used for postoperative analgesia. When patients went back to the ward, doctor would teach patients to perform rehabilitation exercises such as straight-leg-raising movement, ankle pump exercise, toe flexion, and extension. On the second day after surgery, the patient could wear a waist protector and ground exercise and doctor would make an individual excise plan for each patient according to their situation.

(b) For the patients who underwent F-PELD in tradition surgery mode, one day or two preoperative preparation was required before surgery, with routine fasting and water fasting before surgery. General anesthesia with a laryngeal mask airway was also adopted during the operation to achieve sufficient analgesia, appropriate sedation and full muscle relaxation. Due to the general anesthesia, preoperative catheterization is required. Patients with L5/S1 disc herniation were positioned prone, while patients with L3/4 and L4/5 disc herniation were positioned laterally. Then patients were performed by the same surgeon in traditional F-PELD routine. Postoperative fasting for 6 h, cardiac monitoring, oxygen, intravenous flurbiprofen and rehydration were administered, and the urinary catheter was removed the day after surgery. Patients in TS had to be discharged for 2 to 3 days after surgery to make sure they did not suffer from postoperative complications such as throat discomfort, discomfort after catheterization, abdominal distention and nausea.

Advantages of F-PELD in Day Surgery Mode Following ERAS

(a) Preoperative education: The primary goal of preoperative education is to calm patients' nerves and anxiety, which greatly embodies the concept of Bio-Psycho-Social medical model. The surgeon should explain the surgery procedure, duration, possible surgery-related discomfort, postoperative rehabilitation exercise methods, and answer any questions from the patients. During the perioperative period, they kept the patients calm.

(b) Multimodal analgesia (MMA) program: Two hours before surgery, nonsteroidal anti-inflammatory drugs (NSAIDs) (celecoxib 100 mg) and pain threshold raising drugs (pregabalin 75 mg) were taken orally. If there was no contraindication, then mid- and long-acting adrenocortical hormone (betamethasone 4 mg) was administered to the local nerves before the wound was closed, and oral NSAIDs (celecoxib), pain threshold-raising drugs (pregabalin), and topical analgesic plaster around the surgical area were used for postoperative analgesia.

(c) Individualized local anesthesia: Local anesthesia was used for all patients in DS group. Before surgery, patients with L5/S1 disc herniation were positioned prone, while patients with L3/4 and L4/5disc herniation were positioned laterally. The hierarchy of anesthesia via the posterior interlaminar approach is as follows: subcutaneous, fascia, the surface of ligamentum flavum, and the nerve peripheral, whereas the hierarchy of anesthesia via the lateral transforaminal approach is as follows: subcutaneous, fascia, ligamentum flavum surface, intervertebral foramen. Suppose the posterior interlaminar approach is used for patients with severe preoperative pain. In that case, inability to maintain position, severe intervertebral disc calcification, or massive disc herniation, the lateral intermorainal nerve block anesthesia should be used in addition to the level of anesthesia described above. At the end of the surgery, the dural sac and nerve-root were freely mobilized (**Figure 1**).

(d) Postoperative rehabilitation exercise: After surgery, the patient should actively perform rehabilitation exercises such as straight-leg-raising movement, ankle pump exercise, toe flexion, and extension. On the second postoperative day, the patient should wear a waist protector and ground exercise.

Data Collection

The LOS, VAS for low back and leg pain, and ODI were recorded. All patients were followed up at immediately after surgery, one month, and one year postoperatively.

Statistics

Measurement data with a normal distribution were expressed as mean ± standard deviation ($\overline{X} \pm S$), and the paired t-test was used to compare before and after treatment. The independent t-test was used to compare groups; count data were expressed as a rate or composition ratio, and the comparison between groups was performed using the χ^2 test. SPSS 23.0 software

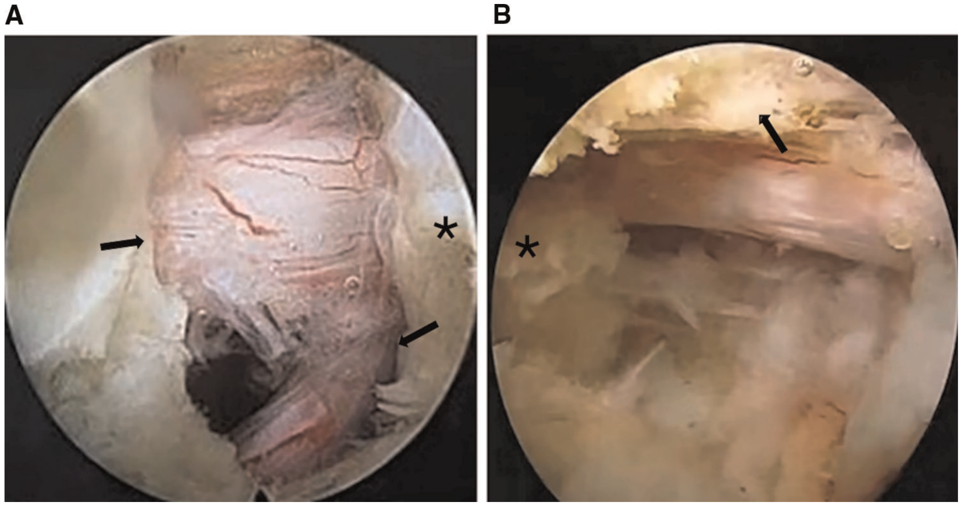

FIGURE 1 | The intraoperative decompressed dural sac and nerve-root. (**A**) F-PELD via the posterior interlaminar approach in L5-S1, variant nerve root(see arrows), cranial side(see star). (**B**) F-PELD via the lateral transforaminal approach in L4-5 showed in the right picture, ventral side of the superior articular process (see arrows), cranial side(see star).

was used for statistical processing, and $p < 0.05$ was considered statistically significant.

RESULTS

A total of 290 patients were included in the follow-up according to the inclusion criteria, fifteen patients were lost to follow up for various reasons (e.g., immigration abroad, accidents, out of touch), and 275 patients finally completed the follow-up. The DS group had 152 patients treated by F-PELD combined with ERAS, with 104 males (68.4%) and 48 females (31.6%), and the average age of DS group was 36.53 ± 12.52 years old. In the TS group, 123 patients were treated by F-PELD combined with the traditional ideas, with 73 males (60.3%) and 50 females (40.7%), and the average age of TS group was 36.14 ± 11.98 years old. There was no statistically significant difference in sex ratio ($p = 0.119$), average age ($p = 0.735$), BMI ($p = 0.693$) between the two groups. However, the difference in LOS between these two groups was statistically significant. LOS of DS group was 1.38 ± 0.49 days, and DS group was 5.83 ± 2.24 days ($p < 0.001$). some postoperative complications occurred in TS group, including throat discomfort ($n = 5$, 4.1%), discomfort after catheterization ($n = 7$, 5.7%), abdominal distention ($n = 3$, 2.4%), and nausea ($n = 5$, 4.1%), none of which had serious consequences. After symptomatic treatment, all patients with complications improved within 72 h. Unlike TS group, DS group did not have these complications (**Table 1**).

Preoperative VAS for back pain was recorded (5.9 ± 1.9) in DS group and (5.8 ± 2.0) in the TS group, $p = 0.668$. Preoperative VAS for leg pain was recorded (6.7 ± 1.4) in DS group and (6.8 ± 1.3) in TS group, with $p = 0.486$. Similarly, we recorded the preoperative ODI between DS group (78.3 ± 11.3) and TS group (78.1 ± 13.2), $p = 0.878$. We could not see a statistically significant difference between the two groups for preoperative VAS for leg pain ($p = 0.668$), preoperative VAS for back pain ($p = 0.486$), and ODI ($p = 0.878$). However, statistically significant differences were found in immediately postoperative VAS (back pain: DS group 1.4 ± 1.1, TS group 2.0 ± 1.2, $p < 0.001$; leg pain: DS group 0.8 ± 0.8, TS group 1.1 ± 1.1, $p = 0.010$) and one-month postoperative VAS (back pain: DS group 0.8 ± 0.9, TS group 1.1 ± 1.0, $p = 0.035$) were

TABLE 1 | General characteristics.

	DS group	TS group	*p*–value
N	152	123	–
Male/female	104/48	73/50	0.119
Age(years)	36.53 ± 12.52 (24–48)	36.14 ± 11.98 (25–48)	0.735
Levels involved			
L3-L4	1 (0.7%)	3 (2.4%)	0.325
L4-L5	75 (49.3%)	59 (48.0%)	
L5-S1	73 (48.0%)	61 (49.6%)	
Two-segment	3 (2.0%)	–	
BMI	24.92 ± 3.75	27.74 ± 3.51	0.693
LOS(days)	1.38 ± 0.49	5.83 ± 2.24	<0.001*
Postoperative symptoms			
Throat sore	–	5 (4.1%)	–
Bloating	–	3 (2.4%)	–
Disgusting	–	5 (4.1%)	–
Post-catheterization discomfort	–	7 (5.7%)	–

*: *The difference is statistically significant.*

statistically significant differences. Similarly, statistically significant differences were also found in immediately postoperative ODI (DS group 5.8 ± 4.3, TS group 7.6 ± 7.4, p = 0.010) and one-month postoperative ODI (DS group 3.2 ± 3.5, TS group 4.5 ± 6.5, p = 0.036). Interestingly, the subsequent follow-up showed that this was not the case. The VAS (back pain: DS group 0.3 ± 0.6, TS group 0.3 ± 0.7, p = 0.798; leg pain: DS group 0.2 ± 0.4, TS group 0.1 ± 0.4, p = 0.485) and ODI (DS group 0.8 ± 1.2, TS group 0.7 ± 1.7, p = 0.729) was recorded one year postoperatively with improved postoperative pain and dyskinesia in both groups. However, no statistically significant difference was found between the two groups (Tables **2–4**). The follow-up data indicate that DS group had the maximal differences compared with TS group at immediate post-operation, and ERAS provided significant advantages. As the patient recovered, the differences between the two groups shrank, and the benefits of ERAS began to fade (**Figures 2–4**).

DISCUSSION

Day surgery is a safe and dependable operation mode that involves selecting suitable patients and arranging hospitalization, surgery, short-term postoperative observation, and discharge from the hospital within 1–2 working days (17). Day surgery has two modes. The first mode of day surgery entails discharge on the same day as the procedure, with a 2–6 h postoperative observation period. Another option is overnight observation, with discharge on the first day after surgery if the total observation time is less than 24 h or the LOS is less than 48 h. ERAS, which advocates a series of perioperative optimization measures such as preoperative education, shorter abrosia time, MMA, individualized anesthesia program, intraoperative temperature, fluid management, and postoperative rehabilitation exercise, has recently become widely used in surgery. In contrast, traditional surgery may be more conservative than the ERAS concept, such as longer abrosia time, more frequent gastrointestinal decompression, catheterization, and general anesthesia, leading to several postoperative complications and discomfort. Thus, ERAS is well represented in the DS mode. Previous research concluded that combining DS with ERAS significantly reduced LOS, relieved perioperative physical and psychological stress, reduced perioperative complications, and produced a better clinical effect (18–20). As a result, the new spinal DS mode, which combined ERAS with minimally invasive spinal surgery, was widely used to treat spinal disease to achieve a safe, minimally invasive, and efficient result. For example, F-PELD combined with the ERAS concept to achieve the DS mode to treat LDH. However, few studies have been conducted to determine whether the DS mode has better short-term and long-term postoperative effects than the TS mode.

The purpose of this study was to see if F-PELD with DS mode produced better clinical results than F-PELD with TS mode. The results show that implementing DS reduced the LOS from 5.83 ± 2.24 days for day surgery to 1.38 ± 0.49 days, allowing patients to return to normal life and considerably improving the ward turnover rate. Compared to the TS group, the DS group can treat 2–3 times as many patients simultaneously. It was assisting more patients earlier in relieving pain caused by LDH. However, ERAS considers not only the improvement but also the recovery. As a result, VAS and ODI are used to assess the clinical efficacy of these two surgery modes. The findings suggested that there were no significant statistical differences in preoperative VAS between two groups. But the VAS and ODI at immediate post-operation (VAS for back pain: DS group 1.4 ± 1.1, TS group 2.0 ± 1.2, $p < 0.001$; VAS for leg pain: DS group 0.8 ± 0.8, TS group 1.1 ± 1.1, p = 0.010; ODI: DS group 5.8 ± 4.3, TS group 7.6 ± 7.4, p = 0.010) and one-month after surgery (VAS for back pain: DS group 0.8 ± 0.9, TS group 1.1 ± 1.0, p = 0.035; ODI: DS group 3.2 ± 3.5, TS group 4.5 ± 6.5, p = 0.036) had significant statistical differences. These results suggested that postoperative pain and dyskinesia were improved in both groups, and F-PELD in DS group could produce a better short-term effect. Interestingly, the VAS and ODI were further improved at one year after surgery, but no statistically significant difference was found between the two groups. It implies that the differences between the two groups will gradually narrow as the patient recovers and F-PELD in DS

TABLE 2. | Comparison of VAS for back pain between DS group and TS group.

Follow-up time	DS group ($\overline{X} \pm S$)	TS group ($\overline{X} \pm S$)	*p* value
Preoperative	5.9 ± 1.9	5.8 ± 2.0	0.668
Immediately postoperative	1.4 ± 1.1	2.0 ± 1.2	<0.001*
One-month postoperative	0.8 ± 0.9	1.1 ± 1.0	0.035*
One-year postoperative	0.3 ± 0.6	0.3 ± 0.7	0.798

*: *The difference is statistically significant.*

TABLE 3. | Comparison of VAS for leg pain between DS group and TS group.

Follow-up time	DS group ($\overline{X} \pm S$)	TS group ($\overline{X} \pm S$)	*p* value
preoperative	6.7 ± 1.4	6.8 ± 1.3	0.486
Immediately postoperative	0.8 ± 0.8	1.1 ± 1.1	0.010*
One-month postoperative	0.4 ± 0.6	0.6 ± 1.0	0.144
One-year postoperative	0.2 ± 0.4	0.1 ± 0.4	0.485

*: *The difference is statistically significant.*

TABLE 4 | Comparison of ODI between DS group and TS group.

Follow-up time	DS group ($\overline{X} \pm S$)	TS group ($\overline{X} \pm S$)	*p* value
preoperative	78.3 ± 11.3	78.1 ± 13.2	0.878
Immediately postoperative	5.8 ± 4.3	7.6 ± 7.4	0.010*
One-month postoperative	3.2 ± 3.5	4.5 ± 6.5	0.036*
One-year postoperative	0.8 ± 1.2	0.7 ± 1.7	0.729

*: *The difference is statistically significant.*

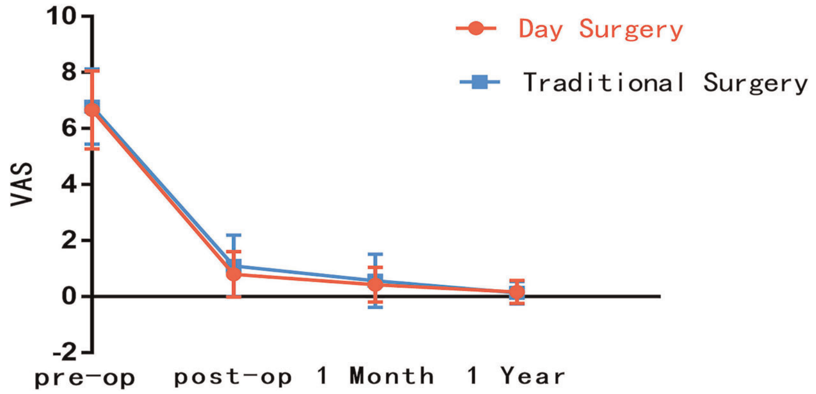

FIGURE 2 | Comparison of VAS for back pain between DS group and TS group.

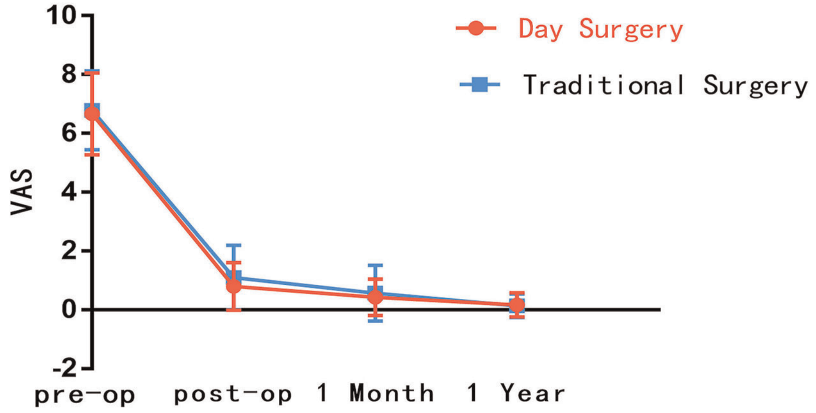

FIGURE 3 | Comparison of VAS for leg pain between DS group and TS group.

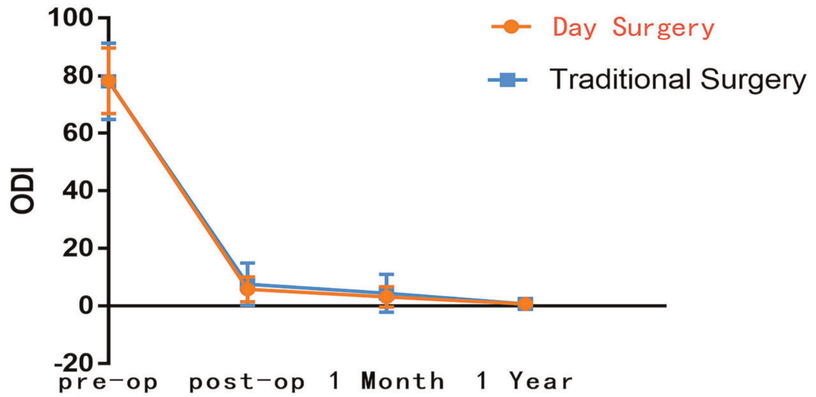

FIGURE 4 | Comparison of ODI between DS group and TS group.

group produced a similar clinical effect compared with TS group at one year postoperatively. After surgery, ERAS plays a critical role in improving symptoms and enhancing recovery in the short term. However, more research into the long-term effects is required. Furthermore, throat discomfort ($n = 5$, 4.1%), discomfort after catheterization ($n = 7$, 5.7%), abdominal distention ($n = 3$, 2.4%), and nausea ($n = 5$, 4.1%) occurred in the TS group as postoperative complications, but none of the above complications happened in the DS group. In a word, the F-PELD in DS mode following ERAS should be promoted more widely due to these significant advantages in promoting rapid recovery, improving patients experience and shortening LOS.

This finding may change the perception that day surgery has a better clinical effect than traditional surgery. We believe that there are several reasons for the above results. Research has shown that stress, anxiety, and other negative emotions can lower the pain threshold. Preoperative education and optimized perioperative management were advocated by ERAS to make patients more relaxed and comfortable perioperatively, improving patient compliance and experience, assisting patients in tolerating postoperative discomfort, and lowering pain score and disability index. Also, the MMA program of ERAS effectively alleviates perioperative pain, allowing patients to exercise and return to normal life, increasing the efficiency of functional exercise, and assisting with patient recovery (21–28). Finally, the outcomes of F-PELD performed under local anesthesia are satisfactory. Local anesthesia not only reduces preoperative preparation time and requirements but also reduces postoperative recovery time. All patients in the DS group were given local anesthesia with no need for catheterization, preoperative intestinal preparation, or anything else. As a result, they experience less postoperative pain (29–31). This is also why patients in the TS group experience throat discomfort, discomfort after catheterization, abdominal distention, and nausea, whereas none of the aforementioned complications occur in the DS group. These patients typically have severe nerve root compression for calcification of disc herniation and massive disc herniation. These patients may experience severe pain if the surgeon detects and decompresses the nerve root. Furthermore, two obese patients experienced severe pain during surgery. Factors such as calcification of disc herniation, massive disc herniation, or obesity could cause severe pain in patients during surgery (32–34). Thus, we recommend that the surgeon use posterior local anesthesia combined with lateral foraminal area infiltration anesthesia or directly general anesthesia by experienced doctors when using the posterior interlaminar approach.

This research has some limitations. All the TS were carried out in 2019, but the DS was performed in 2020, so there may be influences of the surgical team's tacit cooperation and experience. Furthermore, this study is a retrospective study, which inevitably produces bias in patient selection, information acquisition and other aspects.

CONCLUSIONS

In combination with ERAS, F-PELD provides an effective day surgery mode for LDH. The day surgery with ERAS produced more satisfactory short-term clinical effects and reduced LOS, which promoted the rapid postoperative recovery of patients and accelerated turnover efficiency, and which is worthy of promotion.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by 2022 medical ethical review 095, Tianjin Hospital Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LK, WW, CC and QY contributed to conception and design of the study. LK, XS and HW contributed to acquisition of data. LK, WW, CC, DZ and QY contributed to analysis or interpretation of data. LK, WW, ZG and MD contributed to drafting the manuscript. QY and CC contributed to revising the manuscript critically for important intellectual content. All authors approved the final version. All authors contributed to the article and approved the submitted version.

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Whether Out-of-Bed Activity Restriction in the Early Postoperative Period of PELD Is Beneficial to Therapeutic Efficacy or Reduce Recurrence

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Objective: To detect the influences of postoperative out-of-bed activity restriction on recurrence rate, low back and leg pain, functional rehabilitation after percutaneous endoscopic lumbar discectomy (PELD).

Methods: In this research, 213 patients with lumbar intervertebral disc herniation (LDH) who underwent PELD were divided into the out-of-bed activity restriction group and out-of-bed activity non-restriction group. The visual analog scale (VAS) and Oswestry disability index (ODI) scores were used to evaluate postoperative clinical efficacy at 1 and 3 months after the operation, and to count the recurrence rates. All of these operations were performed between August 2017 and July 2020, and they were followed in the outpatient department for 12 months at least.

Results: Both of the groups showed significantly lower VAS and higher ODI scores at 1 month and 3 months post-operation, respectively, when compared with pre-operation. At 1 month after the operation, the restriction group performed lower VAS scores of low back pain compared with the non-restriction group, but this advantage disappeared at 3months post-operation. However, there was no statistical difference in the VAS scores of leg pain and ODI scores between the two groups, neither at 1 nor 3 months after the surgery. The recurrence rate is significantly lower in the restriction group than in the non-restriction group at a 12-month follow-up after the surgery.

Conclusion: Out-of-bed activity restriction in the early postoperative period of PELD could reduce LDH recurrence effectively, and it may relieve the low back pain to some extent. It has no benefit in the recovery of leg pain and functional rehabilitation.

Keywords: PELD, out-of-bed activity, recurrence, pain, LDH

INTRODUCTION

With the development of endoscope instruments and minimally invasive techniques, percutaneous endoscopic lumbar discectomy (PELD) has been widely used in the treatment of lumbar intervertebral disc herniation (LDH). This kind of technique became more and more popular mainly attributed to its minimally invasive, early ambulant, fast rehabilitation, and short hospital stay (1, 2). Numerous studies (3–5) have shown that correct low back muscle exercise after surgery is crucial for functional recovery. On the other hand, it was observed that engaging in daily activities immediately after the surgery may lead to a higher recurrence rate, longer duration of pain, and even affect the therapeutic efficacy (6). So in the early stage after PELD, the choice of participating in daily activities right away or restricting out-of-bed activity remains to be discussed. In this study, we aimed to compare the effects of these two approaches for patients after the surgery, to explore which way may maximize the benefit for patients with LDH.

MATERIALS AND METHODS

Patients

The study was approved by our institutional review board. All patients with LDH performed PELD between August 2017 to July 2020 at the Spine Surgery Department of Affiliated Hospital of Jining Medical College in Shandong, China. They were followed up in the outpatient department for 12 months at least.

Inclusion Criteria

(1) unilateral lower limb pain with or without low back pain, (2) single-level LDH, (3) failure of conservative treatment for more than 6 weeks, (4) nerve root compressed by herniated disc fragment which was confirmed by CT or/and MRI, and (5) postoperative radiographs verified that the herniated disc was completely removed.

Exclusion Criteria

(1) cauda equina syndrome, (2) recurrent LDH, (3) complicated with lumbar spinal stenosis, lumbar instability or spondylolisthesis, (4) lumbar spinal infection, tumor, deformity, (5) combined with other systemic diseases who cannot tolerate or cooperate surgery, (6) unable to follow up on schedule, and (7) postoperative radiographs verified that the herniated disc was not completely removed.

General Information

All patients in this study were fully counted for the following indicators: gender, age, body mass index (BMI), operative level, modic change rate (confirmed by MRI), nucleus pulposus prolapse rate, operation time, intraoperative hemorrhage volume, hospital stay, and complication (epidural hematoma, nerve root injury, dural sac laceration, infection).

Grouping

The out-of-bed activity restriction group demands that: in the first 2 weeks after surgery, out-of-bed activity time was limited to no more than 1 h each day, and no more than half an hour each time. Waist support must be guaranteed and a good habit of sitting up sideways must be established when getting out of bed. Furthermore, the waist bending, rotation, burden, and sedentariness were not permitted until 2 weeks post-operation. During bed stay, the patient performed a five-point support exercise to strengthen lower back muscles, ankle pump movement to prevent thrombosis and muscle atrophy, straight leg lifting exercise to prevent nerve root adhesion after postoperation.

The out-of-bed activity non-restriction group demands that: the patients start to walk with waist support and participate in daily activities the day after surgery. The intensity of labor was based on their own condition, but the weight-bearing and waist activity should be avoided.

Two kinds of rehabilitation programs were provided to the postoperative patients of PELD, a total of 213 patients chose the program completely depending on their own wishes. There were 108 patients in the out-of-bed activity restriction group and 105 patients in the out-of-bed activity non-restriction group.

Surgical Procedure

According to the patients' own condition of LDH, they performed PELD successfully with two endoscopic approaches: the transforaminal (TF) approach and the interlaminar (IL) approach.

Transforaminal-PELD was performed under local anesthesia, patients were placed in the prone position on a radiolucent table and the puncture sites for the TF approach were marked under C-arm fluoroscopy. The final target point of the puncture needle was at the posterosuperior of the vertebra inferior on the lateral image and at the medial pedicular line on the anteroposterior image. A solution of 0.5% lidocaine and 0.25% ropivacaine is injected for infiltration anesthesia. An incision of nearly 7 mm was made at the puncture point of the skin, then the guidewire was put through the puncture needle, and a series of expansion channels were sequentially inserted along the guidewire to dilate the surgical channel. The circular saw was used to remove the tip and ventral part of the superior articular, to expand the intervertebral foramen and spine canal adequately. After the endoscopic insertion into the surgical area through the cannula, radiofrequency ablation was used to stop the bleeding and to expose the nerve root compressed by the herniated disc tissues. Finally, the herniated fragment was removed by nucleus pulposus forceps, and the synechia was separated by radiofrequency ablation, so as to loosen the nerve root and dural sac (**Figure 1**).

Interlaminar-PELD was performed under general anesthesia, and the patients were placed in the prone position on a radiolucent table. With the help of C-arm fluoroscopy, the entry point was marked on the affected side of the back skin 0.5 cm next to the spinous process line. And the exact location was called the V-point, which is the intersection of the inferior margin of the vertebral plate superior and the superior margin of the vertebral plate inferior on the anteroposterior image. An incision of nearly 7 mm was made at the entry point of the skin, and a series of expansion channels were sequentially inserted into the surface of the ligamentum flavum. Then, the ligamentum flavum and soft tissue around it were removed by nucleus pulposus forceps and scissors under endoscopic observation until the spinal canal was revealed. After the dural sac and nerve root were completely exposed, the tongue of the working cannula was inserted and rotated into the lateral nerve root. Released the adhesion around the nerve with the use of radiofrequency bipolar, and push the nerve root softly

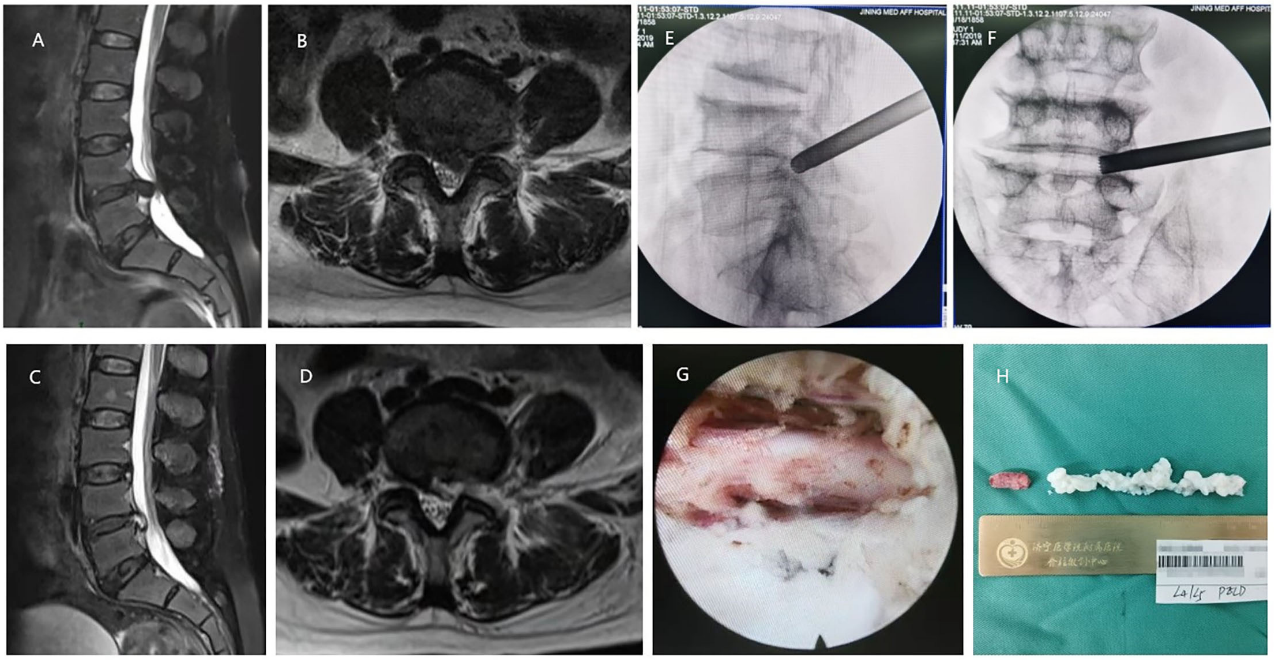

FIGURE 1 | A 67-year-old female with the L4/5 lumbar intervertebral disc herniation (LDH) underwent percutaneous endoscopic lumbar discectomy (PELD) with the approach of transforaminal. **(A,B)** Preoperative MRI showed LDH was located at the L4/5 level. **(C,D)** Postoperative MRI revealed the herniated nucleus pulposus tissues were removed and the nerve root was decompressed. **(E)** Intraoperative C-arm fluoroscopy showed the location of the working channel on lateral film. **(F)** Intraoperative C-arm fluoroscopy showed the location of the working channel on anteroposterior film. **(G)** The decompressed nerve root under endoscopic view. **(H)** Resected nucleus pulposus tissues in the operation.

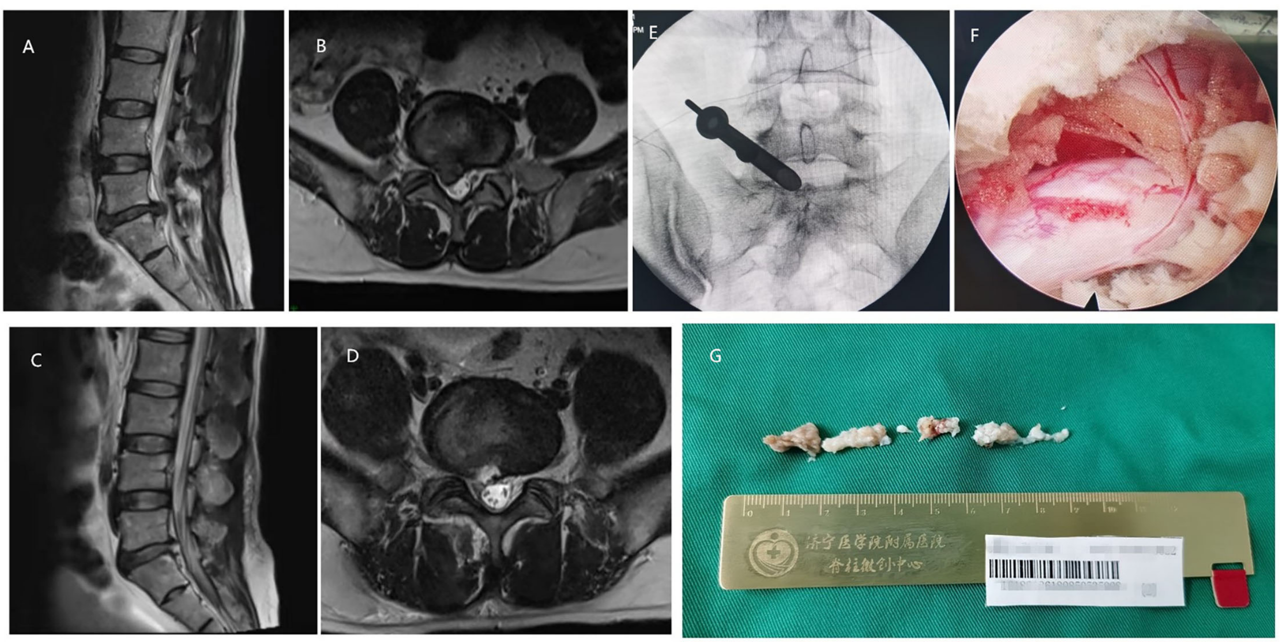

FIGURE 2 | A 56-year-old male with the L5/S1 LDH underwent PELD with the approach of interlaminar. **(A,B)** Preoperative MRI showed LDH was located at the L5/S1 level. **(C,D)** Postoperative MRI revealed the herniated nucleus pulposus tissues were removed and the nerve root was decompressed. **(E)** Intraoperative C-arm fluoroscopy showed the location of the working channel. **(F)** The decompressed nerve root under endoscopic view. **(G)** Resected nucleus pulposus tissues in the operation.

to the direction of centerline, to protect the nerve and expose the prominent nucleus pulposus tissue. Removed the prominent nucleus pulposus by various nucleus pulposus forceps. Finally, examined the remaining herniated fragment and the bleeding points in the spinal canal, then checked the flexibility of the nerve root once again (**Figure 2**).

Evaluation Methods

Low back pain and lower limb pain were evaluated respectively, by the visual analog scale (VAS), 1 month postoperatively and 3 months postoperatively. The patient's functional disorder conditions were evaluated by Oswestry disability index (ODI) scores at the above time points. An imaging review was performed during pain assessment (**Figure 3**). All patients were followed up in the outpatient department for 12 months at least, and the recurrences were recorded.

Statistical Analysis

The statistical data were analyzed by the SPSS 23.0 software (IBM, NY, USA). Quantitative data were expressed as mean ± SD. The paired *t*-test was used to compare the difference of continuous variables between the two groups. The chi-squared test was used to compare the difference of dichotomous variables between the two groups. $P < 0.05$ was considered to be statistically significant.

RESULTS

Demographic Characteristics

There was no significant difference between the two groups in gender, age, BMI, operative level, modic change rate, nucleus pulposus prolapse rate, operation time, intraoperative hemorrhage volume, hospital stay, and complication (**Table 1**).

Comparison of VAS Scores

Compared with the VAS scores of low back and leg pain preoperatively, the scores at 1 and 3 months postoperatively were significantly declined in both of the 2 groups. At 1month after the operation, the restriction group performed lower VAS scores of low back pain compared with those in the non-restriction group, and the difference was statistically significant. However, the difference of VAS scores in low back pain between the 2 groups disappeared at 3 months postoperatively. There was no statistical difference in the VAS scores of leg pain between the two groups neither at 1 month nor 3months postoperatively (**Table 2**).

Comparison of ODI Scores

In both of the two groups, the patients' ODI scores significantly improved at 1 and 3 months postoperatively compared with those preoperatively. But there were no statistically significant differences in ODI scores between the two groups at 1 and 3 months postoperatively (**Table 3**).

Comparison of Recurrence Rate

All the patients were followed up for 12 months after the operation, and the recurrence cases were confirmed by clinical symptoms and image logical examinations 0.5 cases of recurrence were revealed in the restriction group, whose recurrence rate was 4.63%, and all of them were underwent operation again. Correspondingly, 13 cases of recurrence were revealed in the non-restriction group, which recurrence rate was 12.38%. In total, 10 of them underwent operation again, and the rest recovered with conservative treatment. The restriction group showed a significantly lower recurrence rate than that in the non-restriction group with statistical differences (**Table 4**).

DISCUSSION

With the development of endoscopic technology, PELD has gradually become the mainstream surgical method for the treatment of LDH. It is mainly divided into the TF and the IL different surgical approaches and is widely used in clinical practice. Even when compared with other types of minimally invasive surgery, such as MIS-TLIF and unilateral biportal endoscopic discectomy, PELD performed obviously less intraoperative blood loss, shorter operative time, lighter low back, and leg pain postoperative (7, 8). Although it has minimally invasive features, PELD requires the destruction of back soft tissue and lumbar disc structure, which inevitably leads to postoperative pain and recurrence in patients, and recurrence rates of LDH have been reported in the literature ranging from 5 to 15 percent (9). Numerous studies have shown the factors of recurrence as age, BMI, disc degeneration, surgical approaches, early ambulation, postoperative instability, or hypermobility (2, 6, 10).

Almost the vast majority of surgeons require patients to get out of bed within 1–3 days after surgery for early functional exercise. However, we found that early out-of-bed activity restriction significantly reduced low back pain in this research. Early participation in daily activities may increase the load on the lumbar spine and enhance intradiscal pressure (IDP). From the supine position to the standing position, the IDP can increase significantly, and the flexion position can increase the IDP further. However, the change in intradiscal pressure may lead to the nucleus pulposus tissue re-entering the spinal canal through the annulus fibrosus breach and induced clinical symptoms, which can be seen as the pathological basis of recurrent LDH.

The correlation between compression force and intervertebral disc degeneration has been confirmed by many mechanically induced disc degeneration studies (11, 12). In the experimental model of Guehring (13), prolonging the time of compression may lead to more severe disc degeneration. This conclusion reflects the result in our study that restricting out-of-bed activity time in the early postoperative period of PELD could reduce recurrence rates. Although PELD can effectively remove the nucleus pulposus tissues to achieve the satisfactory therapeutic effect, most annulus fibrosus defects remain unrepaired at last, which might affects intervertebral disc integrity and stability. From the perspective of biomechanics, Fujii (14) confirmed that fibrous ring injury significantly altered several biomechanical parameters, such as axial range of motion, torsional stiffness, torque range, neutral zone, and stress-relaxation compared to the intact intervertebral disc. As the intervertebral disc is repaired, some biomechanical parameters gradually recover,

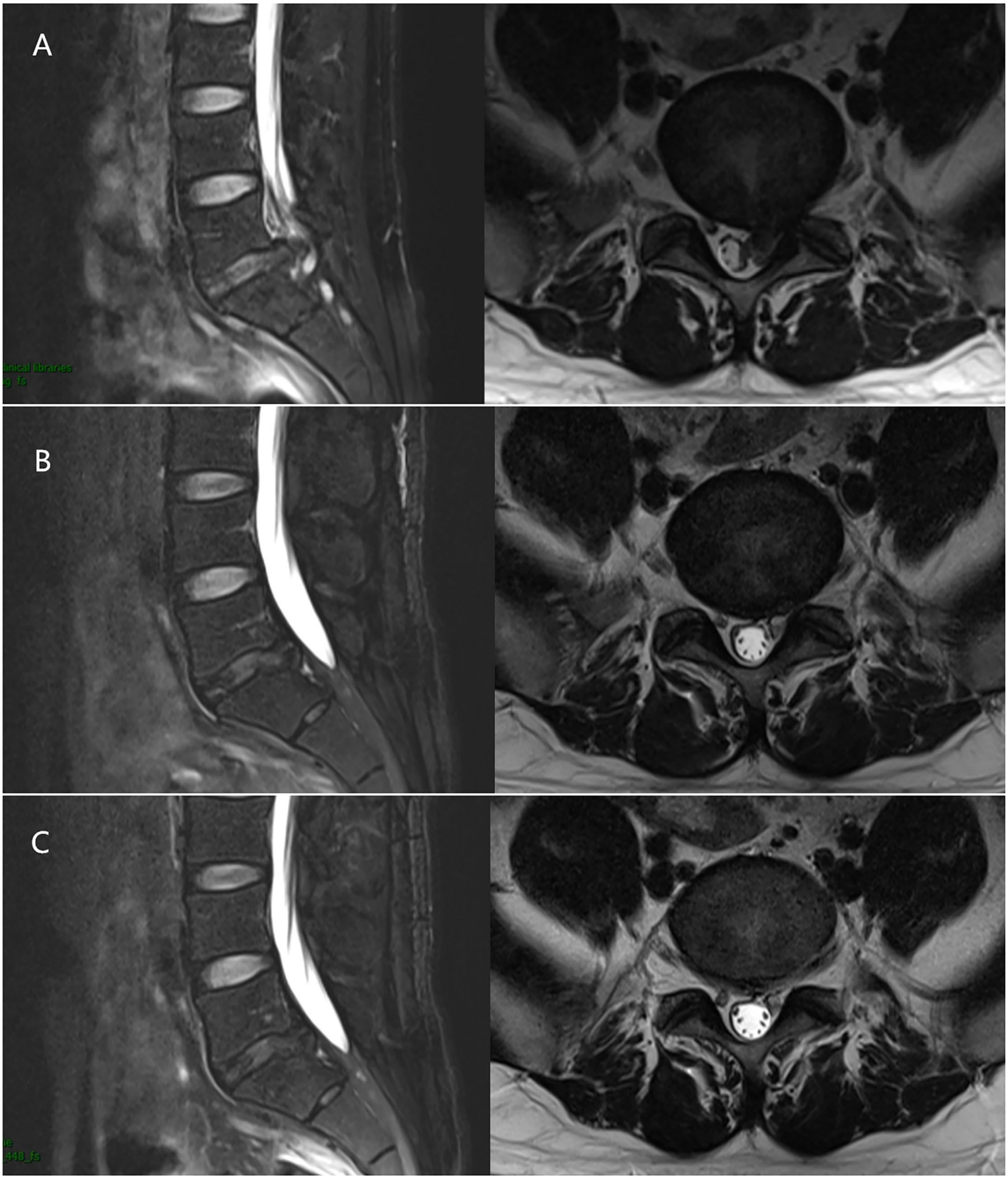

FIGURE 3 | A 33-year-old male with the L5/S1 LDH underwent PELD. **(A)** Preoperative MRI showed LDH was located at the L5/S1 level. **(B)** 1 month after surgery, MRI revealed the nerve root was decompressed without recurrence. **(C)** 3 months after surgery, MRI revealed the nerve root was decompressed without recurrence as well.

TABLE 1 | Demographic characteristics.

	Restriction group	Non-restriction group	*P*-value
Number of patients	108	105	
Gender male: (%)	59 (54.63%)	56 (53.33%)	0.85
Age (years)	51.45±12.70	49.56±13.96	0.30
BMI	26.14±2.46	25.84±2.46	0.37
Operative level:L3-4 (%)	5 (4.63%)	4 (3.80%)	1.00
Operative level:L4-5 (%)	56 (51.85%)	52 (49.52%)	0.73
Operative level:L5-S1 (%)	47 (43.52%)	49 (46.67%)	0.64
Modic change:n (%)	29 (26.85%)	39 (37.14%)	0.11
Nucleus pulposus prolapse:n (%)	68 (62.96%)	55 (52.38%)	0.12
Operation time (min)	84.42±23.19	81.49±23.94	0.37
Intraoperative hemorrhage volume (ml)	16.28±6.37	17.72±6.88	0.11
Hospital stay (days)	3.36±0.93	3.33±0.85	0.82
Complication: n (%)	7 (6.48%)	5 (4.76%)	0.59

TABLE 2 | Comparison of VAS scores.

VAS scores		Restriction group	Non-restriction group	*P*-value
Low back pain	Preoperative	3.84±1.25	3.91±1.19	0.67
	1 month postoperative	1.14±0.66a	1.60±0.91a	0.00
	3 months postoperative	1.06±0.75a	1.12±0.80a	0.52
Leg pain	Preoperative	7.05±1.38	7.25±1.52	0.31
	1 month postoperative	1.99±0.78a	1.88±0.83a	0.30
	3 months postoperative	1.60±0.84a	1.59±0.87a	0.92

a, Statistically significant difference compared with preoperative VAS scores.

TABLE 3 | Comparison of the ODI scores.

ODI scores	Restriction group	Non-restriction group	*P*-value
Preoperative	53.01±15.50	53.43±14.65	0.84
1 month postoperative	12.56±7.36b	13.60±7.71b	0.31
3 months postoperative	8.04±3.75b	8.90±3.99b	0.10

b, Statistically significant difference compared with preoperative ODI scores.

TABLE 4 | Comparison of recurrence rate.

	Restriction group	Non-restriction group	*P*-value
Recurrence (%)	5 (4.63%)	13 (12.38%)	0.042

which indicates that the intervertebral disc defect encapsulation improved its stability to some extent. The repair of the intervertebral disc is usually limited to the annulus fibrosus outer layer. Results of an animal study revealed that, after pressure was removed from the rabbit, signs of intervertebral disks tissue recovery were observed on a biologic, cellular, and biomechanical level. Its manifest disc regeneration can be induced by axial dynamic distraction (15). So by limiting the time and intensity of the postoperative ambulation, on the one hand, the recurrence can be reduced by reducing the intervertebral disc pressure, on the other hand, by reducing the intervertebral disc axial stress, so as to improve tissue repair efficiency in the intervertebral disc, rebuild the outer fiber ring to restore the biomechanical stability as early as possible, which also can reduce the recurrence rate.

In fact, it can be found sometimes that patients with successfully completed PELD still suffer low back and lower limbs pain, which persists for a period of time, even though nucleus pulposus residue has been ruled out by imaging examination. Eliminating the factor of early recurrence, incomplete removal of the herniated disc, and nerve root injury, Zhang (16) found that 10.4% of patients had short-term rebound low back and leg pain usually began within 1 month after PELD, then the symptoms were relieved after conservative treatment. Research revealed that the nerve growth into the intervertebral disc through the fissures of the fibrous ring and express substance P plays an important role in the pathogenesis of chronic low back pain caused by the destruction of annulus fibrosus in surgery (17). Internal disc disruption is a pathologic condition that can result in discogenic pain (18). After surgery interference, intervertebral disc nucleus pulposus tissue may be mixed with vertebral endplate fragments, fibrous ring debris, liquid, or gas, and small fragments of the endplate and fibrous ring may fall into the intervertebral disc degeneration region. With the change of the position, an acute discogenic pain will be caused when the fragments are just in the main load-bearing area. Additionally, it is quite common to destroy parts of zygapophysial joints for dilating the foramen, but it causes joint instability to some extent, in fact, it will lead to instability (19). When the patients resume daily activities just out of surgery, a sudden load change on the joint may lead to discomfort. Consistent with the results of this study, even if there is no recurrence, excessive and premature postoperative activity is more likely to cause postoperative low back pain.

Some research found that there were 10.4 to 20.4% of patients reappeared lower limb pain after PELD (16, 20). This kind of reappeared lower limb pain is also very common in the cases we observed. That's probably due to intraoperative nerve pulling and stimulation, the nerve root is still in a state of inflammation and edema post-operation, even if decompression is sufficient (21). Furthermore, local hematoma formed after herniated intervertebral disc tissue is removed may take time to absorb, and insufficient blood supply to local vessels can further aggravate inflammatory edema. In this study, out-of-bed activity time restriction didn't benefit reducing lower limb pain or raising ODI scores. The possible explanation is that, in the absence of recurrence, out-of-bed activity did not change the anatomical structure of the spinal canal contents, resulting in no further effect on lower limbs pain. The restriction group reached the same level as the non-restriction group in functional recovery profited from rigorous rehabilitation exercise during bedtime. It seems to be that early activity time has little impact on lower limbs pain and recovery of motor function post-operation.

CONCLUSION

This study detected that the lack of appropriate restrictions on out-of-bed activity time in the early period after PELD should be one risk factor for recurrence. It may affect the recovery of low back pain in the early postoperative period just like 1-month post-operation, however, its influence disappeared 2 months later. Out-of-bed activity time in the early period after PELD has no effect on the recovery of lower limbs pain or the ability to participate in daily activities.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Medical Ethics Committee of Affiliated Hospital of Jining Medical College, Jining Medical College. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

CM was responsible for the design of research and formulation of experimental methods, performed PELD surgery as the chief surgeon, and revised and finalized the article. XL participated in the screening and enrollment of the patients underwent PELD surgery for this research, recorded the general information and the operation data of patients, participated in the operation, and wrote this article. YW participated in the operations, educated the patient about out-of-bed activity restriction requirements postoperatively, was responsible for the follow-up of patients, and counted and recorded the patients who got recurrence after surgery. YY participated in data arrangement and statistical analysis. YL was responsible for the preoperative and postoperative VAS and ODI evaluation of patients. All authors contributed to the article and approved the submitted version.

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A Novel Trajectory for a Transpedicular Approach in the Treatment of a Highly Downward-Migrated Lumbar Herniation with a Full Endoscopic Technique

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Background: To evaluate the clinical outcome of full endoscopic discectomy using a novel trajectory *via* a transpedicular approach.

Method: Thirty-five patients were enrolled in this retrospective study between July 2014 and October 2019 in the Beijing Haidian Hospital. All patients were treated with full-endoscopic lumbar discectomy *via* a transpedicular approach with an oblique trajectory. The imaging parameters, including pedicle height and angle of trajectory, were recorded. The preoperative and postoperative clinical data were collected for statistical analysis.

Results: All patients underwent successful surgery without severe complications. We compared the visual analogue scale and Oswestry disability index scores before and after surgery. The differences were statistically significant ($p < 0.05$). According to the modified Macnab criteria, the good-to-excellent rate was 85.7% at the last follow-up. The average angles of trajectory in the sagittal and coronal planes were 34.5° ± 2.9° and 47.1° ± 5.0°, respectively.

Conclusion: The new trajectory of the transpedicular approach with a full endoscopic technique for an extremely downward-migrated disc herniation showed excellent results in a small sample study. A precise surgical plan is required, comprising measurements of the pedicle height and angle of the bone tunnel.

Keywords: transpedicular approach, full endoscopic technique, migrated nucleus, trajectory, lumbar disc herniation

INTRODUCTION

The endoscopic spinal technique has achieved satisfactory results in the treatment of lumbar disc herniation (LDH) after continuous development. Currently, the transforaminal and interlaminar approaches are the most widely used approaches. Due to foraminoplasty in the transforaminal procedure, the surgical indications have expanded. However, it still has certain limitations in the treatment of special types of LDH, such as severe prolapse and displacement. In a classification by Lee et al. (1), zone 4, with the disc far downward from the center to the inferior margin of the lower pedicle, was defined as a high-grade inferior-migrated LDH. The likelihood of missing the fragment or disconnecting the stalk is higher in far-migrated discs. Two other studies (2, 3) showed that the incomplete removal of nucleus pulposus was the most important cause of failed percutaneous endoscopic lumbar discectomy. Meanwhile, most researchers (4, 5) suggest that the complete removal of the high-grade inferior-migrated nucleus is still a challenge, because the fragmented free nucleus may increase the residual possibility.

The challenge in removing the highly down-migrated nucleus is due to an occlusion of the pedicle structure. There are some reported methods for overcoming this problem, including the supra-pedicular, contralateral transforaminal, and interlaminar approaches; *via* the adjacent interlaminar approach; dual working channels technology; and the transpedicular approach (3, 6–8). However, these studies are mostly limited as case reports due to a lack of detailed analysis. Gao et al. (5) recommended that the transpedicular approach should be adopted when performing percutaneous endoscopic lumbar discectomy treatment in patients with L5/S1 LDH. Previous studies did not elaborate on this approach and lacked an analysis of its trajectory. In this study, the transpedicular techniques, which can directly expose the migrated nucleus by cutting through a bony channel in the pedicle, will be further expounded.

MATERIALS AND METHODS

Patient Population

Between July 2014 and October 2019, 35 consecutive patients with an extremely downward-migrated LDH were included in this retrospective study. All patients were treated with full-endoscopic lumbar discectomy *via* a transpedicular approach. The inclusion criteria were as follows: (1) unilateral lower limb radiating pain, with or without lower back pain; (2) the lower limb being more painful than the lower back; (3) conservative treatment for 6–8 weeks, which was ineffective; (4) computed tomography (CT) or magnetic resonance imaging (MRI) showed symptoms and signs consistent with the respective segment; (5) MRI sagittal images showed nucleus prolapse to zone 4; and (6) patients who are willing to undergo endoscopic surgery. The exclusion criteria were as follows: (1) imaging data were inconsistent with the patient's symptoms and signs, and the diagnosis was unclear; (2) severe spinal stenosis; (3) pedicle dysplasia; (4) lumbar instability; (5) the lower pedicle of the surgical segment had pedicle screw fixation; (6) pathological changes such as infection, fracture, or tumor in the responsible segment; and (7) other diseases and inability of the patient to tolerate surgery. Informed written consent was obtained from all patients.

Surgical Procedure and Postoperative Management

Preoperative Planning

(1) By observing the position of the herniated disc and the anatomical relationship with the affected nerve root and the dural sac on CT and MRI axial images, we assessed intervertebral disc calcification, ligamentum flavum hypertrophy, lateral recess stenosis, and facet joint degeneration. The thin-layer scanning MRI sequence of the distal transect for migrated nucleus was recommended to clarify the relationship between the nerve root and the nucleus pulposus. During the measurement of the pedicle height and transverse diameter on CT scan, the transpedicular bony approach needs to meet the placement of the endoscopic working tube. The working channel diameter was 7.5 mm, implying that the pedicle bony channel should be approximately 7–8 mm.
(2) We observed the direction and degree of the migrated disc on the MRI sagittal images and the pedicle morphology on CT sagittal images. To avoid the occurrence of intraoperative fractures, it was recommended that the pedicle height be at least 12 mm for the transpedicular approach.
(3) The pedicle height was measured on the lateral radiograph, and the position of the migrated disc was marked. We observed the structural features of the pedicle.

Patient and Medical Team Positioning

The prone and lateral patient positions can be utilized for the surgery. The prone position is recommended because this position is more stable than the lateral position and conducive for the safe application of the dynamic grinding system to treat the pedicle cortex. Simultaneously, it is recommended to bend the knee and hip, because this position can reduce the lumbar lordosis, expand the intervertebral foramen, and relax the exit nerve root. The procedure was performed using dexmedetomidine as sedative and lidocaine as local anesthesia.

Portal Design

Location

The landing point needs to be moved from the superior facet to the pedicle. If the projection of the pedicle in the anteroposterior (AP) fluoroscopic view is similar to a clock (**Figure 1A**), the landing point is at 11 or 1 o'clock. According to the displacement of the prolapsed nucleus, the puncture direction should be from 11 o'clock to 2 or 3 o'clock on the right pedicle (**Figure 1B**). On the contralateral left pedicle, the puncture direction should be from 1 o'clock to 10 or 9 o'clock. The distance from the skin puncture point to the midline should be based on the patient's body type. A previous study (9) suggested that the skin puncture point should be 12 cm away from the midline at L5, 11 cm at L4, and 10 cm at L3.

Establishment of the Working Channel

After the administration of local anesthesia and sometimes combined sedation, an 18-gauge needle punctured to the point

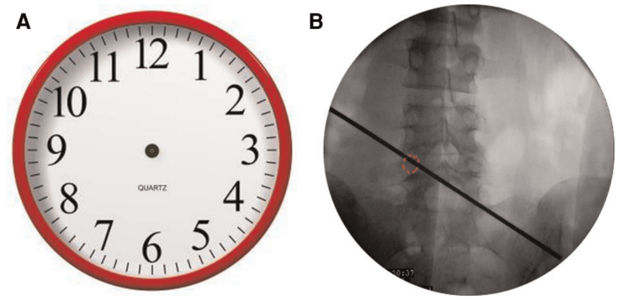

FIGURE 1 | (**A**) The projection of the pedicle in the anteroposterior fluoroscopic view is similar to a clock. (**B**) The puncture direction should be from 11 o'clock to 2 or 3 o'clock on the right pedicle.

at 11 or 1 o'clock of the pedicle on the prone position of the patient in AP fluoroscopy, and the needle tip projection in lateral fluoroscopy should be on the posterior part of the pedicle. After accurately positioning the needle, the guide wire and dilators were introduced sequentially. After the soft tissue tunnel was established, the 2.5-mm guide rod with the guide wire was replaced by the 2.5-mm Kirschner wire, which was hammered into the pedicle. The tip of the wire should not enter the median margin of the pedicle. After the Kirschner wire was stably fixed, the 6.5-mm trephine was introduced to cut the bony structure directly. The 7.5-mm trephine was used when necessary. To prevent injury to the dura and nerve root, the reaming should be stopped when it approximates the median pedicle wall, which was monitored with fluoroscopy. The 7.9-mm diameter working tube was inserted after tunnel preparation. The position of the working tube was determined by AP and lateral fluoroscopy. The 6.9-mm-diameter endoscope, which has a 30° angle of view, was introduced in the working tube. During the surgery, continuous irrigation with saline was used.

Step-by-Step Description of the Technique(s)

Exposure and Observation of the Spinal Canal Structures

First, the soft tissue was cleaned and the endoscope was placed, after which hemostasis was induced with bipolar radiofrequency. Second, the bone of the pedicular medial wall was probed (**Figure 2A**). If the medial wall was intact, the dynamic grinding system was used to open the medial wall. The use of steel bur is generally recommended. Although it is more efficient, it may cause bleeding (**Figure 2B**). There is no ligamentum flavum and less adipose tissue in the lateral recess; therefore, while entering the spinal canal, if the adipose tissue appears, the steel tip grinding drill should be replaced by a diamond bur to reduce bleeding and prevent nerve root injury. The Kerrison rongeur is a good alternative for fenestration to avoid the drill tip entering the spinal canal directly (**Figure 2C**). Third, after preparing the medial wall of the pedicle, the nerve root and prolapsed nucleus pulposus will appear directly. If the prolapsed nucleus is inferior to the posterior longitudinal ligament, the ligament was opened.

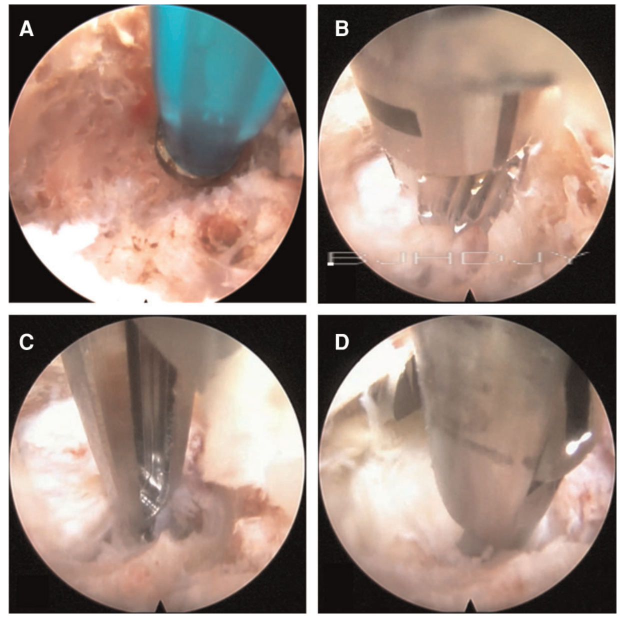

FIGURE 2 | (**A**) Checking the bone of the pedicular medial wall. (**B**) Using the cutting bur to deal with the bone tunnel. (**C**) The Kerrison Rongeur exposes the bone tunnel. (**D**) Removal of the prolapsed nucleus pulposus under the ventral side of the nerve root and dura with the 2.5-mm grasping forceps.

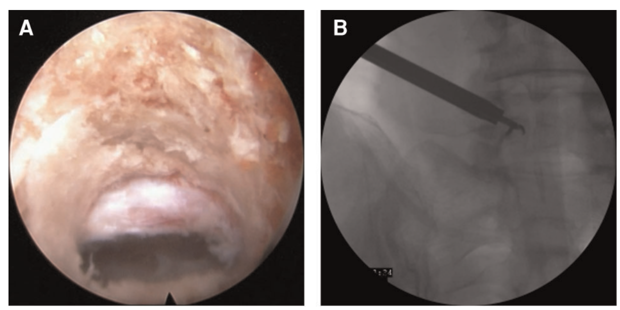

FIGURE 3 | (**A**) The bone tunnel and released nerve root. (**B**) The anteroposterior fluoroscopy to verify the position of the equipment.

Resection of the Prolapsed Nucleus Pulposus

After exploring the nerve root and prolapsed nucleus pulposus with bipolar radiofrequency and nerve probe, the prolapsed nucleus pulposus was resected under the ventral side of the nerve root and dura with a 2.5-mm grasping forceps and a semiflexible grasping forceps (**Figure 2D**). It should be noted that the ganglia structures can sometimes be observed using this approach; therefore, the surgeon should avoid irritation and injury of the ganglia. After complete decompression, the free nerve root and pure bony tunnel were observed on endoscopy (**Figure 3A**). During the surgery, in case of concern regarding the prolapsed nucleus pulposus residue, the

AP fluoroscopy was used to verify the position of the equipment (**Figure 3B**).

Before Completing the Surgery

After resection of the prolapsed nucleus pulposus, it was carefully explored to avoid nucleus pulposus residue. Bone surface bleeding can be stopped using bone wax. Before completing the surgery, we spoke to the patient to determine whether the symptoms had disappeared. If necessary, the straight leg raising (SLR) test was performed intraoperatively. When the patient's symptoms disappeared, the SLR test was negative, nerve root activity was good, and the endoscope and the working tube were removed. The surgical incision was covered with a sterile dressing after suturing, and drainage was not needed.

Complications and Management

Pedicle fracture can be avoided by adopting the following precautions: the diameter of the tunnel should not exceed 8 mm; when the endoscope is inside the tunnel, movements of the system are not recommended; and although it is possible to make the tunnel with a trephine, the use of an endoscopic bone drill under direct endoscopic visualization is highly recommended. Bone bleeding during the drilling of the pedicle can be significant and challenging to stop with the use of a radiofrequency probe. Therefore, we recommend increasing the pressure of continuous saline irrigation and the use of hemostatic agents. Hemostasis, after removing the herniated disc, should be confirmed meticulously to avoid epidural hematoma.

Postoperative Care

Patients can rise from the bed four hours after the surgery. Wearing a lumbar brace for protection while sitting and walking is recommended for 6 weeks after the surgery. Non-steroidal drugs can help relieve pain caused by local inflammation in the early stage. We encourage patients to rise from the bed and to do basic functional exercises early.

Outcome Measurement

Demographic data included sex, age, and segment involved in the surgery. The clinical data included visual analogue scale (VAS) for back and leg pain and the Oswestry disability index (ODI) for functional status. The pedicle height was measured using CT and radiography before the surgery, and the angles of trajectory were measured using CT scan postoperatively (**Figures 4A,B**). The $\angle\alpha$ is the angle from the bone tunnel to the medial wall of the pedicle on a sagittal section. The $\angle\beta$ is the angle from the bone tunnel to the posterior vertebral wall on a cross section. The modified Macnab criteria were used for satisfaction assessment in the final follow-up. All patients were followed up for over 2 years.

Statistical Analysis

The clinical results were analyzed using SPSS version 22 (IBM, Armonk, USA) software. The mean outcome scores (mean ± standard deviation) of pre- and postoperative variables were compared using repeated measures analysis of variance. $p < 0.05$ was considered statistically significant.

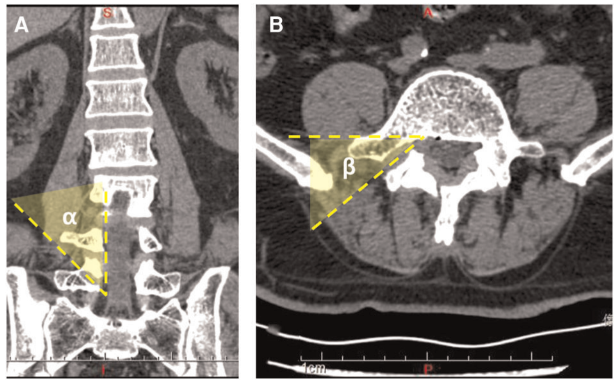

FIGURE 4 | (**A**) Three-dimensional computed tomography scan shows the angle of trajectory in the coronal plane. (**B**) Three-dimensional computed tomography scan shows the angle of trajectory in the sagittal plane.

RESULTS

All the procedures were successfully performed without converting to open surgery. The segmental level was L1/2 in 1 case, L2/3 in 1 case, L3/4 in 4 cases, L4/L5 in 27 cases, and L5/S1 in 2 cases. The mean age of patients was 50.7 ± 10.1 years. The mean duration of surgery was 67.7 ± 12.5 min. The mean preoperative VAS of back pain score was 1.9 ± 0.9, which improved to 0.9 ± 0.8, 1.0 ± 0.7, 1.0 ± 0.8, 0.9 ± 0.9, and 0.9 ± 0.8 at post surgery, 3 months, 6 months, 12 months, and 24 months after surgery, respectively (**Figure 5A**). The mean preoperative VAS of leg pain score was 6.2 ± 1.6, which improved to 1.9 ± 0.8, 1.6 ± 0.5, 1.0 ± 0.8, 0.8 ± 0.9, and 0.9 ± 0.8 at post surgery, 3 months, 6 months, 12 months, and 24 months after surgery, respectively ($p < 0.05$) (**Figure 5B**). The VAS of leg pain showed further improvement at 6 months after surgery compared with that at post surgery. The ODI improved from 57.6 ± 18.8 preoperatively to 7.5 ± 5.0 at the final follow-up ($p < 0.05$) (**Figure 5C**). The VAS and ODI scores significantly improved at each postoperative time point. The good-to-excellent rate in patients was 85.7% (30/35); 18 reported excellent results, 12 reported good results, 5 evaluated their results as fair, and none reported a poor outcome (**Figure 5D**).

For the imaging parameters, the mean angles of bone tunnel trajectory were 34.5° ± 2.9° ($\angle\alpha$) and 47.1° ± 5.0° ($\angle\beta$), respectively. The mean value of the pedicle height was 12.8 ± 1.1 mm. The mean follow-up was at 42.6 ± 12.6 months. The bone tunnel was found on postoperative CT scan, and no pedicle fractures were observed in the cohort (**Figures 6A,B**). During the follow-up at 6 months, the hole was healed in all patients compared with that in the postoperative CT scan (**Figures 6C,D**).

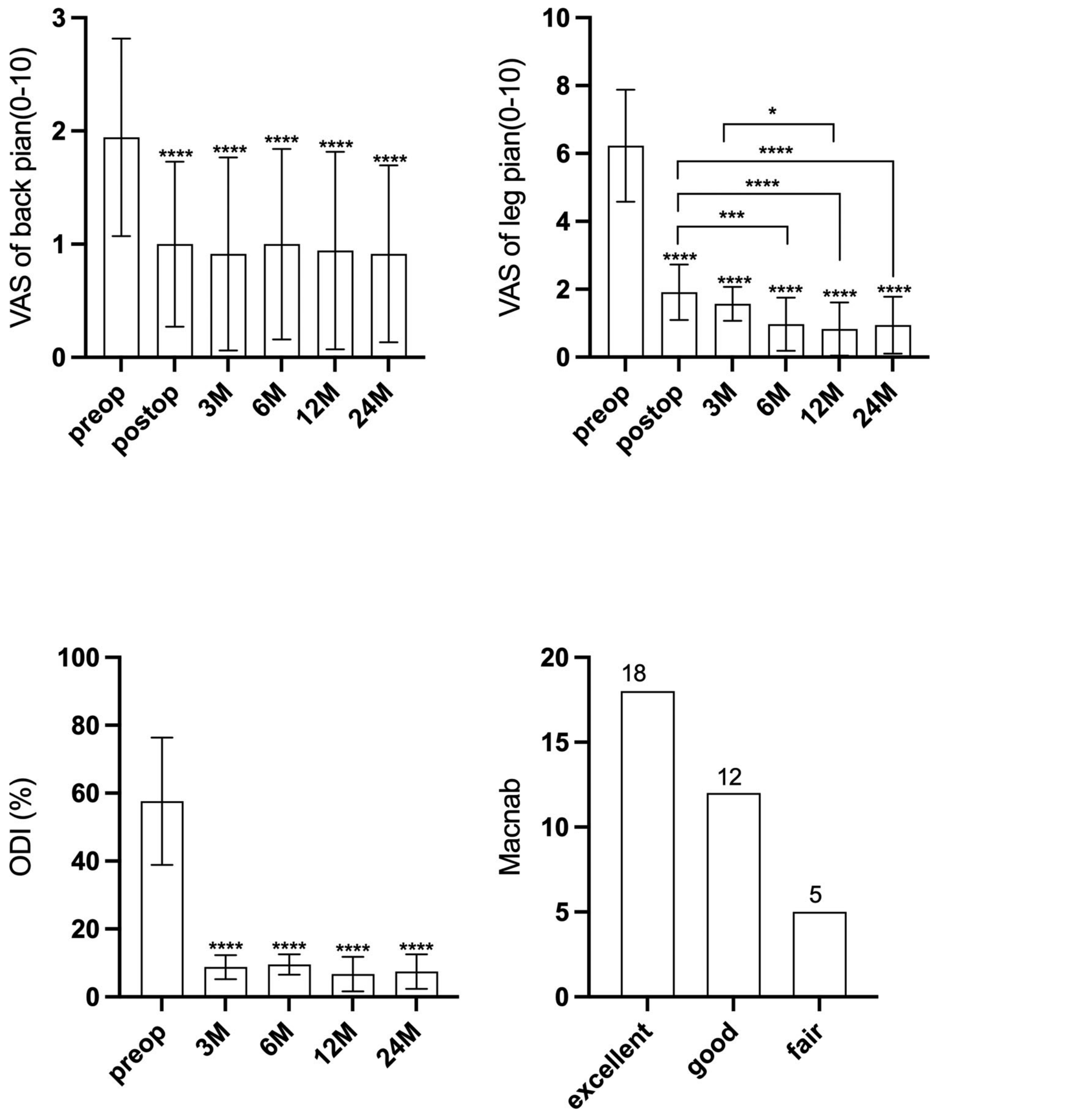

FIGURE 5 | (**A**) The visual analogue scale score of back pain at different intervals. (**B**) The visual analogue scale score of leg pain at different intervals. (**C**) The Oswestry disability index score at different intervals. (**D**) The Macnab criteria at last follow-up.

Typical Case

A 66-year-old man presented with lumbosacral pain that had been ongoing for 2 years, which developed to aggravating pain accompanied by radiation pain and numbness in the right lower extremity for over 3 months. Conservative treatment failed. The patient was in a wheelchair when he was admitted to the ward. There was no deformity of the spine, the muscles of all extremities had no atrophy or hypertrophy, and lumbar movement was limited. Interspinous tenderness was found at the L4/5 level, and dorsiflexion myodynamia of the right first toe was of grade II. The rest of the bilateral extremity muscles were normal. The skin sensation of both lower extremities was normal, except the skin at the lateral right calf, lateral right ankle, and dorsum of the right foot. The SLR test was positive (45°) for the right leg. The femoral nerve stretching test was negative. The knee and Achilles tendon reflexes were normal. The VAS score of the back was 3; the VAS score of the right leg was 8; and the ODI score was 80%. Preoperative imaging data included (1) a lumbar spine radiograph (**Figure 7**) that showed lumbar degeneration without lumbar scoliosis, spondylolisthesis, or instability and (2) a CT scan in the sagittal, coronal, and axial planes showed that the distal end of the prolapsed nucleus pulposus was downward beyond the inferior margin of the L5 pedicle, implying that it was classified as type 4 according to Lee's classification. The L5 pedicle height was 11.3 mm. MRI in the sagittal plane showed that the L4/5 nucleus pulposus migrated downward substantially (**Figure 8**).

In the prone position, the patient flexed his bilateral hip and knee joints on the operating table. Guided by the C-arm fluoroscopy, the marker line, connecting from 1 to 10 o'clock on the pedicular projection, was marked on the back skin (**Figure 9**). To easily distinguish the prolapsed nucleus pulposus, intervertebral disc puncture surgery under local anesthesia was performed, and 1:10 methylene blue was injected into the disc to stain the nucleus pulposus.

The Kirschner wire was advanced from the skin entry point to the target vertebral pedicle along the marker line on the skin.

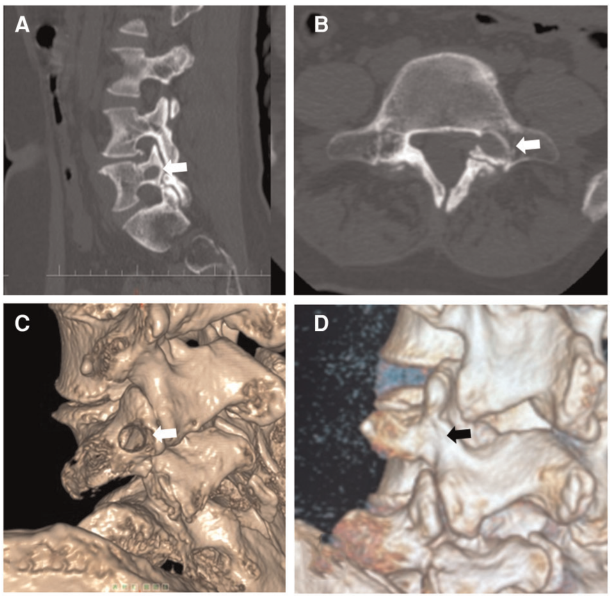

FIGURE 6 | (**A**) Postoperative computed tomography shows a bone tunnel in the sagittal plane. (**B**) Postoperative computed tomography shows a bone tunnel in the horizontal plane.

AP position C-arm fluoroscopic images were used to confirm the wire's final position (**Figure 10**). The wire was then tapped into the pedicle with a surgical hammer. Soft tissue was progressively expanded by the dilators. The pedicular bone around the Kirschner wire was sawn by the trephine (Figure **11A**). A lump of bone was extracted by the first trephine (Figure **11B**). This step was monitored by C-arm fluoroscopy. The medial wall of the pedicle was the safety margin (Figures **11C,D**). A working channel was established after removing the trephine (**Figure 12**).

The L5 traversing nerve root and the prolapsed nucleus pulposus (at the ventral side of the L5 traversing nerve root) could be directly exposed under the endoscope *via* the transpedicular approach (**Figure 13A**). There was no yellow ligament and annulus fibrosus in this view, due to which we could expose the posterior vertebral wall and posterior longitudinal ligament after the free nucleus pulposus was removed (**Figure 13B**). Further exploration from distal to proximal aspect was performed to ensure that all the free nucleus pulposus was removed, and the whole traversing nerve root was not compressed (Figure **13C**). After hemostasis, the bony channel in the pedicle could be observed when the endoscope was withdrawn (Figure **13D**).

The radiation pain in the right lower extremity was rapidly relieved after surgery. The SLR test was negative. The postoperative three-dimensional CT reconstruction image showed the entrance and exit of the bony channel on the pedicle (Figures **14A,B**). Bony channels at the sagittal and coronal sections and in the cross section were observed. The postoperative MRI images showed good decompression (Figure **14C**).

DISCUSSION

Patients with a highly migrated nucleus remain challenging for endoscopic discectomy, although the technique has been widely

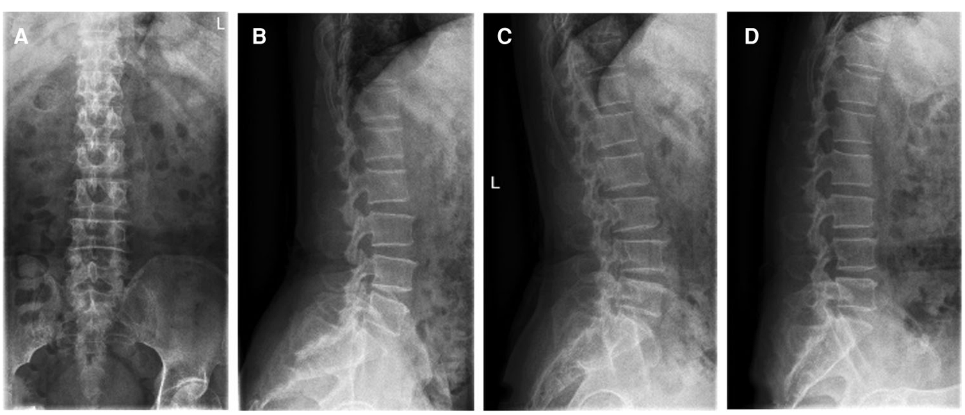

FIGURE 7 | (**A**) The anteroposterior view of the radiograph shows no scoliosis. (**B**) The lateral view of the radiograph shows no spondylolisthesis. (**C**) The extension view of the radiograph shows no instability. (**D**) The flexion view of the radiograph shows no instability.

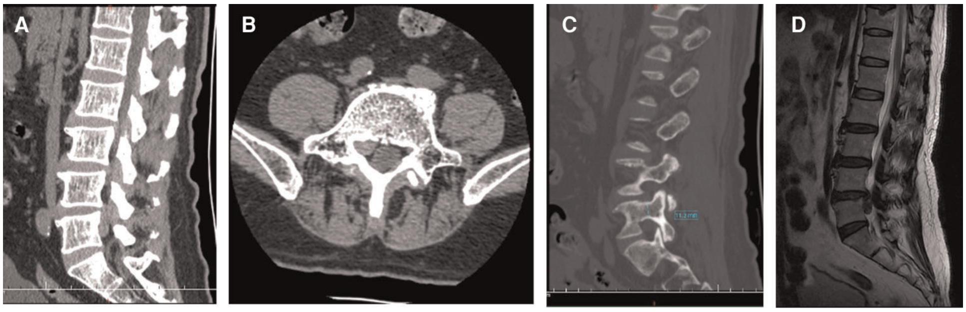

FIGURE 8 | (**A**) Computed tomography scan shows that the distal end of the prolapsed nucleus pulposus is downward beyond the inferior margin of the L5 pedicle. (**B**) Computed tomography scan shows the migrated nucleus that compressed the nerve root. (**C**) The measurement of the pedicle height is 11 mm. (**D**) The magnetic resonance imaging shows that the migrated herniation can be classified into type 4 according to Lee's classification.

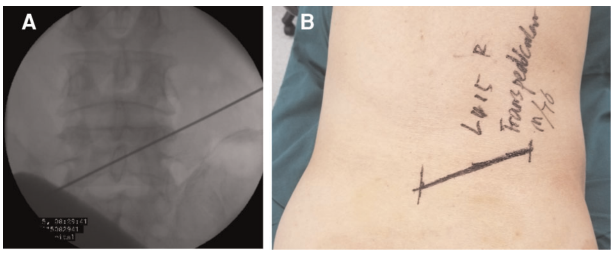

FIGURE 9 | (**A**) Identification of the trajectory guided by the C-arm fluoroscopy. (**B**) The marker line is drawn, connecting from 1 to 10 o'clock on the pedicular projection.

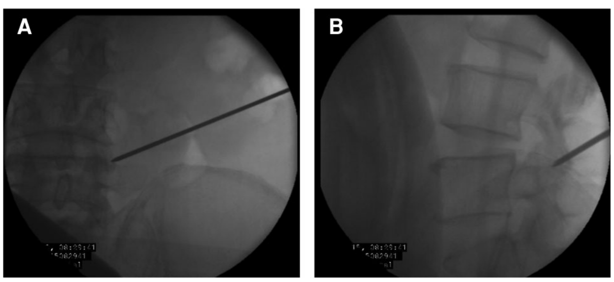

FIGURE 10 | (**A**) The Kirschner wire position by the anteroposterior position of C-arm fluoroscopy. (**B**) The Kirschner wire position by the lateral position of C-arm fluoroscopy.

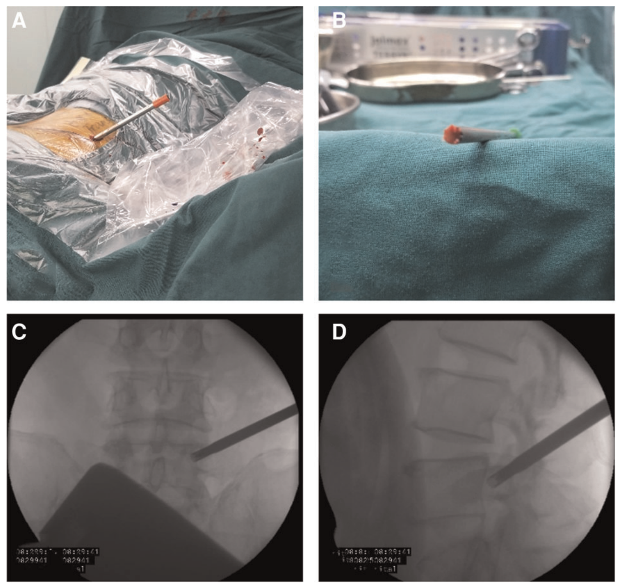

FIGURE 11 | (**A**) The pedicular bone around the Kirschner wire is sawn by the trephine. (**B**) Bone can be brought out by the trephine. (**C**) The medial wall of the pedicle is the safety margin in the anteroposterior view. (**D**) The lateral view of the radiograph shows the position of the trephine.

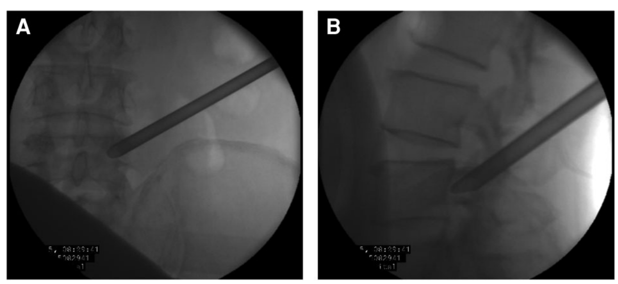

FIGURE 12 | (**A**) The working tube position in the anteroposterior view. (**B**) The working tube position in the lateral view.

improved in past decades. In the present case, the displaced nucleus certainly increased the complexity of the procedure because of the occlusion of the bone and nervous structures. During the surgery *via* transforaminal approach, the exiting nerve root usually opposes the manipulation of the endoscope in case of an upward-migrated herniation, and the pedicle could be the obstacle to the downward-migrated herniation.

Lee et al. (1) developed a classification based on the location of the nucleus pulposus that is displaced on the sagittal plane of the MRI and noted that the type of severe upward- and downward-migrated prolapses was not suitable for treatment with transforaminal approach endoscopic surgery due to a high failure rate, and traditional surgery was recommended. Choi et al. (10) proposed that the interlaminar approach can provide more exposure space to deal with a highly migrated disc herniation and is superior to endoscopic surgery *via* the transforaminal approach. A study (11) that compared the efficacy and safety of interlaminar endoscopic lumbar discectomy (IELD) and interlaminar microscopic lumbar discectomy (IMLD) to treat far-migrated LDH noted that both IELD and IMLD achieved favorable clinical results in the treatment of far-migrated LDH, with only minor complications. Compared with IMLD, low back pain was significantly reduced with IELD, presumably because it involved less trauma. Gizatullin et al. (12) compared the clinical outcomes after translaminar microsurgical sequestrectomy and transpedicular endoscopic surgeries and noted that the results were similar. However, postoperative back and leg pain regression, neurological recovery, and improvement in the quality of life according to the Oswestry scoring system were more common after transpedicular surgery. Meanwhile, if the interlaminar space is small, it is necessary to expand the bony window. Nevertheless, the nerve root is inevitably pulled and pushed several times during the surgery using the interlaminar approach, and some patients may have abnormal neural reactions after the surgery. In cases under local anesthesia, it is a challenge to the patients' endurance and the surgeons' mentality.

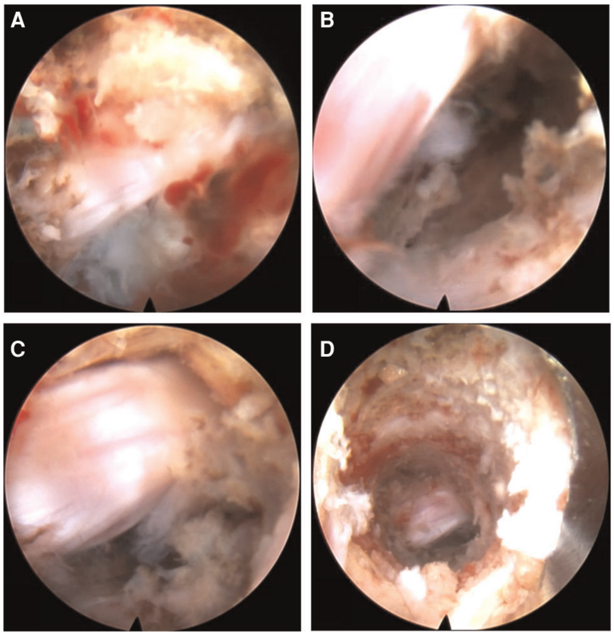

FIGURE 13 | (**A**) The nerve root and the blue-staining nucleus pulposus. (**B**) The decompressed nerve root after discectomy. (**C**) The completely free nerve root. (**D**) The bone tunnel *via* the pedicle.

Krozk et al. (9) was the first researcher to handle a severely downward-migrated disc herniation through a bony channel, attempting to establish a bony channel vertically on the pedicle, in which good clinical results were achieved in the treatment of patients. This technique was later duplicated by some other researchers and similar experiments were conducted, but most of them were limited to case reports. The technique was not elaborated in detail, and long-term clinical follow-up was lacking, especially for the outcome of bony defects caused by creating the approach, which led to a lack of clarity (13–15). In a study in 2007, our team identified that for a highly migrated disc herniation, transforaminal, interlaminar, and transpedicular approaches can all be good at removing the protruding and displaced nucleus pulposus, of which the transpedicular approach is more direct, but requires good technical and equipment support (16). The method of entering the pedicle that we used in this study differed from

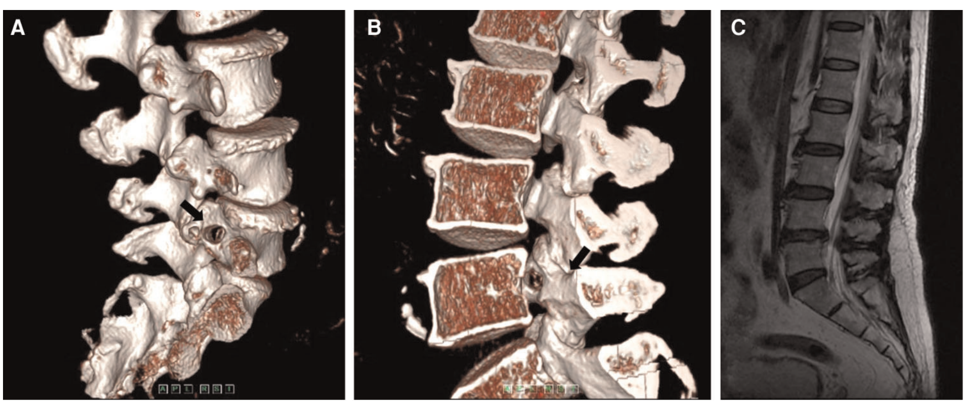

FIGURE 14 | (**A**) The postoperative computed tomography shows the entrance of the bony channel on the pedicle. (**B**) The postoperative computed tomography shows the exit of the bony channel on the pedicle. (**C**) The postoperative magnetic resonance imaging shows no residual matter.

that in the previous study with the vertical trajectory. We used a certain angle to enter the pedicle from the exterior superiorly to the interior inferiorly. The vertical entry into the pedicle to create a bone channel requires high anatomical parameters of the pedicle, and if the height of the pedicle is extremely small, the possibility of fracture and surgical failure is high. Previous research was mostly limited to European races; this interracial anatomical characteristic may not have been a consideration for previous scholars. Our cases were obtained from the Chinese population, in which the body shape and anatomical parameters varied from those of western populations. The pedicle height of the patients in this study was 11–14 mm; using a method with a certain angle to enter the pedicle could avoid this disadvantage. The lumbar segment artery travels on the side of the lumbar vertebral body, and the trephine or working cannula slides forward along the vertical trajectory; therefore, the possibility of injury to the segmental artery is extremely high. This injury can have terrible consequences, triggering retroperitoneal hemorrhage and even shock. This kind of complication, although never reported in the previous transpedicular approach discectomy, has occurred during vertebroplasty in the extra-pedicle approach with the same trajectory (17).

It is easier to enter the pedicle at a certain angle. First, the position of the bony anchor point is the deformation structure of the pedicle and the superior articular process, which has a small notch and is easily anchored by the Kirschner wire. Although the entrance we chose was on the upper pedicle, the opening in the spinal canal was still facing the position of the migrated nucleus (**Figure 14**). Furthermore, we could use the endoscopic 30°-angle of view to observe the proximal and distal areas and utilize some flexible tools to grasp the nucleus. During the procedure, we found that the angle between the bony tunnel and the posterior vertebral wall was the important parameter for trajectory. The angle was extremely small to explore the central region of the spinal canal. We suggest that the angle between the bony tunnel and the posterior vertebra wall should be 40°. The obvious disadvantage of this technique is that it is difficult to deal with the intervertebral space due to the limitation of the working channel in this trajectory. If necessary, it can be withdrawn from the working canal and re-entered into the intervertebral space to address the herniation through the Kambin triangle zone. In this study, we did not treat the intervertebral space again. We suggest that if the prolapsed nucleus pulposus is larger, only the discectomy in the spinal canal can be completed by the release of the nerve root. In previous studies (18), the removal of the sequestrated disc in the spinal canal and aggressive resection were compared, showing that the patient satisfaction at 2-year follow-up was higher in the limited discectomy group with a high recurrence rate. During our long-term follow-up, there was no recurrence in this group. Theoretically, the risk of recurrence might be high, because the surgery *via* the transpedicular approach cannot reach the intervertebral space. However, the fact is that most of the nucleus pulposus had prolapsed into the spinal canal and there were few residues in the intervertebral space. The number of cases in our study was small, and large samples are needed to determine the reliability of this approach in further research.

Through our regular follow-up of patients after surgery, we found that the patient's bony channels had healed after 6 months, which was similar to the phenomenon in which the nail tunnel heals after internal fixation removal in long bone fractures, and also follows the principle of Wolff's law.

In our opinion, precise preoperative measurement and design are essential for the transpedicular approach. A basic condition for choosing the transpedicular approach is adequate pedicle height. The oblique trajectory through the pedicle is convenient for directly finding and removing the migrated nucleus pulposus with a low risk of blood vessel injury (among pedicle and vertebral body). Care should be taken when using a trephine, and a grinding drill can be used as an assistant tool to reduce the risk of nerve root injury while establishing the bony channel. When the decompression range is found to be insufficient during the operation, the bone access can be enlarged by using drills to obtain flexible angle for decompression procedure. However, it must be noted that the use of drills to expand bone access must be performed under the guidance of the C-arm to avoid pedicle fractures.

CONCLUSION

The new trajectory of the transpedicular approach with the full endoscopic technique for an extremely downward-migrated disc herniation showed excellent results in a small sample study. A precise surgical plan should be made, including measurements of pedicle height and angle of the bone tunnel.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Beijing Haidian Hospital Medical Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

The corresponding author contributed to the operation and the design of the study. RZ and SY were in charge of data collection. JZ and MM contributed to the information of follow-up. JL contributed to the pictures' adjustment and statistical analysis. All authors contributed to the article and approved the submitted version.

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Percutaneous Endoscopic Posterior Lumbar Interbody Fusion with Unilateral Laminotomy for Bilateral Decompression Vs. Open Posterior Lumbar Interbody Fusion for the Treatment of Lumbar Spondylolisthesis

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Background: Endoscopic lumbar interbody fusion is a new technology that is mostly used for single-segment and unilateral lumbar spine surgery. The purpose of this study is to introduce percutaneous endoscopic posterior lumbar interbody fusion (PE-PLIF) with unilateral laminotomy for bilateral decompression (ULBD) for lumbar spondylolisthesis and evaluate the efficacy by comparing it with open posterior lumbar interbody fusion (PLIF).

Methods: Twenty-eight patients were enrolled in PE-PLIF with the ULBD group and the open PLIF group. The perioperative data of the two groups were compared to evaluate the safety of PE-PLIF with ULBD. The visual analog scale (VAS) back pain, VAS leg pain, and Oswestry Disability Index (ODI) scores of the two groups preoperatively and postoperatively were compared to evaluate clinical efficacy. Preoperative and postoperative imaging data were collected to evaluate the effectiveness of the operation.

Results: No differences in baseline data were found between the two groups ($p > 0.05$). The operation time in PE-PLIF with the ULBD group (221.2 ± 32.9 min) was significantly longer than that in the PLIF group (138.4 ± 25.7 min) ($p < 0.05$), and the estimated blood loss and postoperative hospitalization were lower than those of the PLIF group ($p < 0.05$). The postoperative VAS and ODI scores were significantly improved in both groups ($p < 0.05$), but the postoperative VAS back pain score in the PE-PLIF group was significantly lower than that in the PLIF group ($p < 0.05$). The excellent and good rates in both groups were

Abbreviations: CSAC, cross-sectional area of the spinal canal; DH, disc height; IAP, inferior articular process; LLA, lumbar lordotic angle; ODI, Oswestry Disability Index; PE-PLIF, percutaneous endoscopic posterior lumbar interbody fusion; PLIF, posterior lumbar interbody fusion; RLS, reduction rate of lumbar spondylolisthesis; SAP, superior articular process; SLA, segmental lordotic angle; ULBD, unilateral laminotomy for bilateral decompression; VAS, visual analog scale

96.4% according to MacNab's criteria. The disc height and cross-sectional area of the spinal canal were significantly improved in the two groups after surgery ($p < 0.05$), with no difference between the groups ($p > 0.05$). The fusion rates in PE-PLIF with the ULBD group and the PLIF group were 89.3% and 92.9% ($p > 0.05$), respectively, the cage subsidence rates were 14.3% and 17.9% ($p > 0.05$), respectively, and the lumbar spondylolisthesis reduction rates were 92.72 ± 6.39% and 93.54 ± 5.21%, respectively ($p > 0.05$).

Conclusion: The results from this study indicate that ULBD can be successfully performed during PE-PLIF, and the combined procedure is a safe and reliable treatment method for lumbar spondylolisthesis.

Keywords: unilateral laminotomy for bilateral decompression, percutaneous endoscopy, posterior lumbar interbody fusion, lumbar spondylolisthesis, lumbar spinal stenosis

INTRODUCTION

Joson and McCormick (1) reported a unilateral approach for bilateral decompression with preservation of the supraspinous ligament complex. Poletti (2) initially utilized unilateral laminotomy for bilateral ligamentectomy for lumbar stenosis caused by a thickened ligamentum flavum by establishing a working area through the excision of the ipsilateral laminae and spinous process roots, followed by partial excision of the contralateral lamina and ligamentum flavum to decompress the spinal canal. Spetzger et al. (3) first proposed the concept of unilateral laminotomy for bilateral decompression (ULBD). With advancements in technology, surgeons introduced tubular technology and endoscopic technology into ULBD, achieving satisfactory clinical outcomes (4–7).

Endoscopic lumbar interbody fusion is a new technology and a research hotspot with many advantages, such as significant improvement in surgical visualization and enhanced recovery after surgery (8). We performed percutaneous endoscopic posterior lumbar interbody fusion (PE-PLIF) in 2019. PE-PLIF is a uniportal endoscopic technique with the working channel established through the excision of the medial part of the facet joint and part of the ipsilateral lamina. This methodology has been shown to be a safe and effective method in our preliminary studies (9).

However, for patients with lumbar spondylolisthesis complicated by neurological symptoms in both lower extremities or intermittent claudication, the unilateral approach of PE-PLIF is not suitable, and the bilateral PE-PLIF will obviously increase surgical trauma and operative time in our experience. Therefore, we combined PE-PLIF with ULBD to treat such patients. This report discusses the differences between ULBD procedures in PE-PLIF and classical ULBD procedures and evaluates the safety and efficacy of PE-PLIF with ULBD by comparing it with open PLIF.

MATERIALS AND METHODS

Study Design

This study was approved by the Ethics Committee of Shanxi Bethune Hospital, and written permission was obtained from all included patients. This study was a retrospective study using the guidelines of Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) (10). All surgeries were performed by a team of surgeons. The inclusion criteria were as follows: (1) single-segment lumbar spondylolisthesis (Meyerding grades I and II) with lumbar spinal stenosis; (2) conservative treatment was ineffective for more than 3 months, or symptoms were progressively aggravated; and (3) an age over 18 years. The exclusion criteria were as follows: (1) multisegment lumbar degenerative disease shown by imaging examination and (2) spinal deformities, old fractures, ankylosing spondylitis, or rheumatoid arthritis. For convenience, "the PE-PLIF group" in the text denotes PE-PLIF with ULBD.

Surgical Techniques

PE-PLIF with ULBD: PE-PLIF has been described in detail in previous reports (9). The briefly described procedures are as follows: The patient is placed in the prone position after the induction of general anesthesia. The insertion point is marked at approximately 2 cm from the midline under anteroposterior X-ray. A longitudinal incision of approximately 13 mm is created after positioning the insertion point. After gradually expanding the soft tissues, a working sleeve (11-mm inner diameter) and an endoscope are placed (LUSTA endoscope system, Spinendos, Germany, a 10-mm outer diameter, 7.1-mm working channel, and 15° view angle). The medial portion of the articular process is excised until the working tube can be safely accommodated (**Figure 1A**). A part of the ligamentum flavum is excised to expose the nerve roots, the dural sac, and the intervertebral disc. The nerve roots are protected, discectomy is performed, and endplates are placed. The endoscopy is removed and a funnel-shaped bone graft device is inserted. After grafting the bone into the intervertebral space, an expandable interbody fusion cage is placed and expanded to a suitable height (9–13 mm) under a C-arm (**Figure 1B**). In this procedure, the bevel of the cannula is toward the lateral side to prevent the nerve roots from entering the working space. ULBD is performed as detailed in previous reports (5, 11), with a brief

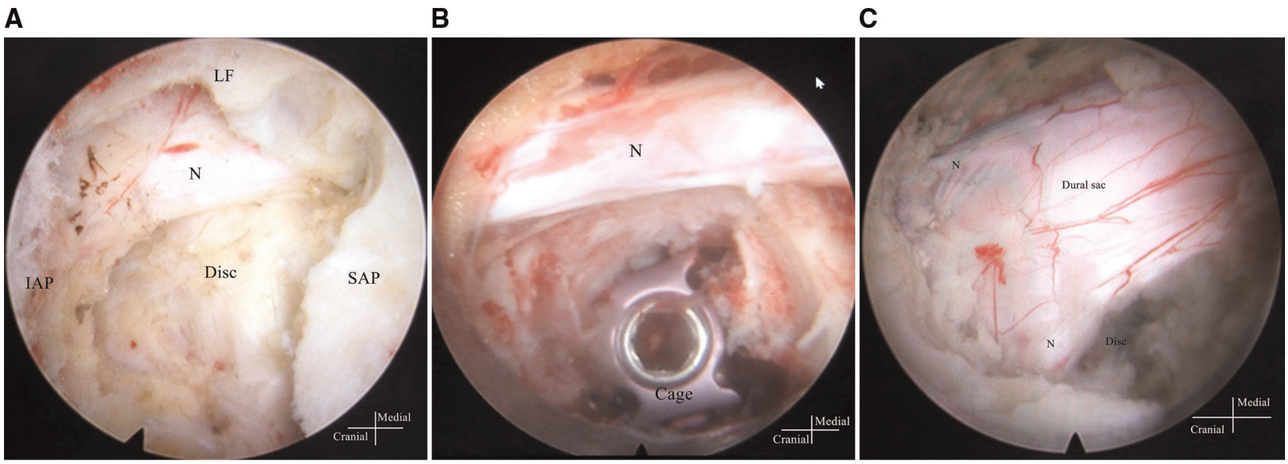

FIGURE 1 | Images under endoscopy. (**A**) The SAP is exposed after the IAP is excised, and the nerve root and disc are exposed after the SAP is excised. (**B**) The cage and the nerve root after inserting the cage. (**C**) The dural sac and the bilateral nerve root after unilateral laminotomy for bilateral decompression. SAP, superior articular process; IAP, inferior articular process; LF, ligamentum flavum; N, nerve root.

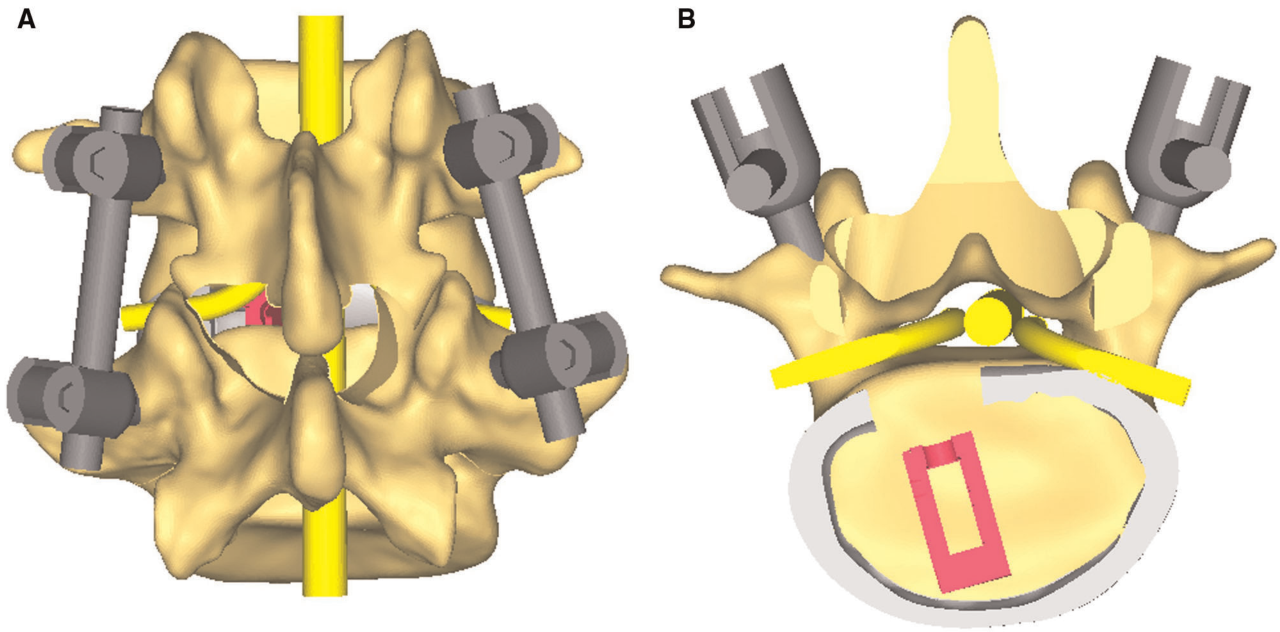

FIGURE 2 | (**A**) A 3D schematic diagram of percutaneous endoscopic posterior lumbar interbody fusion with unilateral laminotomy for bilateral decompression. (**B**) A cross-sectional schematic diagram.

description provided as follows: A grinding drill and a lamina forceps are used to excise the margin of the ipsilateral superior lamina until the superior limit of the ligamentum flavum attachment and the margin of the ipsilateral inferior lamina. The ipsilateral ligamentum flavum is excised. The base of the spinous process is sawed off to expose the contralateral ligamentum flavum and lamina. The contralateral lamina and ligamentum flavum are excised in the same manner. Finally, a part of the contralateral articular process is excised to expose the contralateral nerve root, and decompression is performed (**Figure 1C**). After endoscopic examination of the decompression and fusion cage location, bilateral percutaneous pedicle screw internal fixation is performed. **Figure 2** shows a schematic diagram of PE-PLIF with ULBD and **Figure 3** shows a postoperative CT reconstruction image.

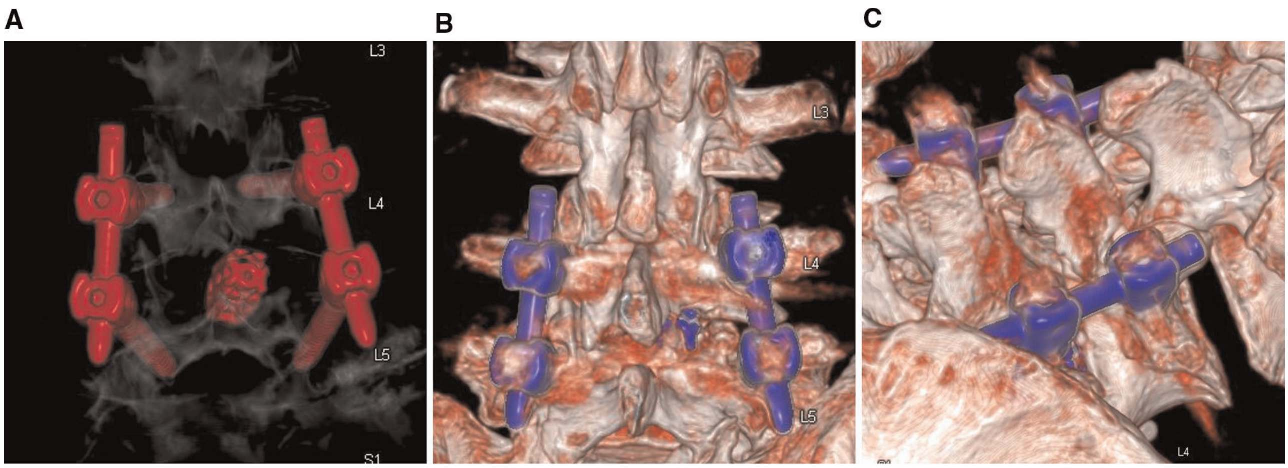

FIGURE 3 | CT reconstructed images. (**A,B**) The extent of intraoperative laminectomy and facetectomy. (**C**) The base of the spinous process is excised.

Open PLIF: The patient is placed in the prone position after the induction of general anesthesia. The operative segment is determined under a C-arm. A posterior median incision of approximately 8 cm is created. The paraspinal muscles are split to expose the lamina and bilateral facet joints. Complete laminar decompression is performed. The medial parts of the superior and inferior facet joints are excised to expose the nerve roots. The nerve roots and dural sac are protected, the intervertebral disc is excised, and endplates are prepared. After testing the model, a conventional cage filled with autologous bone and osteoinductive materials is placed into the intervertebral space. Pedicle screw internal fixation is performed on the operative segment.

Clinical Evaluation

Perioperative data: Operation time: the time between needle positioning and skin suture. Estimated blood loss: Intraoperative blood loss plus the postoperative drainage volume. If the patient has cerebrospinal fluid leakage, the bleeding volume can be estimated by stratifying the drainage fluid. Complications: Surgery-related complications occurring during the operation or within 1 month after the operation. Postoperative hospital stay: The number of days between the day of surgery and the day of discharge.

Clinical results: VAS scores (0–10) for back pain and leg pain were recorded before surgery, 1 week after surgery, 1 month after surgery, 6 months after surgery, and at the last follow-up. The ODI score (0–100) was recorded to evaluate functional status before surgery, 1 month after surgery, 6 months after surgery, and at the last follow-up. Patient satisfaction rates were calculated according to the MacNab criteria (12). All questionnaires were completed by a doctor during an appointment or via telephone. At the same time, a quality controller was set up to evaluate the quality of the questionnaire.

Imaging Evaluation

Preoperative and postoperative imaging data were measured and are listed below. Lumbar lordotic angle (LLA): the angle between the parallel line of the superior end plate of the lumbar 1 vertebra and the parallel line of the superior end plate of the sacrum. Segmental lordotic angle (SLA): L4–L5 is the angle between the parallel line of the upper end plate of L4 and the parallel line of the lower end plate of L5, and L5–S1 is the angle between the upper end plate of L5 and the upper end plate of S1. Disc height (DH): The average value of the distance from the upper endplate to the lower endplate. Cross-sectional area of the spinal canal (CSAC): The area of the spinal canal is measured on T2WI axial images. The front is bounded by the intervertebral disc, the back is bounded by the anterior border of the ligamentum flavum, and the two sides are bordered by the outer border of the nerve root. The above parameters were measured according to the study of Lin et al. (13). Reduction rate of lumbar spondylolisthesis (RLS): (the relative displacement distance of vertebral body on preoperative lateral X-ray – the relative displacement distance of vertebral body on postoperative lateral X-ray) / the relative displacement distance of the vertebral bodies on preoperative lateral X-ray. These distances were measured using the techniques described by Posner et al. (14) and Dupuis et al. (15). Fusion evaluation: The Birdwell criteria (16) were used to evaluate the X-ray or CT images at the last follow-up. Cage subsidence was defined as a cage entering the endplate by more than 2 mm (13). The LLA, SLA, DH, or CSAC changes were calculated as the postoperative data minus the preoperative data. All imaging measurements were performed on the picture archives communication system, syngo.plaza (Siemens, Germany). All data were evaluated by two senior spine surgeons who were blinded to the situation.

Statistical Analysis

The data are displayed as the mean ± standard deviation. Continuous variables such as age, VAS score, ODI score, SLA, LLA, and DH were analyzed with the independent sample t-test for intergroup comparisons and the paired t-test for intragroup comparisons. Nominal data, such as segment, satisfaction rate, and fusion rate, were analyzed with the χ^2 test or Fisher's exact test. A p-value <0.05 was considered indicative of statistical significance. Statistical analysis was performed using IBM SPSS, version 26.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Demographic Data

Fifty-six patients between January 2020 and August 2020 were included according to the inclusion and exclusion criteria, with 28 cases in the PE-PLIF group, an average age of 59.8 ± 10.9 years (31–78 years), 14 males and 14 females, 20 cases at the L4–L5 segment, and 8 cases at the L5–S1 segment. In addition, 28 patients in the PLIF group were included as the control group: the average age was 54.2 ± 10.3 years (31–74 years), with 13 males and 15 females, 17 cases at the L4–L5 segment, and 11 cases at the L5–S1 segment. Detailed demographic data are given in **Table 1**. No significant difference was found in the baseline characteristic data between the PE-PLIF and the open PLIF groups ($p > 0.05$) (**Table 1**).

Perioperative Outcomes

The operative time in the PE-PLIF group was significantly longer than that in the PLIF group ($p < 0.05$), with an average of 33.3 ± 6.7 min for the ULBD procedure. The estimated blood loss and postoperative hospitalization rate in the PE-PLIF group were significantly lower than those in the PLIF group ($p < 0.05$) (**Table 1**). One patient in the PE-PLIF group experienced a dural tear, and the drainage tube was removed the day after the operation. The patient did not have any related symptoms. One patient in the PLIF group experienced a dural tear, and the drainage tube was removed 10 days after surgery when the volume of drainage was significantly reduced.

TABLE I | Comparison of demographic data and perioperative data.

	PE-PLIF (*n* = 28)	Open PLIF (*n* = 28)	*p*
Age (years)	59.8 ± 10.9	54.2 ± 10.3	0.053
Sex ratio (male/female)	14/14	13/15	0.789[a]
BMI	24.6 ± 2.0	24.4 ± 3.5	0.851
Smoke (yes/no)	11/17	8/20	0.573[a]
Diabetes mellitus (yes/no)	2/26	3/25	1.000[a]
Osteoporosis (yes/no)	2/26	2/26	1.000[a]
Segment (L4–L5/L5–S1)	20/8	17/11	0.397[a]
Meyerding grade (I/II)	11/17	13/15	0.787[a]
Mean follow-up (months)	18.4 ± 1.3	18.9 ± 1.7	0.161
Operative times (min)	221.2 ± 32.9	138.4 ± 25.7	<0.001
ULBD time (min)	33.3 ± 6.7		
Estimated blood loss (ml)	169.2 ± 49.5	649.6 ± 119.9	<0.001
Postoperative hospitalization (days)	3.5 ± 0.6	7.3 ± 1.5	<0.001

BMI, body mass index; PE-PLIF, percutaneous endoscopic posterior lumbar interbody fusion; Open PLIF, open posterior lumbar interbody fusion.
[a]*Results from Fisher's exact test or χ^2 test.*

Clinical Efficacy

No significant differences in preoperative scores were identified between the two groups ($p > 0.05$). Both groups had significantly improved postoperative VAS back pain, VSA leg pain, and ODI scores ($p < 0.05$). The VAS back pain score in the PE-PLIF group was lower than that in the PLIF group at each postoperative time point ($p < 0.05$). No significant difference in the VAS leg pain score was noted between the two groups at any postoperative time point ($p > 0.05$). One month after the operation, the ODI score in the PE-PLIF group was lower than that in the PLIF group. No significant difference in the ODI score was found between the two groups at other postoperative time points ($p > 0.05$) (**Table 2**). The above results indicated that the lower back pain score in the PE-PLIF group was lower than that in the PLIF group, and the PE-PLIF group recovered faster than the PLIF group. According to the MacNab criteria, the PE-PLIF group had excellent outcomes in 20 cases, good outcomes in 7 cases, and a fair outcome in 1 case. PLIF group: excellent outcomes in 21 cases, good outcomes in 6 cases, and a fair outcome in 1 case. The excellent and good rates in both groups were 96.4%.

Radiographic Parameters

No significant differences in preoperative radiographic parameters were identified between the two groups ($p > 0.05$), except for the LLA ($p < 0.05$). Since a difference in the LLA was found between the two groups, LLA changes were compared to evaluate the

TABLE 2 | The clinical outcomes of the two groups.

	PE-PLIF (*n* = 28)	Open PLIF (*n* = 28)	*p*
VAS back pain			
Preoperation	4.61 ± 1.42	4.64 ± 1.39	0.925
Postoperation			
1 week	2.25 ± 0.65*	3.21 ± 0.42*	<0.001
1 month	1.46 ± 0.58*	2.04 ± 0.51*	<0.001
6 months	0.79 ± 0.57*	1.14 ± 0.52*	0.018
Last	0.64 ± 0.49*	1.14 ± 0.36*	<0.001
VAS leg pain			
Preoperation	6.29 ± 0.85	6.21 ± 0.88	0.759
Postoperation			
1 week	2.46 ± 0.74*	2.32 ± 0.55*	0.417
1 month	1.21 ± 0.50*	1.36 ± 0.49*	0.283
6 months	0.71 ± 0.60*	0.89 ± 0.42*	0.201
Last	0.68 ± 0.55*	0.61 ± 0.50*	0.612
ODI			
Preoperation	47.36 ± 5.31	45.61 ± 3.87	0.841
Postoperation			
1 month	22.89 ± 4.24*	29.82 ± 5.32*	<0.001
6 months	12.61 ± 3.54*	12.79 ± 3.37*	0.847
Last	10.68 ± 2.86*	9.29 ± 3.22*	0.092

VAS, visual analog scale; ODI, Oswestry Disability Index; PE-PLIF, percutaneous endoscopic posterior lumbar interbody fusion; Open PLIF, open posterior lumbar interbody fusion.
$^*p < 0.05$ compared with the preoperative data.

difference between the two groups ($p > 0.05$). Both groups did not significantly improve the LLA or SLA after surgery ($p > 0.05$). Both groups had significantly improved DHs, and a partial loss of the DH was observed at the last follow-up. The postoperative CSAC was significantly improved in both groups ($p < 0.05$), and the postoperative CSAC in the PLIF group was slightly larger than that in the PLIF group, although with no significant difference ($p > 0.05$). No significant differences in the SLA, DH, or CSAC changes were identified between the two groups ($p > 0.05$). The RLSs were 92.72 ± 6.39% with PE-PLIF and 93.54 ± 5.21% with PLIF, with no significant differences between the two groups ($p < 0.05$). The interbody fusion rate in the PE-PLIF group was 89.3% (Birdwell I 25, II 3), and the rate in the PLIF group was 92.9% (Birdwell I 26, II 2). The incidence rates of fusion device settlement were 14.3% (4/28) in the PE-PLIF group and 17.9% (5/28) in the PLIF group. No significant differences in the fusion rate or cage subsidence were noted between the two groups ($p > 0.05$) (**Table 3**).

Images of the two cases are shown in **Figure 4**.

DISCUSSION

Whether ULBD can be applied in patients with lumbar instability has not been reported, and only a few reports on ULBD for lumbar spondylolisthesis are available (17–19). In a study by Park et al. (17), ULBD achieved satisfactory clinical outcomes for grade I lumbar spondylolisthesis with nerve root symptoms, but foraminal stenosis was a contraindication. In a study by Yoshikane et al. (18), endoscopic ULBD provided favorable outcomes for lumbar spinal stenosis with or without grade I lumbar spondylolisthesis, but 31% of patients with lumbar spondylolisthesis experienced aggravation of their condition. Although a few reports show that ULBD alone can provide positive outcomes, previous studies still support that interbody fusion is an effective method for treating lumbar spondylolisthesis (20).

TABLE 3 | The radiographic outcomes in the PE-PLIF and open PLIF groups.

	PE-PLIF	Open PLIF	*p*
LLA (°)			
Preoperation	35.36 ± 10.27	40.93 ± 7.09	0.022
Postoperation	38.50 ± 7.68	41.75 ± 6.11	0.085
LLA change (°)	0.68 ± 2.04	0.64 ± 3.50	0.963
SLA (°)			
Preoperation	15.86 ± 4.37	17.18 ± 3.39	0.211
Postoperation	15.64 ± 3.42	17.21 ± 3.02	0.074
SLA change (°)	–0.21 ± 2.13	–0.11 ± 2.27	0.856
DH (mm)			
Preoperation	8.66 ± 1.45	8.75 ± 1.65	0.844
Postoperation	11.42 ± 1.19*	11.57 ± 1.35*	0.652
Last follow-up	10.29 ± 1.28*	10.28 ± 1.38*	0.960
DH change (mm)	1.63 ± 1.37	1.53 ± 1.12	0.767
CSAC (cm^2)			
Preoperation	0.65 ± 0.22	0.64 ± 0.19	0.773
Last follow-up	1.70 ± 0.26*	1.78 ± 0.23*	0.253
CSAC change (cm^2)	1.05 ± 0.35	1.14 ± 0.34	0.326
RLS (%)	92.72 ± 6.39	93.54 ± 5.21	0.599
Fusion rate (%)	89.3	92.9	1.000[a]
Cage subsidence (%)	14.3	17.9	1.000[a]

LLA, lumbar lordotic angle; LLA, SLA, DH, or CSAC change: postoperative data minus preoperative data; SLA, segmental lordotic angle; DH, disc height; CSAC, cross-sectional area of the spinal canal; RLS, reduction rate of lumbar spondylolisthesis; RLS, reduction rate of lumbar spondylolisthesis; PE-PLIF, percutaneous endoscopic posterior lumbar interbody fusion; Open PLIF, open posterior lumbar interbody fusion.
[a]*Results from Fisher's exact test.*
**p < 0.05 compared with the preoperative data.*

Review of Unilateral Laminotomy for Bilateral Decompression

Poletti (2) reported the unilateral laminotomy for bilateral ligamentectomy approach, which involves making a median skin incision and a fascial incision 1 cm laterally, splitting the paraspinal muscles to expose the lamina, excising approximately 8 mm of the ipsilateral superior lamina and a part of the inferior lamina, ligamentum flavum, and the base of the spinous process, excising a part of the contralateral lamina and ligamentum flavum, and performing spinal canal decompression. Spetzger et al. (3, 21) proposed the ULBD approach and provided a detailed surgical technique. The surgical approach is similar to that reported by Poletti; however, ULBD is performed under the assistance of a microscope, and a part of the facet joint is removed to enlarge the spinal canal and lateral recess. Oertel et al. (22) reported a 4-year follow-up study of 133 patients with lumbar spinal stenosis who underwent ULBD. They observed favorable clinical outcomes, concluding that ULBD is a very good surgical method for treating lumbar spinal stenosis. Since 2012, ULBD with a tubular retractor has been used in clinical practice (4, 5). With the incision 0.5–1 cm to the midline, this surgical procedure is basically the same as open ULBD but is believed to reduce intraoperative injury and speed up recovery (4, 5, 23). With advancements in lumbar endoscopic technology, endoscopic ULBD has been widely studied and applied since 2020 (24). The position of the incision is slightly different among reports but is generally 0.5–2 cm from the midline (5–7, 24, 25). Endoscopic ULBD can improve surgical visualization, reduce postoperative low back pain, and shorten postoperative hospital stay (6, 7, 18, 24, 25). Some scholars have reported the utilization of unilateral biportal endoscopic ULBD, with the insertion point being more medial than that in unilateral biportal endoscopic interbody fusion (UBE) to protect facet joints, resulting in positive clinical outcomes (26).

Endoscopic Lumbar Interbody Fusion and Unilateral Laminotomy for Bilateral Decompression

Endoscopic lumbar interbody fusion includes percutaneous endoscopic transforaminal lumbar interbody fusion (PE-TLIF) (27), UBE (28, 29), and PE-PLIF. We have utilized all of these procedures. The main difference among the approaches is which part of the facet joint is removed. The superior

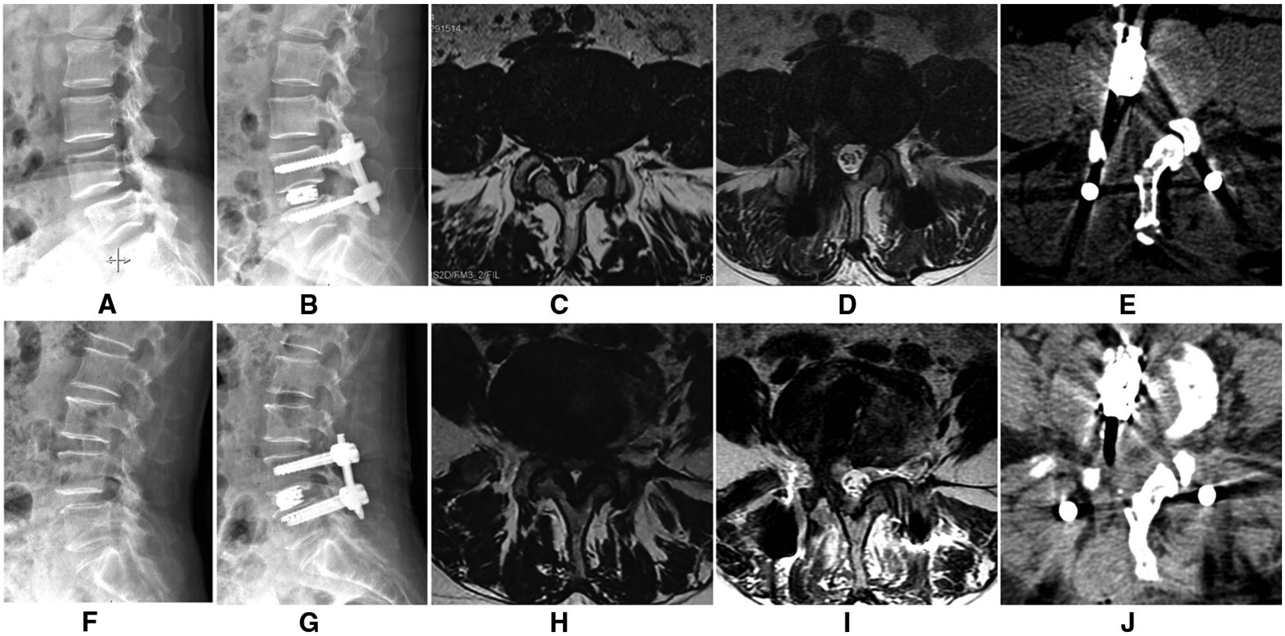

FIGURE 4 | The lateral X-Ray showing L4 spondylolisthesis (**A**), and it was complete reduction after surgery (**B**). A cross-sectional MRI image (**C**) showing lumbar spinal stenosis; the cross-sectional area of the spinal canal significantly improved after surgery (**D**). A cross-sectional CT image (**E**) showing that a part of the lamina, the articular process, and the base of the spinous process are excised to enlarge the spinal canal. The other patient is shown in (**F–J**).

articular process (SAP) is removed to establish a working channel in PE-TLIF (30). The inferior articular process (IAP) and the medial part of the SAP are removed in PE-PLIF (9). The entire articular process is removed in UBE (29). In PE-TLIF, the IAP is preserved, and the working cannula has a larger inclination angle. ULBD cannot be performed during PE-TLIF. In the study of Li et al., if necessary, an additional endoscopic ULBD was performed after PE-LTIF (31). As the working cannula in PE-PLIF is at almost the same position and angle as that in endoscopic ULBD, ULBD can be easily completed during PE-PLIF. Some studies on UBE have also mentioned that ULBD can be performed at the same time, but none of them have been described in detail (28, 32).

The Advantages of Percutaneous Endoscopic Posterior Lumbar Interbody Fusion with Unilateral Laminotomy for Bilateral Decompression

The working channel for PE-PLIF is located approximately 2 cm paravertebrally, which is almost the same as the classic ULBD surgical approach (9, 11). Thus, ULBD can easily be performed during PE-PLIF. Both interbody fusion and bilateral decompression can be completed at one time to avoid the extra contralateral operation, thereby simplifying procedures and minimizing injury. What differs from the classic ULBD approach is that the initial positioning point is at the junction of the articular process and lamina instead of at the junction of the spinous process and lamina. The procedure for ULBD in PE-PLIF is the same as that previously reported (5, 11). More of the contralateral articular process can be removed without worrying about destroying the stability of the lumbar spine.

This study found that PE-PLIF with ULBD can provide similar surgical efficacy and imaging results as PLIF, but there are some differences, which can be explained as follows. First, the estimated blood loss and postoperative hospitalization of PE-PLIF with ULBD were significantly less than those of PLIF. The drainage tube of open PLIF was usually removed at 3–5 days after surgery. Then, the patients were taken imagings and allowed early ambulation. So, their postoperative stay was 7.3 ± 1.5 days. The patients in the PE-PLIF group underwent the same process, with one difference being the drainage tube was removed 1 day after surgery. The estimated blood loss in our study was intraoperative blood loss plus postoperative drainage volume. This may be the explanation for the significant blood loss. Because the paraspinal muscle and spinous ligament complex were protected in PE-PLIF with ULBD, the postoperative low back pain associated with PE-PLIF with ULBD was significantly lower than that with PLIF surgery. Second, the study found that the improvement in the LLA and SLA was not obvious in either group. Because the SLA and LLA in lumbar spondylolisthesis were larger than those in normal lumbar, the angle may be smaller or slightly larger after spondylolisthesis reduction. Since the entire lamina was removed in PLIF, the CSAC after PLIF was slightly larger than that in the PE-PLIF group. In addition, the RLS was comparable between the two groups, indicating that the degree of soft tissue release during PE-PLIF was sufficient to reduce spondylolisthesis. In conclusion, PE-PLIF with ULBD is effective for the treatment of lumbar spondylolisthesis and lumbar spinal stenosis. The advantages of PE-PLIF with ULBD are reducing postoperative back pain, reducing trauma, and enhancing recovery after surgery. The main disadvantage is the long operative time, which is a common problem for all minimally invasive surgeries. Improvements in both surgical techniques and instruments are needed to reduce the operative time in the future.

Complications

The incidence of ULBD complications varies among reports. Dural tears are a very common complication, occurring in approximately 6.8%–18% of open surgeries and tubular procedures (22, 33, 34) and 0%–7.2% of endoscopic ULBD procedures (11, 19, 25). The reason for this difference is that clear surgical visualization and careful operation under endoscopy help prevent dural tears in the narrow surgical space where high-speed drills and osteotomes are used. In our study, dural tears occurred in only one patient. Compared with previous studies, we rarely used the osteotome or ultrasonic osteotome instead of burr during the operation, which are more controllable and safer. Studies have reported that the postoperative reoperation rate is approximately 10% due to restenosis of the surgical segment and secondary segmental instability (22). Some surgeons believe that greater articular process preservation during the operation corresponds to a lower risk of postoperative segmental instability (26). However, in ULBD, a part of the facet joint must be excised, and usually, more of the contralateral facet joint needs to be removed (35). Overall, ULBD has low complication rates and satisfactory clinical outcomes, and endoscopic techniques have lower complication rates than open surgery and tubular approaches in most studies. The utilization of endoscopic techniques can improve surgical visualization and reduce the occurrence of complications. The reoperation rate is associated with the selection of indications and how much the facet joint is excised. Since interbody fusion and pedicle screw fixation are performed in PE-PLIF, the risk of reoperation does not need to be considered. In conclusion, PE-PLIF with ULBD is a safe and effective method to expand the indications for ULBD.

Limitations

This study has some limitations. Although we strictly followed the inclusion and exclusion criteria during case selection, selection bias was inevitable. The sample size was small. Interobserver bias in the measurement of the radiological parameters may have been present.

CONCLUSION

The results from this study indicate that ULBD can be successfully performed during PE-PLIF and that the combined procedure is a safe and reliable treatment method for lumbar spondylolisthesis. Compared with open PLIF, PE-PLIF with ULBD is less invasive and leads to enhanced recovery after surgery. Despite the lengthy operation time, we believe that the benefits outweigh the shortcomings.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of Shanxi Bethune Hospital. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

Conceptualization was done by H-YF and L-MH; the methodology was prepared by H-YF and L-MH; software was applied by L-MH; validation was done by X-MG and ZM; formal analysis was performed by L-MH; investigation was done by J-RL and H-RW; resources were provided by H-RW and QC; data curation was done by L-MH; writing and original draft preparation were done by LH; writing, reviewing and editing were done by H-YF; visualization was performed by L-MH and J-RL; supervision was carried out by H-YF; project administration was looked after by H-YF; funding acquisition was done by H-YF. All authors have read and agreed to the published version of the manuscript.

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CASE REPORT
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Case Report: Bilateral Biportal Endoscopic Open-Door Laminoplasty With the Use of Suture Anchors: A Technical Report and Literature Review

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Background: Unilateral biportal endoscopy (UBE) is a newly developed technique for spine surgery. Owing to the convenience of nerve decompression and compatibility with open surgical instruments under endoscopic guidance, this technique has seen widespread global use. In this study, we first used modified UBE with suture anchor fixation for cervical laminoplasty in a 65-year-old female patient with good clinical outcomes.

Methods: We used bilateral biportal endoscopy (BBE) for cervical laminoplasty with suture anchor fixation in a patient with cervical stenosis. Under endoscopic guidance, a bilateral approach was used to make the gutter and lift the lamina door. After the lamina doors were opened, sutures were tied tightly using facia cannula and knot pusher. After confirming the solidarity of the open-door status, the drainage tube was inserted and the incisions were closed. The patient's pre- and postoperative radiological and clinical results were evaluated.

Results: Postoperative Japanese Orthopaedic Association (JOA) and Neck Disability Index (NDI) scores were improved clinically, and cervical canal was decompressed radiologically.

Conclusions: BBE laminoplasty combined with suture anchor fixation showed a favorable clinical and radiological result and appears to be a safe and effective technique for cervical stenosis.

Keywords: bilateral biportal endoscopy, cervical laminoplasty, suture anchor, endoscopic spine surgery, cervical stenosis

INTRODUCTION

With the advent of an aging society, an increasing number of patients with cervical stenosis require decompression surgery (1). Traditional open surgery has many disadvantages (2) hence, minimally invasive approaches to surgery have emerged, which lead to less injury, faster recovery, and fewer complications (3). Unilateral laminectomy with bilateral decompression in a narrow cervical canal with percutaneous endoscopy and microscopy is risky and has a steep learning curve (4–6).

Unilateral biportal endoscopy (UBE) is a minimally invasive spinal surgery developed in recent years, which has been widely used for degenerative diseases of the lumbar spine with remarkable efficacy (7–11). UBE for cervical decompression has also been reported, but there have been only a few published studies (12, 13). In a technical report, we applied a modified UBE technique for cervical laminoplasty with the aid of suture anchor fixation, and obtained satisfactory clinical results.

MATERIALS AND METHODS

Ethics Statement and Case Presentation

The study approval was obtained from our institutional review board (NO. 2019KY006). Informed consent was obtained from the patient for the publication of the report. A 65-year-old woman was suffering from gait disfunction and numbness in both the upper extremities for 5 years, and her condition deteriorated within 1 month. A physical examination revealed tendon hyperreflexia and the presence of a Babinski sign in the lower extremities with positive Hoffman sign and hypoesthesia in the upper extremities (more severe on the right side). The patient's history included controlled hypertension and hyperlipidemia. Magnetic resonance imaging (MRI) revealed central cervical stenosis at the C4-C5-C6 levels, and the spinal cord was compressed due to ligamentum flavum (LF) hypertrophy and disc herniation at the C4-C5-C6 levels (**Figure 1**). The diagnosis of cervical myelopathy was confirmed. The patient expressed strong opposition to conventional open surgeries, such as anterior fusion and posterior open-door laminoplasty because of a history of cardiovascular diseases and agreed to biportal endoscopic cervical laminoplasty. The Japanese Orthopaedic Association (JOA) score was 9 and Neck Disability Index (NDI) score was 23 when she visited the outpatient department.

Procedure

Position, Incision, and Instruments

Under general anesthesia, the patient was placed prone on a spine table with the head secured in a horseshoe headrest. The cervical spine was mildly flexed and fixed by a tape (**Figure 2A**).

Two horizontal lines were drawn along the C4 and C6 pedicles, a vertical line in the midline of the right lateral mass, while the other one was along the lateral margin of the left lateral mass in the anteroposterior view. The intersection points on the left-hand side served as a viewing portal,

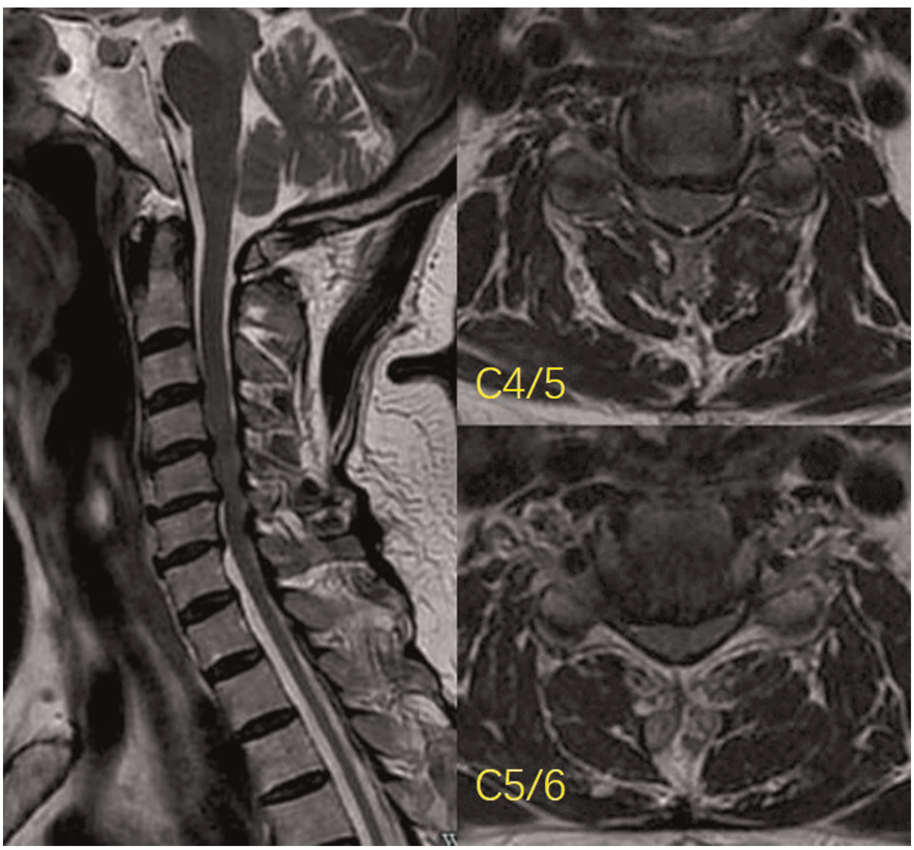

FIGURE 1 | Preoperative MR images show central canal stenosis at the C4-C6. The spinal cord was compressed by herniated discs and a hypertrophied ligamentum flavum.

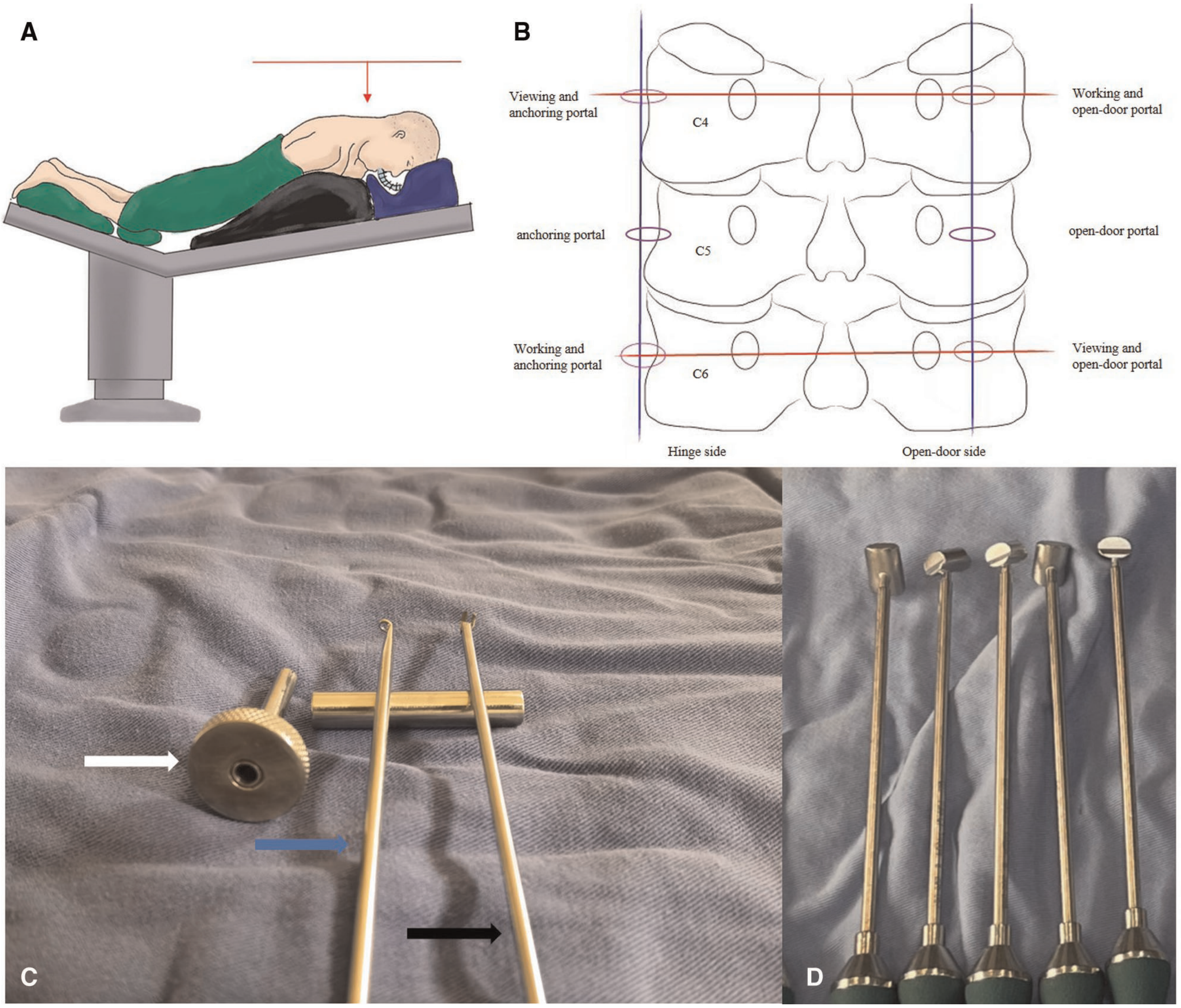

FIGURE 2 | (**A**) A overall view of operating table. The table was adjusted to make sure that the intervertebral space was perpendicular to the ground. (**B**) Schematic representation of the location of the portals; (**C**) Newly designed knotting system for endoscopic laminoplasty. Facia cannula (white arrow), working length 6 cm and inner diameter 0.5 cm; endoscopic knot pusher (blue arrow) and shears (black arrow), diameter 0.3 cm; (**D**) Trials (range, 8 mm–12 mm) for the measurement of LOS.

whereas the intersection points on the right-hand side served as a working portal. Two more incisions were made at the midpoints of the intersections on both sides. The three incisions on the left were used as the anchoring portal while the contralateral incisions were used as the open-door portal (**Figure 2B**).

We used suture anchors with a length of 10 mm and diameter of 2.8 mm. A high-speed burr (Guizhou Zirui Technology, China), specially designed arthroscopic facilities (**Figure 2C**), a tool-kit of radiofrequency (RF) systems (Jiangsu BONSS Medical Technology, China), and open spine surgical instruments, including pituitary forceps, curettes, and Kerrison rongeurs, were used.

Bilateral Biportal Approach for Laminoplasty

The first stage of the procedure was performed on the left side of the patient. A RF was used to expose the lamina, spinous process, and lateral mass of C4-C5-C6. A 4-mm diamond burr was used to remove the dorsal cortex and cancellous bone at the junction of the lamina and lateral mass of C4-C5-C6 (**Figure 3A**), and the bony gutter on the hinge side was completed. Subsequently, a 2-mm diamond burr was employed to make entry points on the center of the lateral mass and spinous processes of C4-C5-C6 (**Figure 3B**); suture anchors were inserted in succession (**Figure 3C**).

The endoscopy and instruments were moved to the right to begin the second stage of the procedure. After C4-C5-C6 lamina

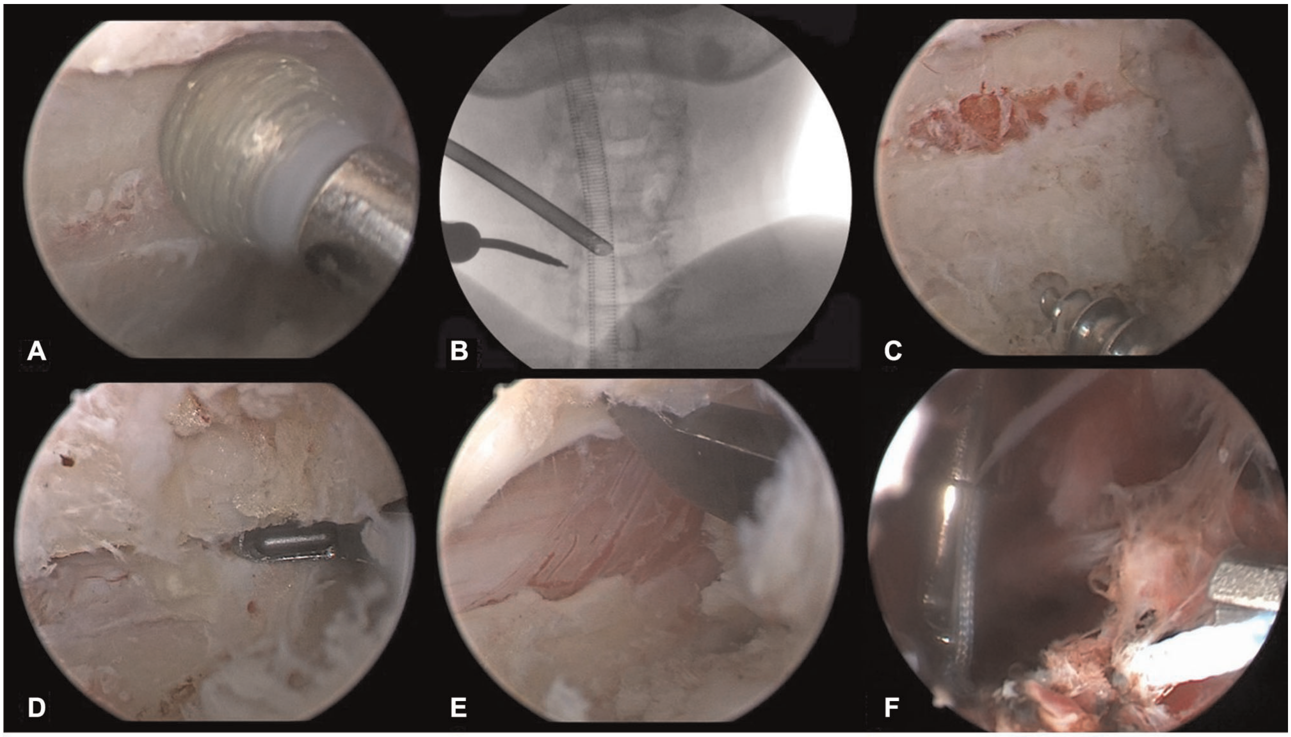

FIGURE 3 | The drilled gutter was first completed using 4-mm diamond burr on the hinge side (**A**) Insertion hole for the suture anchor was also prepared using 2-mm diamond burr on the hinge side and confirmed under fluoroscopy (**B**) Suture anchor was screwed in the lateral mass (**C**) The remained ventral cortical bone on the open-door side was resected using 1-mm Kerrison rongeur (**D**) The lamina door was raised by a 2-mm Kerrison rongeur (**E**) The sutures was knotted tightly to maintain the lamina door in open position (**F**).

and intersections of C34 and C67 were exposed, the same longitudinal gutter was created at the margin between the lamina and the lateral mass of C4-C5-C6 using a 4-mm diamond burr. The remaining ventral cortex was removed by a 1 mm Kerrison rongeur with a thin blade (**Figure 3D**). The LF between C34 and C67 was cut transversely to facilitate the process of floating laminae.

At the beginning of the third stage, the tip of spinous process of C4-C5-C6 was carefully cut. The arthroscopy was passed over the top of the lamina via the interspinous ligament, reaching the contralateral side to observe the knotting process. A retriever was used to take the previously introduced sutures for each segment out of the same soft tissue portal; then, the facia cannula was inserted along the sutures in the anchoring portal. The assistant bent the hinge in a greenstick fashion and held the lamina door in place (**Figure 3E**). The sutures were tied firmly to prevent reclosure of the lifted laminae (**Figures 3F**, **4**).

Drainage and Closure

A drainage tube was inserted on the open-door side, and the incisions were closed using a standard method (**Supplementary Video S1**). The surgery was performed without complications. The estimated blood loss during the operation was 200 mL, and the operation time was 190 min. Cefuroxime (1.5 g, twice a day, intravenous) was administered for 24 h, and the pain was managed with flurbiprofen (100 mg, twice a day, intravenous) postoperatively.

A postoperative semirigid cervical collar was prescribed for 3 months. The patient gave consent to the regular anti-osteoporosis treatment which could effectively improve bone mineral density and prevent anchors from loosening and displacement.

RESULTS

Postoperative computed tomography scan revealed adequate enlargement of cervical canal of C4-C5-C6 and the cord was fully decompressed on MRI (**Figure 5**). The JOA and NDI scores were 11 and 20 on day 3 after surgery, and improved to 14 and 16 at the 6 months follow-up, respectively.

DISCUSSION

To the best of our knowledge, this is the first study to apply the UBE and suture anchor techniques for cervical laminoplasty. An endoscopic open-door laminoplasty with minimal muscle invasion was performed. The patient's clinical symptoms improved significantly.

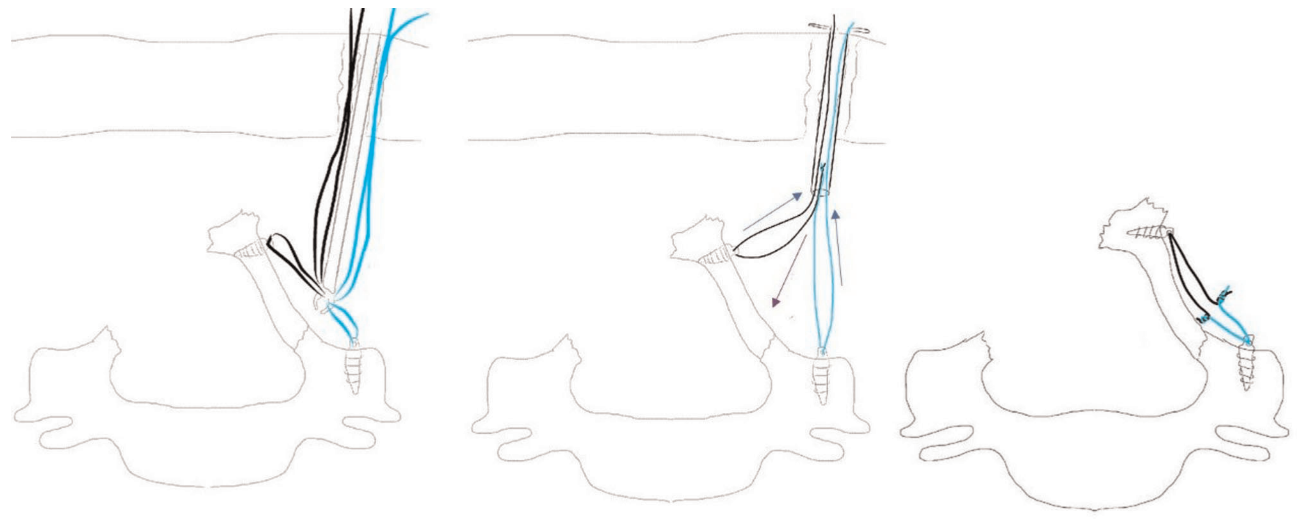

FIGURE 4 | Schematic representation of knotting process.

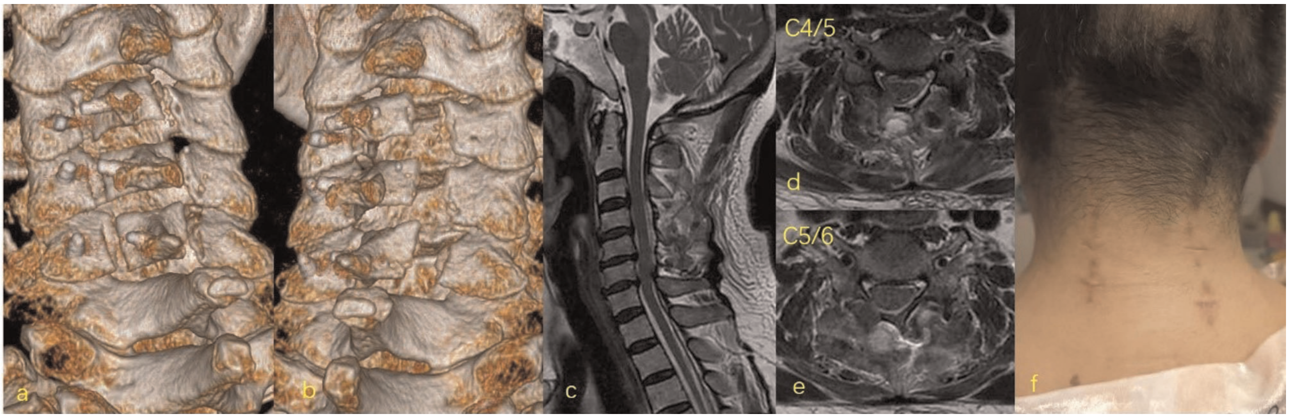

FIGURE 5 | Postoperative 3D CT of C4-C6 showed widening of the spinal canal after BBE laminoplasty using suture anchor fixation (**A**,**B**) Postoperative MRI showed full decompression of spinal cord with an adequate subarachnoid space (**C–E**). Six wounds were created for the cervical laminoplasty at three levels (**F**).

Cervical spondylotic myelopathy caused by posterior compression often requires posterior surgery. Open laminectomy and laminoplasty necessitate extensive paraspinal muscle release and retraction, which may result in axial pain and kyphotic deformity during follow-ups (14). In percutaneous endoscopic and microscopic surgery, contralateral decompression can be completed only when the base of spinous process is excessively removed, which leads to more intraspinal work and a higher risk. The operation and observation in a single portal manifested several difficulties (4, 6).

The UBE technique has been widely used in the treatment of lumbar degenerative diseases, with less iatrogenic injury and faster recovery (15, 16). The application of UBE in cervical spine was mainly in foraminoplasty (12, 17); There is only one report on spinal canal decompression and the technical requirements are relatively high (13). We have designed a contralateral "Zhang's portal" to facilitate cervical canal decompression (18), therefore, we have rich experience in bilateral biportal operations. Kurokaw (19) demonstrated the validity of suture anchors in cervical laminoplasty in a cadaveric study, and we successfully performed suture anchor fixation on the contralateral side using the UBE technique. Compared with open surgery, continuous irrigation not only ensures a clear operative field, but also lowers the risk of infection (7, 20). The working portal is independent of the viewing portal, and thus the operative efficacy is dramatically improved. Moreover, under the arthroscope, the field of vision is enlarged 30 times, and the observation of dural pulsation, tiny blood vessels, and ligaments is very clear, which is conducive for hemostasis and decompression.

Before the operation, we considered placing the plate on the open-door side, however, it was very difficult to operate under the arthroscope. Without specially designed instruments, it was also difficult to find the tiny internal fixation materials once they were lost in the soft tissue. Besides, the cervical canal was opened and the spinal cord exposed, which was vulnerable to internal fixation. Suture anchor repair is technically mature under arthroscopy (21). Our team has a lot of experience in arthroscopic surgery and suture management, so we chose the suture anchor fixation on the hinge side under UBE guidance. The indications of this procedure were the same as those of traditional open cervical laminoplasty, while the contraindications included severe osteophytes around the lateral mass and abnormally distributed vessels which make safe anchor placement difficult, and prior cervical surgery with posterior approach.

There are some tips that surgeons should not overlook. The lateral mass should be fully exposed on the hinge side, but not on the open-door side. Exposure beyond the lateral margin of the lateral mass will significantly increase bleeding. Guttering should be done before anchoring; otherwise, the sutures can easily get tangled. When creating the open side, the ventral cortex of the laminae and LF were removed carefully using a 1 mm Kerrison rongeur, a nerve hook was used to separate the adhesions, and a low frequency probe was used to decrease the bleeding from epidural veins. No force was applied during the open-door procedure. The lamina open-door angle should not exceed 45° (22). After opening the lamina, trials (**Figure 2D**) for miniplate were used to make sure that the laminoplasty opening size (LOS) was large enough for decompression (23). Before knotting, the retriever was used to retrieve the sutures to the same soft tissue portal, and then the fascia cannula was inserted along the sutures to help avoid soft tissue incarceration. Under the arthroscopic supervision, knot in the fascia cannula should be fastened to prevent lamina reclosure.

However, the described technique has some limitations. The operation should be performed by experienced surgeons and assistants. Large sample studies in multicenters should be conducted to determine further clinical outcomes. With the development of surgical instruments and techniques, plate and screw fixation on the hinge side may be a better choice.

In conclusion, we described a bilateral biportal laminoplasty for the treatment of cervical stenosis. With the innovation of endoscopic instruments and techniques, this modified technique will play a role in cervical disorders.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by institutional review board of Hangzhou TCM hospital. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

Conceptualization, CZ and HP; methodology, WZ; validation, WZ and HP; investigation, WC; resources, DW; writing-original draft preparation, CZ; writing-review and editing, WZ; supervision, HP; project administration, JW. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsurg.2022.913456/full#supplementary-material.

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ORIGINAL RESEARCH
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Full Endoscopic Posterolateral Transarticular Lumbar Interbody Fusion Using Transparent Plastic Working Tubes: Technical Note and Preliminary Clinical Results

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Background: A series of full-endoscopic lumbar interbody fusions have been reported, but special fusion cages or operating instruments are often needed, and there are many complications in the operation and the learning curve is long. We have used a single portal endoscopic system for lumbar interbody fusion in a novel posterolateral transarticular approach, which will take advantage of the incision for pedicle screw insertion and avoid nerve root damage by using a transparent plastic working tube. The purpose of this study was to present the surgical technique of full endoscopic posterolateral transarticular lumbar interbody fusion (FE-PTLIF) and to analyze the preliminary clinical results.

Methods: A total of 39 patients (17 men and 22 women; mean age [$\bar{x} \pm s$] 55.2 ± 12.2 years) have been enrolled in this retrospective study between March 2019 and January 2021 in the Second Affiliated Hospital of Chongqing Medical University. All patients were treated with full endoscopic lumbar interbody fusion via posterolateral transarticular approach with a transparent plastic working tube. Demographic characteristics, diagnosis, operative time, and estimated blood loss were evaluated. Intraoperative photo and perioperative imaging were recorded. The preoperative and postoperative clinical data were collected for statistical analysis.

Results: The preliminary clinical follow-up data achieved good results. No patients had serious postoperative complications and none of these patients required revision surgery during the perioperative or follow-up period. We compared the visual analogue scale and Oswestry disability index scores before and after surgery. The differences were statistically significant ($P < 0.05$). The mean total blood loss (including drainage blood) was 54.4 ± 20.3 ml. The mean operative time was 130.5 ± 23.8 min. At the last follow-up, the fusion rate of the lumbar intervertebral space was 100%.

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Conclusions: This novel posterolateral transarticular approach and transparent plastic working tube can reduce the difficulty of the operation, so that the conventional intervertebral fusion cage [bullet-shaped polyetheretherketone (PEEK) nonexpandable fusion cage] and surgical instruments can be used in the full endoscopic lumbar intervertebral fusion surgery, which can reduce the cost and improve the efficiency of the operation.

Keywords: FE-PTLIF, TLIF, conventional interbody cage, transparent plastic working tube, complication, learning curve

INTRODUCTION

Lumbar spinal fusion surgery has been well demonstrated to relieve pain and improve function and quality of life for many patients who suffered from lumbar degenerative disease (1, 2). There are a lot of methods in lumbar fusion surgery, including posterolateral lumbar fusion, posterior lumbar interbody fusion, transforaminal lumbar interbody fusion, direct lateral lumbar interbody fusion, anterior lumbar interbody fusion (ALIF), oblique lateral lumbar interbody fusion (OLIF), minimally invasive TLIF (MIS-TLIF), endoscopic approach for the lumbar interbody fusion, and full endoscopic lumbar interbody fusion (FELIF) (3–5). As the quality of life has become the main goal of health care, there is an increasing and critical demand for the development of minimally invasive spine surgery (MISS) techniques for lumbar fusion surgery. MISS has many advantages including lower risk of complications, lower risk of muscle damage, less pain, and faster recovery time (6, 7). Recently, among all MISS approaches, FELIF surgery has received substantial attention (8, 9).

We have used a single portal endoscopic system for lumbar interbody fusion in a novel posterolateral transarticular approach, which will take advantage of the incision for pedicle screw insertion and avoid nerve root damage by using a transparent plastic working tube. The purpose of this study was to present the surgical technique of full endoscopic posterolateral transarticular lumbar interbody fusion (FE-PTLIF) and to analyze the preliminary clinical results.

MATERIALS AND METHODS

Preoperative Preparations

The chief Surgeons have started single portal percutaneous endoscopic spine surgeries in 2010, and all contributing authors have extensive experience in such percutaneous endoscopic surgeries as discectomy for lumbar disc herniation and decompression for lumbar stenosis by a transforaminal or an interlaminar approach. Before the clinical application of FE-PTLIF, we prospectively practiced such a surgery technique at 12 lumbar levels in four cadavers since 2018.

Indication of FE-PTLIF

We initially only performed single-level fusion surgery from L3–4 to L5–S1. Indications of FE-PTLIF were the same as those for TLIF, including (1) lumbar disc herniation with segmental instability; (2) lumbar spinal stenosis with segmental instability; and (3) lumbar spondylolisthesis (less than Meyerding grade II). We did not perform endoscopic fusion in cases of infection, spondylodiscitis, vertebral fractures, severe central canal stenosis, or spondylolisthesis greater than grade III.

Surgical Technique

Position, Anesthesia, Approach, and Percutaneous Screw Fixation

All patients were placed in the prone position on a radiolucent table and the C-arm should be placed on the contralateral side of FE-PTLIF access (**Figure 1A**).

All operations were performed under general anesthesia and neuromonitoring.

Unlike the previously reported full-endoscopic intervertebral fusion surgery technique, our approach is more like microscopic TLIF; by this posterolateral transarticular approach, we do not need extra incisions for full-endoscopic decompression and fusion. Taking the right side of the L4/5 segment as an example, after completing the remaining three percutaneous pedicle screws, the guide wire for the L5 percutaneous pedicle screw will be retained (**Figures 1B,C**). Taking the implanted L5 pedicle screw incision as the incision, along the upper edge of the guide wire, we place the pencil tip on the superior articular process of L5 and gradually expand to establish the working channel (**Figures 1D,E**).

Endoscopic Partial Facetectomy as Bone Graft and Decompression

After establishing the working channel through the steps described above, the position will be confirmed by the anterior–posterior (AP) and lateral view of the x-ray. The surgeon can see the surface of the facet joint after clearing soft tissue via endoscopic visualization. Once the facet joint is identified according to the anatomy of the articular surface, osteotomy on the superior half of the superior articular process is performed by using this visualized trephine (**Figures 2A,B**). We will confirm the position of the visual trephine through AP-lateral fluoroscopy and the endoscopic anatomical structure (**Figures 2C,D**) and then perform sufficient articular process through the visual trephine to explore the nerve roots and prepare sufficient space for the working tube (**Supplementary Video 1**); partial facetectomy is efficient, convenient, and safe for whole osteotomy to be

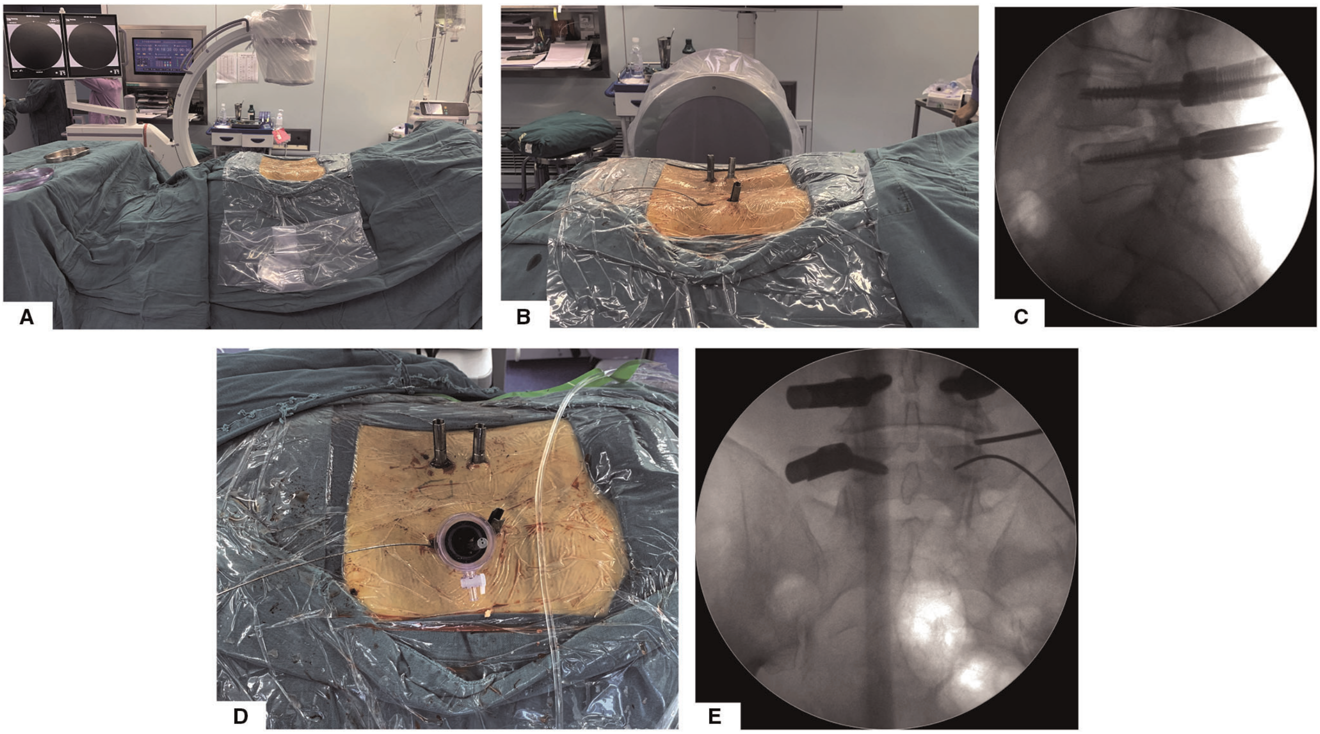

FIGURE 1 | Surgery position, percutaneous pedicle screw fixation, and establishment of endoscopic working channel. (**A**) Prone surgery position and C-arm position. (**B**) General view of surgical incision and percutaneous pedicle screw implantation. (**C**) Lateral view of percutaneous pedicle screw fixation. (**D**) General view after establishing working channel. (**E**) AP view after establishing working channel.

visible, and the bony fragments can be used as a bone graft for fusion. After removing part of the facet joints, the surgeon will remove part of the ligamentum flavum, intervertebral disc, and posterior longitudinal ligament to complete the exposure and decompression of the traversing nerve root and dural sac (**Figure 2E**). The osteotomy of the articular process is a necessary part of the full decompression of the nerve root and dural sac, which can provide bone grafting material for intervertebral fusion and provide enough space for cage insertion. If the patient has bilateral neurological symptoms, we need to take a contralateral inferior percutaneous pedicle screw incision for adequate percutaneous endoscopic decompression via the same approach as a supplementary surgery. Similar to conventional endoscopic decompression surgery, we usually take nerve root relaxation, visible nerve root pulse with the dural sac, and no obvious compression as the decompression standard.

Endplate Preparation, Bone Graft, and Cage Insertion

The replaced custom-made endoscopic working tube is settled to block dura, the exiting and traversing nerve root out (**Figure 3A** and S**upplementary Video 2**). The custom-made working tube is a flexible, transparent plastic of several sizes, as shown in the video (**Supplementary Video 2**); the surgeon gently pushed the nerve root out of the operating space by the custom-made working tube, which can be stuck in the intervertebral foramen of the channel, and the operating space does not need to be very round or too large for the flexibility of the tube. After placing the customized working channel in place, the conventional paddle distractor, ring, and endplate curettes can be used to remove the disc efficiently and safely, the AP and lateral view of the x-ray for various paddle distractors will decide the size of the cage and range of endplate preparation (**Figures 3B,C**). Incomplete endplate preparation may result in fusion failure; endoscopic burr can be used as a supplementary tool to ensure the adequacy of endplate preparation under endoscopic visualization (**Figure 3D**); allograft and the autogenous bone retained from facet joint osteotomy will be placed into the anterior disc space through a regular funnel-shaped bone graft device. The conventional TLIF peek cage (kidney-shaped design) will be inserted into the intervertebral space under AP-lateral fluoroscopy (**Figures 3E,F**). The surgeon can reconfirm the position of the cage and decompression of the nerve root under endoscopic visualization (**Figure 3G**). The last percutaneous pedicle screw will be inserted by the guide wire and the rod will be inserted from the upper incisions for percutaneous screws, a small drainage catheter was finally inserted to prevent postoperative epidural hematoma (**Figures 3H–J**). This custom-made endoscopic working tube is a very useful tool, which can provide a safe space for the use of conventional tools, without the need to use additional

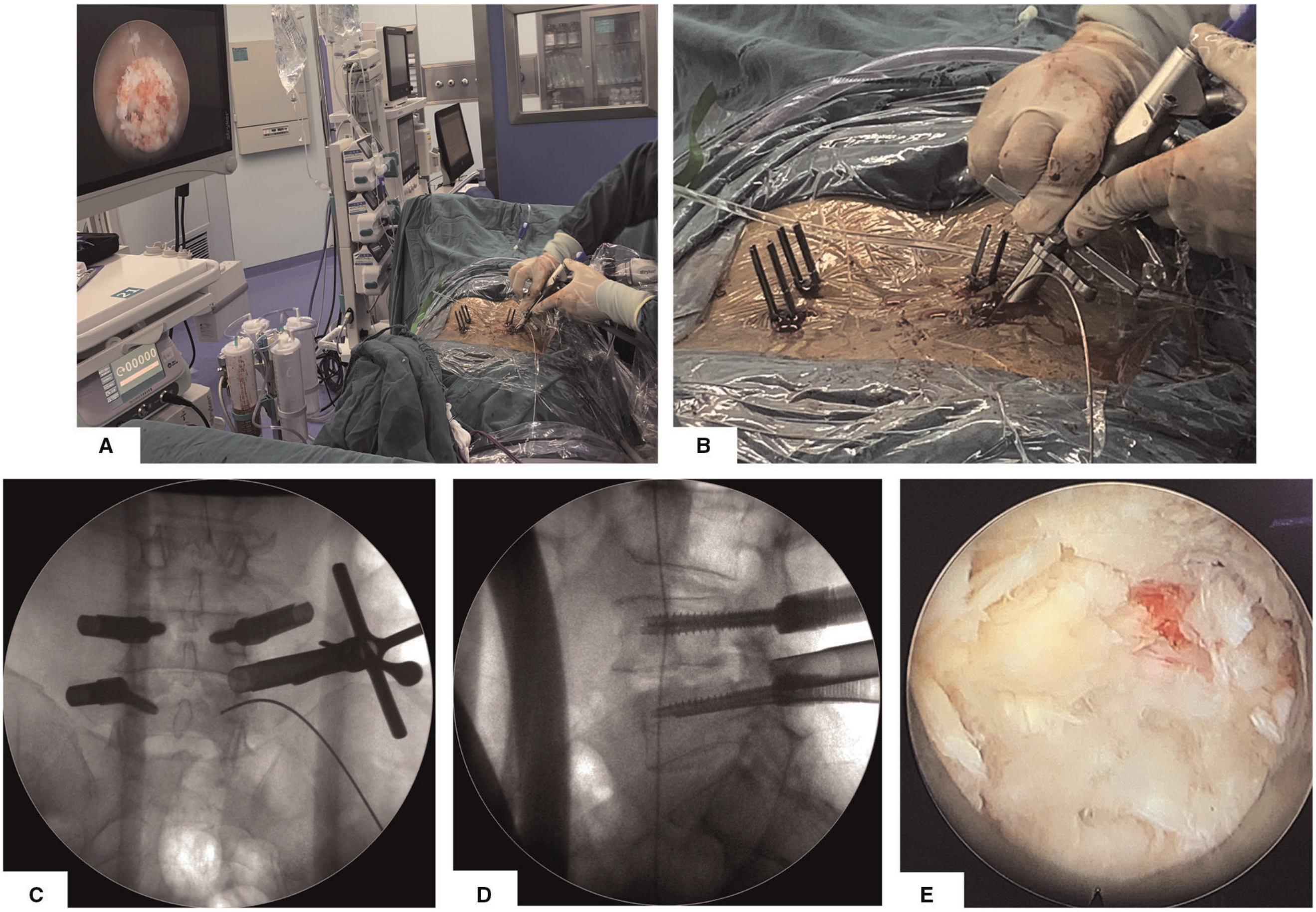

FIGURE 2 | Articular osteotomy is performed by using this visualized trephine. (**A**) General view and endoscopic visual field after establishing the working channel for the visual trephine. (**B**) Detailed view when establishing the working channel for the visual trephine. (**C**,**D**) AP and lateral view after establishing the working channel for the visual trephine. (**E**) Endo-scopic view after articular osteotomy.

special instruments or an intervertebral cage, and at the same time, the operation is more convenient and effective.

Application of the Custom-Made Working Channel

As mentioned before, this working channel was developed for FELIF. When using the traditional working channel, we often worry about whether the nerves are compressed outside the field of vision. At first, because the size of the 10 ml syringe was just right, its inner diameter was about 16 mm, and it could just cut the front end of the 10 ml of syringe into a duckbill opening through the intervertebral fusion cage that does not exceed 13 mm in height, and then, we use this homemade syringe as a working channel (**Figure 4A**). However, due to the limitation of the length and a single diameter model, we have designed a working channel of different diameters and lengths, and we have declared a patent based on this. As shown in **Figure 4B**, the schematic diagram of the section and each face of the working channel showed a similar structure and material to a homemade syringe but with more detailed tick marks. Besides that, we also designed a matching pencil tip in the patent. The schematic diagram in **Figure 4C** shows the cross section of the matching pencil tip, and the inner core can be placed with a 2 mm K-wire. Some differences between the custom-made and traditional working channels are particularly shown in **Table 1**.

Analysis of Clinical Results

We recruited a total of 39 patients who only needed single-segment fusion surgery, all patients were followed up for more than nine months. Diagnosis, operative time, estimated blood loss, general data, and complications were evaluated. The visual analog scale (VAS) and Oswestry Disability Index (ODI) were evaluated during the preoperative and postoperative periods. All enrolled patients signed relevant surgical consent and informed consent. Statistical analyses were performed using SPSS version19.0 statistical software (SPSS, Inc., Chicago, IL). Quantitative data are expressed as $\bar{x} \pm s$. A t-test was used to compare differences between two groups. $P < 0.05$ was considered statistically significant.

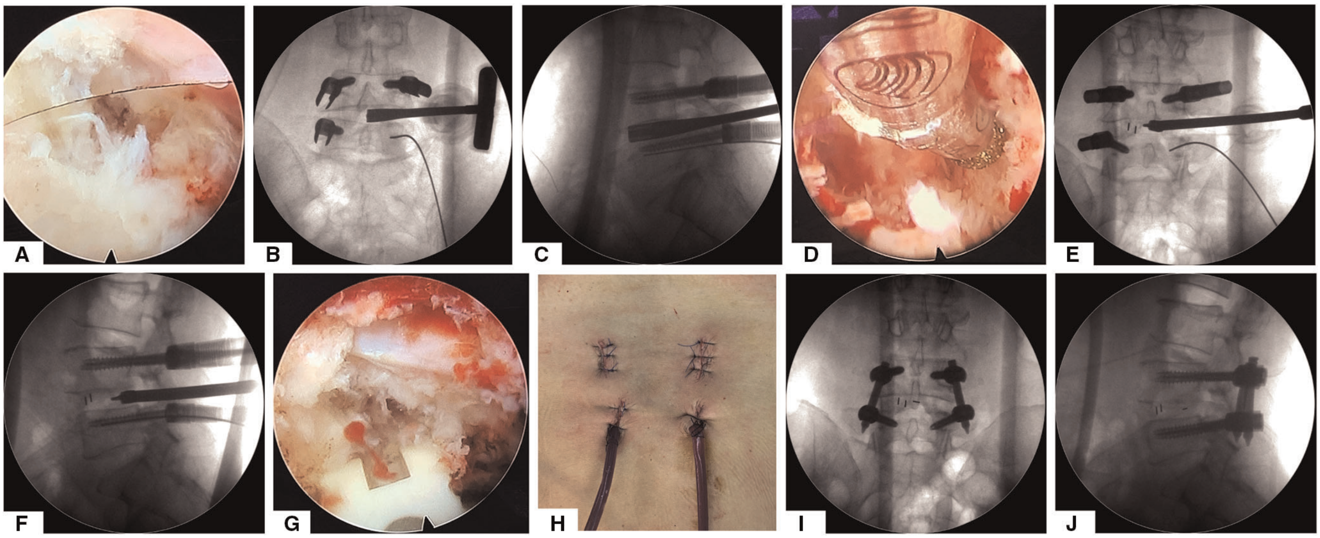

FIGURE 3 | The whole process of decompression and intervertebral disc treatment and implantation of intervertebral fusion cage under the visual channel. (**A**) Endoscope visual field assisted by visual working channel after articular process osteotomy and decompression of the ligamentum flavum. (**B**,**C**) The AP and lateral view of x-ray for discectomy by various paddle distractor. (**D**) Endoscopic view of endplate preparation by using turnable burrs. (**E**,**F**) Implant an intervertebral fusion cage under the guidance of AP and lateral view of x-ray. (**G**) Endoscopic view after implanting the intervertebral fusion cage. (**H**) General view of the postoperative incision. (**I**,**J**) AP and lateral view after surgery.

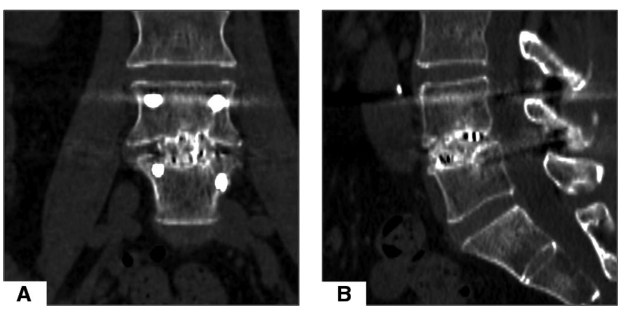

FIGURE 4 | CT scan for three months after surgery. (**A**) Coronary scanning. (**B**) Sagittal scanning.

TABLE 1 | Differences between the custom-made and traditional working channels.

	Custom-made	Traditional
Material	Plastic	Metal
Reusability	Disposable	Reusable
Visibility	Visible	Invisible
Flexibility	Kind of flexible	Rigid
Scale mark	Yes	No

TABLE 2 | Patient characteristics.

Characteristic	Value
Mean age (years)	55.2 ± 12.2
Sex	
M	17
F	22
Mean follow-up period (months)	11.5 ± 8.1
Level treated	
L4/5	21
L5/S1	18
Diagnosis	
Degenerative spondylolisthesis	26
Isthmic spondylolisthesis	3
Central stenosis w/ segmental instability	6
Central stenosis w/ concomitant foraminal stenosis	4
Mean estimated blood loss (ml)	54.4 ± 20.3
Mean operative time (mins)	130.5 ± 23.8
Postop complications	
Numbness	6

RESULTS

A total of 39 patients (17 men and 22 women; mean age [$\bar{x} \pm s$] 55.2 ± 12.2 years) have been enrolled in this study since March 2019. The mean follow-up period was 11.5 ± 8.1 months. A total of 39 vertebral levels in 39 patients were treated using fully endoscopic posterolateral transarticular lumbar interbody fusion; 26 patients had degenerative spondylolisthesis, 6 patients had central stenosis with segmental instability, 4 patients had central stenosis with concomitant foraminal stenosis, and 3 patients had isthmic spondylolisthesis. The operative levels focused on L4/5 to L5/S1: L4/5 in 21 patients and L5/S1 in 18 patients (**Table 2**).

VAS and ODI scores improved significantly after surgery. The VAS scores decreased from 7.26 ± 1.23 preoperatively to 1.44 ± 1.04 at the last follow-up visit ($p < 0.05$), and the ODI scores decreased from 41.38 ± 5.36 to 7.28 ± 2.15 ($p < 0.05$). No patients experienced deterioration of neurological function after surgery. The mean total blood loss (including drainage blood) was 54.4 ± 20.3 ml. The mean operative time was 130.5 ± 23.8 min.

Six patients experienced numbness in the corresponding segmental distribution area after the operation, but all recovered spontaneously within 3 months. No patients had serious postoperative complications and none of these patients required revision surgery during the perioperative or follow-up period.

A total of 39 enrolled patients were observed intervertebral fusion at the last follow-up. Our criteria for judging intervertebral fusion include no obvious active low back pain and a CT scan showing the bone connection in the intervertebral space. **Figure 5** shows the imaging manifestations of typical cases during postoperative CT follow-up.

DISCUSSION

Due to substantial technological advancements in minimally invasive spinal surgery, endoscopic TLIF has become accessible in clinical practice. Compared with traditional open spinal fusion surgery, endoscopic TLIF does less damage to soft and bone tissues, has less blood loss, has faster recovery, has clearer vision under the endoscope, has more adequate treatment of nerve decompression, and has endplate preparation to increase the chance of intervertebral fusion and make the effect more accurate (10). In this study, FE-PTLIF adopts the posterolateral transforaminal approach, which can obtain an appropriate amount of autogenous bone during

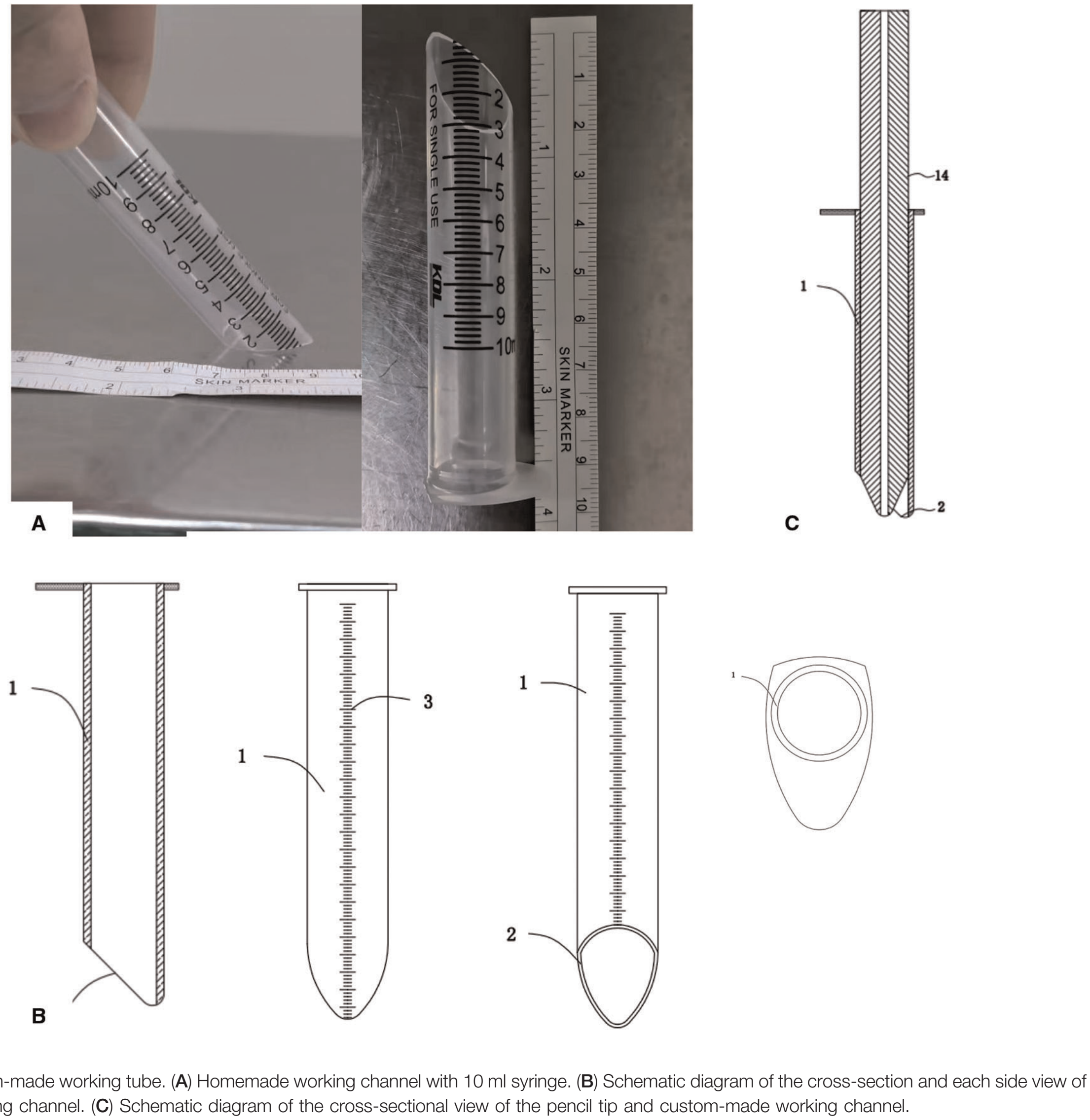

FIGURE 5 | Custom-made working tube. (**A**) Homemade working channel with 10 ml syringe. (**B**) Schematic diagram of the cross-section and each side view of the custom-made working channel. (**C**) Schematic diagram of the cross-sectional view of the pencil tip and custom-made working channel.

surgery and get a better decompression for the nerve root and dura. We can use conventional operation instruments and fusion devices to make operation more convenient and safe without increasing the cost to the patient by using this custom-made transparent plastic working tube.

Like the reports of endoscopic TLIF surgery in recent years, all the 39 patients in this study achieved very satisfactory clinical results and intervertebral fusion, and there were no related complications. The most commonly reported complications of endoscopic TLIF surgery include dural tear, infection, and epidural hematoma (11, 12); although there is a lack of prospective randomized controlled studies, the currently available case series and comparative studies seem to support a lower overall complication rate of endoscopic TLIF surgery compared to their MIS or traditional spinal surgery (13). Furthermore, endoscopic TLIF can be distinguished into three surgical techniques based on the type of the endoscope used (percutaneous endoscopic TLIF with a working channel, biportal endoscopic TLIF, microendoscopic TLIF, and Full-Endoscopic Oblique Lateral Lumbar Interbody Fusion) (14). Almost all these studies mentioned the problem of the steep and potentially dangerous learning curve (11, 15); the possible reason includes (1) the anatomy of the intervertebral foramina under the endoscope is unfamiliar (16), and the risk of exiting nerve root injury is high, especially during the placement of the cage, so there are some reports in the literature about expandable mesh interbody fusion cage (4, 17); its main advantages appear to be decreased anatomical disruption during delivery and deployment. The problem is that this will increase the financial burden on the patients, and a larger number of patients and further long-term follow-up are warranted (18). (2) Surgical operation time is too long (19), especially in early cases, which may be safer for osteotomy of the articular process and endplate preparation by using burrs under the endoscopic visualization, but with a lower efficiency; to overcome the above-mentioned problems as much as possible, we adopted this posterolateral transforaminal approach, which is similar as the traditional open surgical approach, surgeons may be more familiar with the anatomy to get a better posterior decompression than regular endoscopic TLIF, and we can obtain autogenous bone for bone grafting during facetectomy to expect a higher fusion rate, the application of this novel transparent plastic channel can be equipped with conventional instruments, making the surgical operation more efficient and safe, and will not increase the burden of the patient compared with endoscopic lumbar interbody fusion by using expandable cage.

Kenji et al. mentioned the problem of excessive radiation exposure, which may increase the risk of health problems for the surgical team and the patients (20, 21), In our research, skilled surgeons can stay behind the lead screen when radiation exposure is needed, so the surgical team does not require radiation exposure in the whole process. However, the patient's radiation exposure is higher than that of traditional open TLIF surgery (20, 21).

Although our new surgical approach and instruments may make the learning curve smoother, there are still some limitations compared with traditional open TLIF surgery, which includes more radiation exposure to patients during surgery and there are still many spinal diseases that cannot be resolved by endoscopic surgery. Also, because of the use of percutaneous screws and endoscopy, it will still increase the burden on some patients. Clinical study of additional pedicle screw fixation. In the next study, we may consider the clinical study of pure intervertebral fusion without additional pedicle screw fixation.

CONCLUSION

FE-PTLIF surgery has the advantages of less trauma and faster recovery because of its clear vision, enough decompression, adequate endplate preparation, and autologous bone graft materials can be obtained during the operation. Our preliminary clinical results also showed that this surgical method has a good fusion rate and clinical efficacy. In general, FE-PTLIF is a safe and effective interbody fusion option for most lumbar degenerative diseases, which can be equipped with conventional instruments by using a transparent plastic working tube.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article/ **Supplementary Material** will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The Ethics Committee of the Second Affiliated Hospital of Chongqing Medical University. The patients/ participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

YD, FJ, ZY, YL, LC, and LW performed the surgery. YD, XZ, and HZ collected and interpreted the patient's clinical data. YD, FJ, XZ, and LC drafted the manuscript. XY and XZ contributed to the revision. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsurg.2022.884794/full#supplementary-material.

Supplementary Video S1 | Process of arthroplasty and exposure of nerve roots with a visual trephine by posterolateral transarticular approach.

Supplementary Video S2 | Application of self-made visual working channel under endoscope.

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Comparison of Postoperative Outcomes Between Percutaneous Endoscopic Lumbar Interbody Fusion and Minimally Invasive Transforaminal Lumbar Interbody Fusion for Lumbar Spinal Stenosis

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Objective: This study aimed to compare postoperative outcomes in surgical and patient-reported outcomes (PROs) between percutaneous endoscopic lumbar interbody fusion (PE-LIF) and minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) for the treatment of lumbar spinal stenosis (LSS).

Methods: We reviewed a total of 89 patients undergoing single-level surgery for lumbar spinal stenosis from January 2018 to July 2021. The cases were categorized as PE-LIF (Group PE-LIF, 41 cases) or MIS-TLIF (Group MIS-TLIF, 48 cases) approach. Parameters obtained at baseline through at least six months of follow-up were collected. The surgical outcomes involving the operative time, estimated blood loss, postoperative bed staying time, and length of hospital stays were analyzed. PROs included the Visual Analogue Scale (VAS), Oswestry Disability Index (ODI), modified MacNab standard evaluation, intervertebral fusion rate, and postoperative complications.

Results: A total of 89 patients were included in this analysis involving 41 patients who underwent PE-LIF and 48 patients who underwent MIS-TLIF. The 2 groups were similar in gender, age, body mass index, follow-up time and surgery levels ($P > 0.05$), and were not significantly different in the length of hospital stays ($P > 0.05$). PE-LIF had a significantly longer operative time, greater fluoroscopy time, lower estimated blood loss and shorter bed rest time than MIS-TLIF. Both groups improved significantly from baseline for the VAS and ODI scores. PE-LIF was associated with a lower VAS score for back pain at three-day after surgery. There were no significant differences between PE-LIF and MIS-TLIF in the excellent or good rates and intervertebral fusion rates at the last follow-up ($P > 0.05$). As for related complications, there were no significant complications occurred, and no significant differences were seen in the complications between both groups ($P > 0.05$).

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Conclusions: To summarize, PE-LIF and MIS-TLIF are both safe and effective for LSS. PE-LIF has a definite short-term curative effect with less trauma.

Keywords: lumbar spinal stenosis, postoperative outcomes, transforaminal lumbar interbody fusion, endoscopy, minimally invasive

INTRODUCTION

Lumbar spinal stenosis (LSS) is highly prevalent in patients older than 60 years of age and is one of the most common reasons for spinal surgery (1). The incidence of LSS is expected to grow further as the Chinese population ages. It is believed that LSS is a frequent cause of low back pain and neurogenic claudication and can dramatically decrease patient quality of life (2). LSS makes patients suffer from substantial pain and reduces physical activity, and potentially increases the risk of chronic diseases, including cardiovascular diseases and neurodegenerative diseases (3). Conservative management (therapeutic lifestyle changes, physiotherapy, rehabilitation training, drugs, and epidural steroid injection) is always recommended before symptoms worsen (4).

Surgical treatment is essential when conservative treatment fails. Surgical treatment of LSS aims to decompress neural structures, restore stability to the spine, relieve symptoms, and improve function (5). The posterior lumbar interbody fusion (PLIF) is considered the gold standard, performed well by most spinal surgeons. However, it may be limited by iatrogenic injury of posterior ligament complex, inadequate restore lordosis, and potential retraction injury of nerve roots (6). The transforaminal lumbar interbody fusion (TLIF), first reported by Harms and Rolinger and developed by Harms and Blumes, could result in lower structural damage than the PLIF procedure (7). So far, both PLIF and TLIF have been extensively accepted and successfully applied in the management of LSS. But some scholars still doubt these traditional operations by their much soft-tissue disruption and high complication rates (8). With the development of minimally invasive surgery (MIS), MIS-TLIF has been reported to be a safe procedure with satisfactory outcomes and acceptable complications when compared with TLIF (9). In recent years, spinal surgeons have shown increased interest in percutaneous endoscopic lumbar interbody fusion (PE-LIF). This procedure is performed under a working channel and endoscopic system, which theoretically achieves less surgical trauma (10).

Both PE-LIF and MIS-TLIF are derived from the theory of open LIF. Despite more consensus on the sufficient efficacy of these surgical techniques, relevant evidence is still insufficient. Therefore, we conducted the present study to demonstrate the efficacy and safety of PE-LIF compared with MIS-TLIF in the treatment of LSS. We also briefly describe the technical notes and notable matters of PE-LIF.

METHODS

Patient Selection and Data Collection

The present study was approved by the Ethics Committee of the Second Affiliated Hospital of Chongqing Medical University. All patients had signed a written informed consent before surgery. We retrospectively collected the clinical data of patients with LSS who underwent PE-LIF or MIS-TLIF by the same team of senior surgeons from January 2018 to July 2021. Relevant demographic information, clinical symptoms, and radiological outcomes were obtained.

The inclusion criteria were: (1) participants 45 years of age or older with a symptom of intermittent neurogenic claudication and at least one typical sign; (2) imaging indicating single-level lumbar central/lateral recess stenosis; (3) failing to relieve of symptoms after 4-6 weeks of conservative treatment; (4) at least six months of postoperative follow-up and complete patient-reported outcomes (PROs). The exclusion criteria included: (1) previous surgical history of the corresponding segment; (2) spinal trauma, infection, tuberculosis, tumor, and degenerative deformity.

Surgical Technique

PE-LIF (L4/5 Segment)

After general anesthesia, the patient was positioned prone on the operating table with appropriate abdominal suspension. A C-arm fluoroscope was used to locate the surgical segment and marked the projection of the spinous process, intervertebral space, and pedicle. The puncture site was located at 2 cm lateral to the spinous process, and a 1.5 cm incision was made laterally on the significant symptom side. The puncture needle was placed at the posterior edge of the disc and vertebral body while it approached near the medial site of the articular process with the AP view of the C-arm fluoroscope. With the assistance of a puncture needle, the dilating cannulas were inserted progressively to establish a working cannula. A part of the facet joint and lamina was removed by the circular saw to enlarge the vision of the surgical field. Under direct endoscopic visualization, the nuclear material and proliferative ligamentum flavum were removed to expose and decompress the dural sac and nerve roots. For patients with bilateral symptoms, the spinous process root, the contralateral ligamentum flavum, and part of the contralateral articular process were removed to achieve bilateral decompression. Attention was paid to ensure the dural sac and nerve roots achieved adequate decompression (the neural tissue reached the conditions of blood supply improvement, recovery anatomical position recovery, and independent pulsation). The nerve roots and dura were protected while the annulus fibrosus was opened. A minimally invasive reamer was used to treat the disc.

After confirming the protected neural structures, the intervertebral disc tissues were minced using different diameters' reamers. The nuclear material and annulus fibrosus were removed while the upper and lower endplate cartilage were scraped through a working cannula. A model case is first used to determine the appropriate case size. Autogenous and allogeneic bone was implanted into the intervertebral space through the working cannula, and the titanium expandable cage was inserted into the bone graft site. The cage was placed nearly in the middle of the intervertebral space and was confirmed by the C-arm fluoroscope. The dural sac and nerve roots were ensured to exist outside of the working cannula before placing cage, and would be re-checked after completing cage placement.

Four small longitudinal incisions were made from the marked pedicle projection. The skin, subcutaneous tissue, and deep fascia were incised successively, and the muscles were passively separated. The pedicle screws with appropriate diameter and length were inserted percutaneously under the guidance of the C-arm fluoroscope. The incision was repeatedly irrigated and checked for active bleeding before the incision was closed. After the screw and cage position was judged satisfactory, the incisions were sutured directly.

MIS-TLIF (L4/5 Segment)

After anesthesia, the procedure was performed on the prone. A skin incision of 3 cm to 2–3 cm lateral to the midline is made after determining the operative level and marking the skin with a C-arm image. Through this incision, a tubular retractor system was placed. The lamina, facet joint, and transverse process were exposed through a working retractor. The procedures were undergone under direct visualization rather than endoscopic visualization. The inferior and superior articular processes, ligamentum flavum, and part of the vertebral lamina were removed to expose the ipsilateral nerve root and dural sac. After extensive decompression, a discectomy was performed to remove the nuclear material and annulus fibrosus in Kambin's triangle. If there were contralateral symptoms, contralateral decompression was also performed on cutting of the spinous process root and ligamentum flavum. Progressively large dilating bougies stretched the intervertebral space. A cage was obliquely inserted into the intervertebral space after the autogenous and allogeneic bone was implanted. The procedures of the bilateral pedicle screw were similar to PE-LIF.

Postoperative Treatment

Both groups were treated with preventive antibiotics within 24 h following the operation. The mannitol and non-steroidal drugs were used appropriately. The patients were guided to carry out lower limb activities and low back muscle training in bed within 24 h after the operation. They started the out-of-bed movement two days post-operation. The patients were reminded to perform regular life under the protection of a brace within three months after the operation.

Outcome Measures

The perioperative factors involving the operative time, fluoroscopy time, estimated blood loss, bed rest time, length of hospital stays, and complication rate were obtained. Patient-reported outcomes (PROs) questionnaires were administered preoperatively at three days, three months, six months, and last follow-up postoperatively, including VAS, Oswestry Disability Index (ODI). The modified MacNab standard evaluation was calculated at the last follow-up. Radiologic outcomes included intervertebral fusion rates assessed with the Bidwell evaluation criterion at the last follow-up (11).

Statistical Analysis

All data were analyzed using IBM SPSS Version 26 (IBM Corporation, Armonk, New York, USA). The independent sample t-test was applied to compare the continuous data, which complies with the normal distribution between the two groups. Those non-normal distribution variables were analyzed by Mann-Whitney U test. We used the Chi-Square test or Fisher's exact test to compare categorical data. Statistical significance was defined as $P < 0.05$ for all analyses.

RESULT

Baseline Characteristics and Clinical Outcomes

Eighty-nine patients were qualified for the study. The 41 patients (15 men and 26 women) who underwent the PE-LIF had a mean age of 61.85 ± 10.45 years old. The 48 patients (18 men and 30 women) who underwent MIS-TLIF had a mean age of 62.98 ± 10.52 years. The mean follow-up period was 14.13 ± 3.91 months in the PE-LIF group and 13.66 ± 3.67 months in the MIS-TLIF group. There was no significant difference between the 2 groups in terms of gender, age, body mass index, follow-up period, and surgery levels ($P > 0.05$). Demographics and baseline characteristics of the two groups are presented in **Table 1**.

Compared with the MIS-TLIF group, the PE-LIF group had a significantly longer operative time (193.41 ± 28.42 vs. 167.33 ± 28.91 min, $P < 0.001$), greater fluoroscopy time (40.32 ± 4.17 vs. 25.38 ± 3.58, $P < 0.001$), lower estimated blood loss (122.24 ± 18.29 vs. 157.90 ± 28.61 mL), and shorter bed rest time (39.80 ± 6.65 vs. 43.46 ± 6.28 h, $P < 0.05$). The length of hospital stays was similar between the PE-LIF group and the MIS-TLIF group (8.87 ± 1.64 vs. 9.38 ± 1.88 h, $P > 0.05$) (**Table 1**).

Therapeutic Evaluation

Both groups showed significant improvements in the VAS for back pain (PE-LIF: 6.46 ± 1.14 to 1.37 ± 0.66; MIS-TLIF: 6.75 ± 0.93 to 1.40 ± 0.54) and leg pain (PE-LIF: 7.83 ± 0.92 to 0.98 ± 0.61; MIS-TLIF: 7.58 ± 0.85 to 0.90 ± 0.59) ($P < 0.001$). The ODI score also significantly improved at the last follow-

TABLE 1 | Demographics and baseline characteristics of the two groups: PE-LIF versus MIS-TLIF.

Variable	PE-LIF	MIS-TLIF	*P*-value
No. of patient	41	48	
Gender			0.929
Male	15	18	
Female	26	30	
Age (years) (mean ± SD)	61.85 ± 10.45	62.98 ± 10.52	0.531
BMI (kg/m^2) (mean ± SD)	25.11 ± 2.58	24.47 ± 2.45	0.231
Follow-up time (months) (mean ± SD)	14.13 ± 3.91	13.66 ± 3.67	0.558
Levels of surgery			0.91
L3/4	3	1	
L4/5	24	33	
L5/S1	14	14	
Operative time (minutes) (mean ± SD)	193.41 ± 28.42	167.33 ± 28.91	<0.001*
Fluoroscopy time	40.32 ± 4.17	25.38 ± 3.58	<0.001*
Estimated blood loss (mL)	122.24 ± 18.29	157.90 ± 28.61	<0.001*
Bed rest time (hours)	39.80 ± 6.65	43.46 ± 6.28	0.009*
Hospital stays (days)	8.87 ± 1.64	9.38 ± 1.88	0.179
Complications	1	2	0.467

**Statistically significant.*

TABLE 2 | Preoperative and postoperative visual analogue scale (VAS), Oswestry disability index (ODI) scores and Modified MacNab (mean ± SD).

	PE-LIF	MIS-TLIF	*P*-value
VAS (back)			
Preoperative	6.46 ± 1.14	6.75 ± 0.93	0.196
Postoperative 3 days	3.10 ± 0.70	3.48 ± 0.88	0.025*
Postoperative 3 months	2.37 ± 0.77	2.40 ± 0.82	0.86
Postoperative 6 months	1.54 ± 0.60	1.71 ± 0.58	0.173
Last follow-up	1.37 ± 0.66	1.40 ± 0.54	0.814
P value (last vs. pre)	<0.001*	<0.001*	
VAS (leg)			
Preoperative	7.83 ± 0.92	7.58 ± 0.85	0.193
Postoperative 3 days	3.78 ± 0.76	4.02 ± 0.79	0.147
Postoperative 3 months	2.46 ± 0.64	2.33 ± 0.66	0.35
Postoperative 6 months	1.68 ± 0.61	1.71 ± 0.54	0.836
Last follow-up	0.98 ± 0.61	0.90 ± 0.59	0.534
P value (last vs. pre)	<0.001*	<0.001*	
ODI index			
Preoperative	56.32 ± 9.54	57.96 ± 6.92	0.351
Postoperative 3 days	32.54 ± 4.70	34.13 ± 5.13	0.134
Postoperative 3 months	25.12 ± 3.69	26.17 ± 3.99	0.206
Postoperative 6 months	20.68 ± 2.43	21.13 ± 2.47	0.399
Last follow-up	15.32 ± 3.05	14.35 ± 2.91	0.132
P value (last vs. pre)	<0.001*	<0.001*	
Modified MacNab			0.872
Excellence	26	37	
Good	13	9	
Fair	2	1	
Poor	0	1	
Excellence/good rate (%)	95.12	95.83	

**Statistically significant.*

up after the operation (PE-LIF: 56.32 ± 9.54 to 15.32 ± 3.05; MIS-TLIF: 57.96 ± 6.92 to 14.35 ± 2.91). The VAS for both back and leg pain, and ODI scores were similar between the two groups preoperatively and at 3-month, 6-month, and the last follow-up after surgery. However, comparing the three-day postoperative data, the VAS score for back pain in the PE-LIF group was lower than that in the MIS-TLIF group with significant differences (2.55 ± 0.75 vs. 3.18 ± 0.67, $P < 0.05$) (**Table 2**). Following the modified Macnab standard of evaluation, the excellent or good rate was 95.12% in the PE-LIF group and 95.83% in the MIS-TLIF group at the last follow-up ($P > 0.05$) (**Table 2**). According to the Bridwell grading system, fusion grades in the PE-LIF group were 73.17% ($n = 30$) for grade I and 26.83% ($n = 11$) for grade II. In the MIS-TLIF group, fusion grades were 75.00% ($n = 36$) for grade I and 25.00% ($n = 12$) for grade II. There were no significant differences between the two groups in intervertebral fusion rates ($P = 0.844$). The representative cases are shown in **Figures 1**, **2**.

Related Complications

There was one case of transient ankle dorsiflexion weakness in the PE-LIF group and, one case of superficial infection, one case of postoperative epidural hematoma in the MIS-TLIF group. No significant differences were seen in the complications between both groups ($P > 0.05$) (**Table 1**). All patients recovered without major complications such as significant vessel injury, peritoneal injury, and pulmonary embolism. No patient required revision surgery during the follow-up period.

DISCUSSION

LSS is defined as a degenerative condition always accompanied by loss of intervertebral disc height, degenerative lumbar spondylolisthesis, thickening of ligamentum flavum, and facet joint hypertrophy with aging, causing the spinal neurovascular structures to compressed (1). It may occur on a congenital (developmental) narrow lumbar canal, degenerative processes, or both. Neurogenic claudication is the most typical clinical feature of LSS, which is always required to be distinguished from vascular claudication (4). To date, no clear gold-standard criteria have been established to diagnose LSS. Clinicians need to integrate the combination of age, symptoms, physical examinations, and imaging findings before making medical decisions (12). The symptomatic LSS has limited patients'

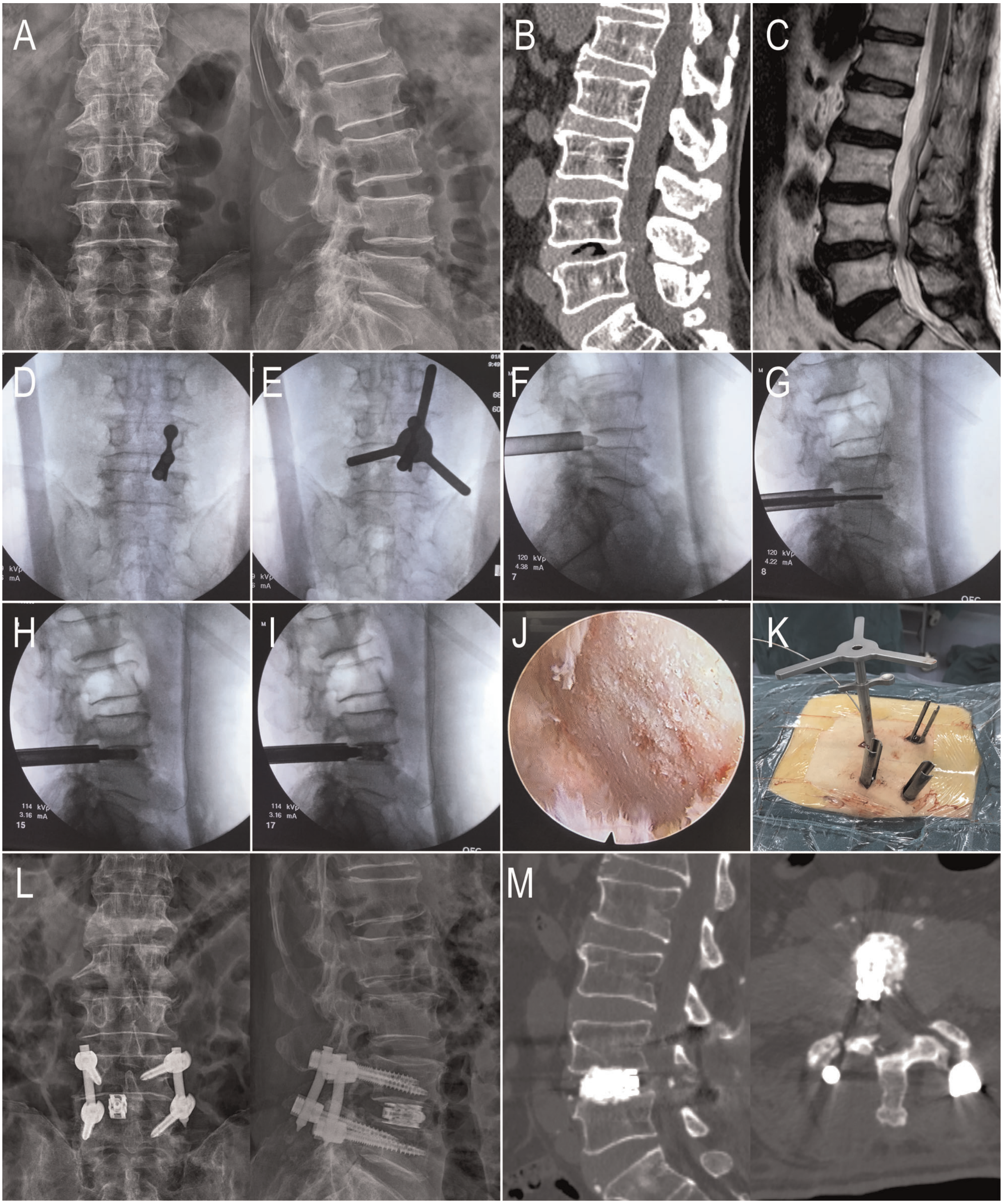

FIGURE 1 | An 81-year-old male with L4-5 LSS in the PE-LIF group. (**A–C**) Preoperative X-ray, CT, and MRI showed that L4 and L5 vertebra body and the intervertebral; (**D**) The puncture needle was placed; (**E**) Using the circular saw to remove a part of the facet joint; (**F**) the working cannula were placed percutaneously; (**G,H**) using reamers of different diameters to mince the intervertebral disc tissues and conduct endplate preparation; (**I**) the titanium expandable cage was placed through the working cannula; (**J**) Decompression of the nerve root and handling the endplates under endoscopic vision (**K**) Direct vision of the working channel and the circular saw. (L-M) X-ray and CT showed the percutaneous pedicle screw fixation and the titanium expandable cage.

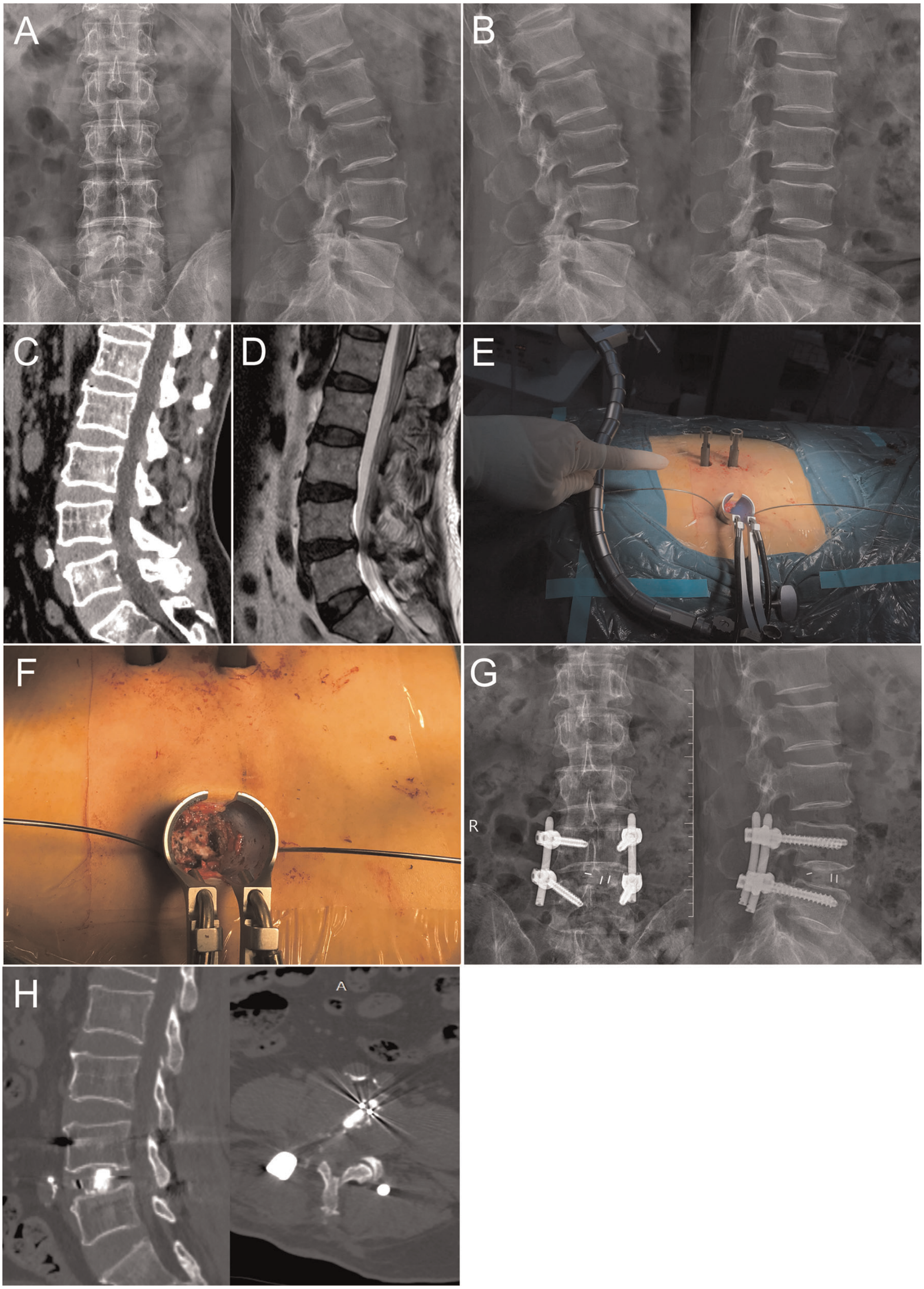

FIGURE 2 | A 68-year-old male with L4-5 LSS in the MIS-TLIF group. (**A–D**) Preoperative X-ray, CT, and MRI showed the condition of the symptomatic segment, and the dynamic flexion-extension radiographs showed L4 instability; (**E**) The tubular retractor system was placed; (**F**) Decompression of nerve root and dural sac were performed under direct visualization; (**G,H**) X-ray and CT showed the posterior instrument and the cage was appropriate.

daily activities and decreased their quality of life. It was reported that the costs of LSS surgeries were estimated at nearly $1.65 billion in 2007 in the United States, which placed a substantial economic burden on the medical system (13).

Traditional surgical techniques of decompression plus fusion (P/TLIF) have been widely accepted. MIS has gotten the attention of surgeons. The MIS-TLIF technique has been widely applied, which is performed under the working channel using the tubular retractor (14). Previous studies suggest that MIS-TLIF achieves satisfactory relief of symptoms in treating various degenerative lumbar diseases and can lessen tissue trauma, reduce postoperative pain, shorten hospital stays, and allow faster recovery (9, 15). Wong et al. provided evidence that MIS-TLIF was found to have a statistically significant reduction in the lower rate of reoperations and deep wound infection than open TLIF (16). In addition, a meta-analysis from Ray et al. reported that fusion rates for MIS-TLIF and open TLIF were similar and relatively high (17).

In the last decades, percutaneous endoscopic lumbar discectomy (PELD) has undergone significant development in managing lumbar degenerative diseases. The operative approach avoided largely removing the lamina, ligament flavum, or facet joints, which maintained the stability of the surgical segment. Benefiting from the minimal trauma, patients undergoing PELD have often experienced shorter bed rest and hospitalization time, and early return to work (18). However, PELD also had some downsides. This technique requires surgeons to develop skill proficiency in endoscopic spine surgery. Some scholars still questioned its incomplete removal of the disc and high incidence of revisions (19).

Based on the theory of PELD, recently developed techniques of PE-LIF achieved important minimal invasive goals. Theoretically, PE-LIF requires a smaller skin incision with less muscle dilation than other lumbar interbody fusion procedures. Osman et al. firstly applied this technique to patients with lumbar degenerative diseases in 2012 (20). The follow-up results indicated that the overall outcomes were satisfying, but there was a high complication rate. With the innovation of relevant surgical instruments and the increased technical proficiency of surgeons, more promising clinical outcomes with fewer complications were reported in recent literature (10, 21). In seven cases, Yang JC et al. (22) applied this surgical method for L4/5 single-segment LSS. There were significant improvements in symptoms for all patients, and no serious complications occurred during follow-up. A prospective cohort study by Ao et al. (23) demonstrated no significant differences in medium-short term surgical outcomes between PE-LIF and MIS-TLIF (e.g., the VAS scores, the ODI scores, the fusion rates, and complications). In fact, on average, patients of PE-LIF had faster functional recovery. A meta-analysis from Kou et al. (24) provided further evidence that the PE-LIF had advantages in terms of less intraoperative blood loss and shorter hospital stay.

For clinical outcomes based on this retrospective cohort study including 89 patients with LSS treated by PE-LIF and MIS-TLIF, it revealed no difference in clinical efficacy and safety (involving pain intensity, ODI scores, fusion rates, and complications) at the last follow postoperatively. Both groups were of satisfactory outcomes for LSS without any significant complications. The results suggested that PE-LIF presents significantly lower estimated blood loss and a shorter bed rest time than MIS-TLIF. PE-LIF provided significantly better lower back pain relief in the immediate postoperative period than MIS-TLIF. However, the cohort of patients who underwent PE-LIF appears to experience considerably more fluoroscopy times and longer operative times than the MIS-TLIF group. Previous reports showed that PE-LIF had significantly lower hospital stays than MIS-TLIF (10, 23). In this study, the length of hospital stays trended towards being lower in the PE-LIF group, but the difference was not significant ($P = 0.179$). More high-level clinical evidence should be explored.

The diameter of the single hole endoscopic channel of PE-LIF is shorter than the tubular retractor system of MIS-TLIF, which theoretically reduces tissue trauma. Moreover, a significant additional advantage of PE-LIF is that it can be operated under endoscopy. Therefore, some scholars considered that PE-LIF could reach precise decompression of the nerves and reduce the destruction of bony structures such as the articular processes or lamina, which remarkably reserve the stability of the posterior lumbar column (25). It was thought that less traumatic operation helped to restore low back muscle function, reduce the incidence of postoperative residual back pain, and allow patients to move around early while reducing bed-rest complications (26). Comparing the two groups of patients in this study cohort showed that patients in the PE-LIF group had a better early recovery than MIS-TLIF.

Despite these potential advantages, it remained unclear if PE-LIF had advantages for managing intervertebral space. Some scholars believe that with the endoscopic surgical technique, surgeons can handle the endplates under direct vision and determine adequate cartilage endplate removal (27). This may theoretically promote interbody fusion and reduce the risk of cage collapse. However, some studies also conclude that PE-LIF is prone to inadequate treatment of the cartilaginous endplate, leading to complications involving cage displacement and pseudarthrosis formation (28). In this study, compared with MIS-TLIF, PE-LIF was of similar good clinical outcomes for fusion rates, without cage displacement or collapse at the last follow-up. In our experience, PE-LIF was perhaps less efficient in treating intervertebral discs, which led to the prolongation of operation time.

Almost studies have reported the appliance of interbody implant cage. Previous studies have mainly focused on nano-hydroxyapatite/polyamide-66 Cage (n-HA/PA66) and Polyetheretherketone (PEEK), which have been widely recognized. Recent studies have suggested that the titanium expandable cage can reduce nerve roots injury, restore lumbar lordosis, and achieve indirect decompression of the spinal canal and intervertebral foramen (22, 27). However, the potential complications of bone endplate injury and pseudarthrosis could not be ignored during these procedures.

Some drawbacks deserve to be pointed out about PE-LIF. One concern for PE-LIF is the risk of increasing the ionizing radiation exposure for both patients and surgeons. The locations of the operation area and the pedicle placement were mainly confirmed by C-arm fluoroscopy rather than direct vision. Although not directly addressed in our research, repeat fluoroscopy could potentially increase the operation time. On the other hand, PE-LIF requires significant time to improve the learning curve. Surgeons should strictly grasp the indications and be familiar with percutaneous endoscopy and percutaneous pedicle screw placement techniques. Electromyography monitoring is recommended for avoiding potential serious complications, including nerve root injury and dural tears (29).

The present study had several limitations. Firstly, this was a retrospective study and the sample size was relatively small. All patients included in this research were treated in a single center. Secondly, only patient with single-level LSS is recruited, which may result in selection bias. Thirdly, some postoperative radiographic parameters involving the disc height, foraminal height, and lumbar canal cross-sectional area were not reported in this study and should be investigated in future studies. Lastly, the follow-up period was relatively short for evaluating long-term effects.

CONCLUSION

The present study results demonstrate that both PE-LIF and MIS-TLIF are safe and effective for LSS. PE-LIF has a definite short-term curative effect with less trauma. Nevertheless, considering the limitations, further evidence with long-term follow-up and larger sample size should be carried out to explore the differences in outcomes after PE-LIF and MIS-TLIF.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The Ethics Committee of the Second Affiliated Hospital of Chongqing Medical University. The patients/participants provided their written informed consent to participate in this study.

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

LC and LL provided ideas and design of the study. LC, LL, LS and SC collected the clinical data. LL and Z-Q W performed the statistical analysis. Q-JG and D-ZG contributed to investigation and the relevant literature review. LL wrote this manuscript. LC, X-QL and Amadou CI revised the paper. The study was performed under the Supervision of X-QL and Z-YK. All authors contributed to the article and approved the submitted version.

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CASE REPORT
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Case Report: Five-Level Unilateral Laminectomy Bilateral Decompression (ULBD) by Two-Stage Unilateral Biportal Endoscopy (UBE)

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Introduction: Unilateral biportal endoscopy (UBE) is a relatively new yet common minimally invasive procedure in spine surgery, capable of achieving adequate decompression for lumbar spinal stenosis through unilateral laminectomy bilateral decompression (ULBD). Neither additional fusion nor rigid fixation is required, as UBE-ULBD rarely causes iatrogenic lumbar instability. However, to our knowledge, five-level ULBD *via* two-stage UBE without lumbar fusion has been yet to be reported in the treatment of multilevel lumbar spinal stenosis.

Case description: We present a case of an 80-year-old female patient who developed progressive paralysis of the lower extremities. Radiographic examinations showed multilevel degenerative lumbar spinal stenosis and extensive compression of the dural sac and nerve roots from L1-2 to L5-S1. The patient underwent five-level ULBD through two-stage UBE without lumbar fusion or fixation. One week after the final procedure, the patient could ambulate with walking aids and braces. Moreover, no back pain or limited lumbar motion was observed at the 6-month follow-up.

Conclusion: Multilevel ULBD through UBE may provide elderly patients with an alternative, minimally invasive procedure for treating spinal stenosis. This procedure could be achieved by staging surgeries. In this case, we reported complaints of little back pain, despite not needing to perform lumbar fusion or fixation.

Keywords: case report, unilateral laminectomy bilateral decompression (ULBD), unilateral biportal endoscopy (UBE), lumbar spinal stenosis (LSS), multilevel

INTRODUCTION

Unilateral biportal endoscopy (UBE) is a minimally invasive procedure in which water-medium endoscopic surgery is performed to achieve neural decompression or spinal fusion. Unilateral laminectomy bilateral decompression (ULBD) *via* UBE is indicated for lumbar spinal stenosis (LSS), as confirmed by several randomized controlled trials (1, 2). Although many studies on this technique have published, most only reported 1- or 2-level UBE-ULBD. This is the first report on 5-level ULBD *via* two-stage UBE for multilevel LSS.

Abbreviations: UBE, unilateral biportal endoscopic; ULBD, unilateral laminectomy bilateral decompression; LSS, lumbar spinal stenosis; CT, computed tomography; MRI, magnetic resonance imaging.

CASE DESCRIPTION

The patient was an 80-year-old female who developed progressive paralysis of the lower extremities and radicular pain of the left leg, which confined her to a wheelchair daily over the past two years. Sensory disturbances of the anterior bilateral thighs, lateral crura and dorsum of the feet were found through physical examination. The Lasegue sign of the left leg was positive, and the bilateral Babinski signs were negative. Flexion and extension lateral lumbar radiographs showed relative dynamic stability at all lumbar segments (**Figure 1A**). Lumbar computed tomography (CT) showed multilevel degenerative stenosis and L4 spondylolisthesis (**Figure 1B**). Magnetic resonance imaging (MRI) revealed serious stenosis from L1-2 to L5-S1 and left lateral recess stenosis at L5-S1 (**Figure 1C**).

According to the patient's symptoms, physical examination, and imaging findings, the patient did not have significant lumbar instability, which was also the indication of non-fusion surgery. Because of multilevel severe stenosis and extensive neurological defects, it was difficult to identify one or two segments as the responsible segments. One stage surgery would take longer operation time and more intraoperative blood loss. So we performed staged procedures. In the first stage procedure, the patient's radicular pain of lower limb was considered, double ULBD at L4-5 and L5-S1 from the left side was performed through first-stage UBE to decompress the bilateral L5 and S1 nerve roots and dural sacs (**Figure 2**).

The left leg pain improved significantly the first day after the first-stage procedure. But the patient still could not realize to walk independently. So we continued to perform ULBD at L3-4, L2-3 and L1-2 from the same side one week after the first-stage surgery. The bilateral L3, L2, and L1 nerve roots and dural sacs were decompressed through the second-stage procedure (**Figure 3**). Bilateral nerve roots were exposed at all segments to ensure adequate lateral decompression of the lumbar canal (**Supplementary Video 1**).

Celecoxib was given to relieve the low back pain postoperatively. The patient recovered to ambulate with a Boston brace after the second-stage surgery and rehabilitative training. The patient was discharged home after her low back pain was relieved, and she was able to bend and stretch her

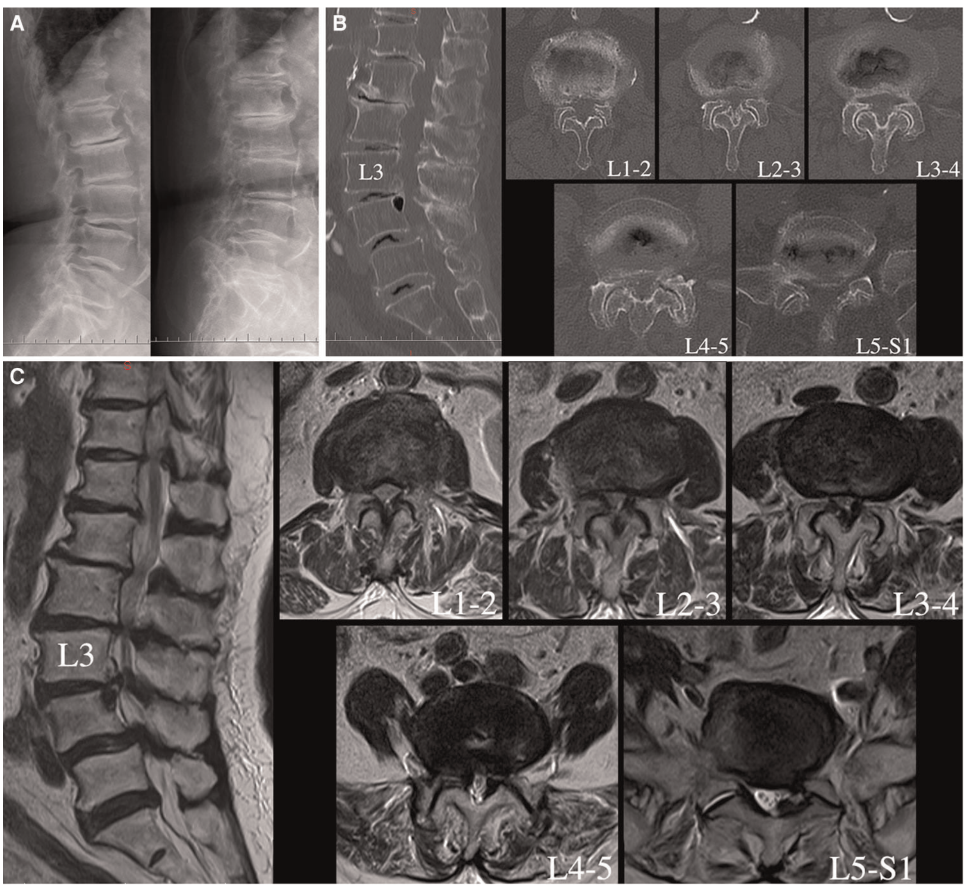

FIGURE 1 | Flexion and extension lateral lumbar X-ray radiograph demonstrating relative dynamic stability at all lumbar segments (**A**). Lumbar CT showing hyperplasia and cohesion of the facet joints, ossification of the ligamentum flavum and multilevel stenosis of the lateral recesses and central canals (**B**). Sagittal and axial T2-weighted lumbar MRI revealing serious central canal stenosis from L1-2 to L4-5, lumbar disc herniation and left lateral recess stenosis at L5-S1 (**C**).

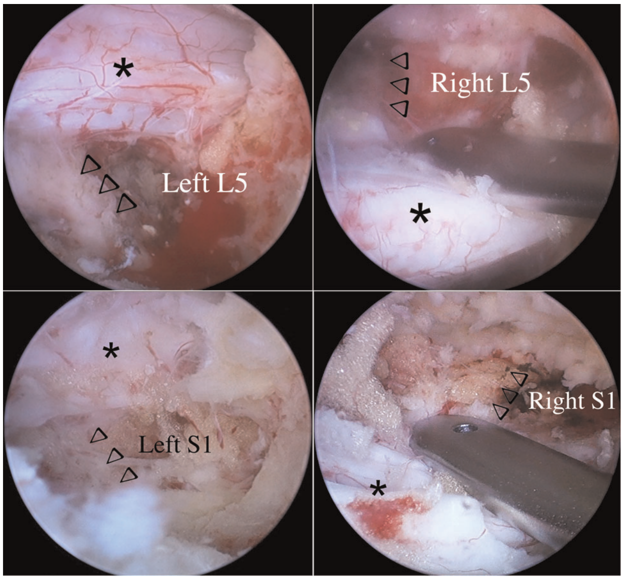

FIGURE 2 | Bilateral L5 and S1 nerve roots and dural sacs after first-stage first stage UBE-ULBD (arrowheads indicate nerve roots, asterisks indicate dural sacs).

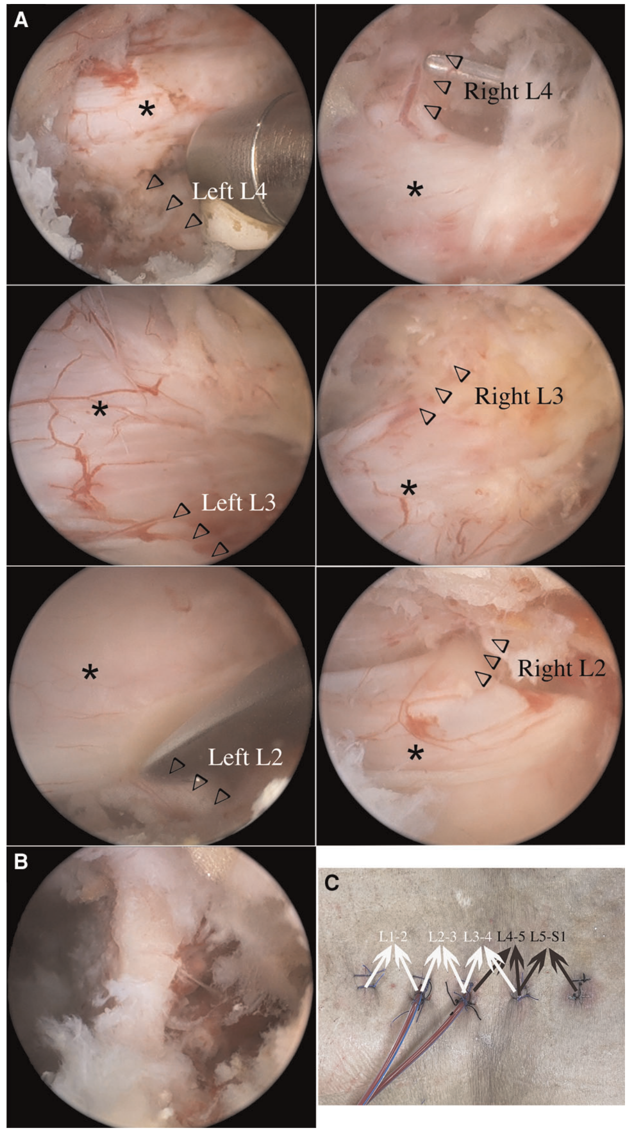

FIGURE 3 | Bilateral L4, L3 and L2 nerve roots and dural sacs after second-stage UBE-ULBD (arrowheads indicate nerve roots, asterisks indicate dural sacs) (**A**). Residual left lamina of L4 after L4-5 and L3-4 UBE-ULBD (**B**). The surgical incisions after the two-stage procedure and the counterparts of the surgical segments (black arrowheads indicate the first-stage operation, white arrowheads indicate the second-stage operation) (**C**).

back (**Figure 4A**). Postoperative lumbar radiographs showed the range of laminectomies and decompressed lumbar spinal canals (**Figure 4B**). The patient has been followed-up for 1 year since the second-stage operation and reports significantly improved pain levels and the ability to complete daily activities. The 1-year follow-up's imagings showed satisfactory decompression of lumbar spinal canals, and the spondylolisthesis of L4 still not progressed (**Figure 5**).

DISCUSSION

LSS is caused by gradual degenerative narrowing of the spinal canal. According to a randomized controlled trial study, compared with decompression plus fusion surgery, single decompression surgery showed considerable clinical results (3). The ULBD technique was first reported by Young in 1988, and it has been rapidly improved by the use of various minimally invasive techniques, such as microscopy and microendoscopy. Nevertheless, the air medium required under microscopy and microendoscopy cannot provide a clear visual field, especially in contralateral decompression procedures (4, 5). Full endoscopic ULBD can achieve effective bilateral decompression *via* water medium, and several studies have reported favorable outcomes from this version of the procedure in the treatment of LSS (6). However, full endoscopic ULBD has a steep learning curve and a high rate of complications (7). ULBD *via* UBE is a relatively newly emerging technique that provides surgeons an alternative for conducting ULBD in a minimally invasive manner. Following the first report of this procedure from Egyptian and South Korean researchers, UBE-ULBD has been suggested to be a safe and effective surgery for LSS decompression (8, 9). Nevertheless, few studies have reported the clinical outcomes of multilevel UBE-ULBD, and its efficacy and safety remain unclear. In this case, a patient with multilevel LSS underwent five-level UBE-ULBD in two stages, which is the first report to our knowledge on such a large number of ULBD procedures for one patient.

For this patient, the long segmental lumbar fusion defects, including extensive detachment of the paravertebral extensors and limited back movement, were the reasons why we chose this minimally invasive, nonfusion surgery. In addition, this

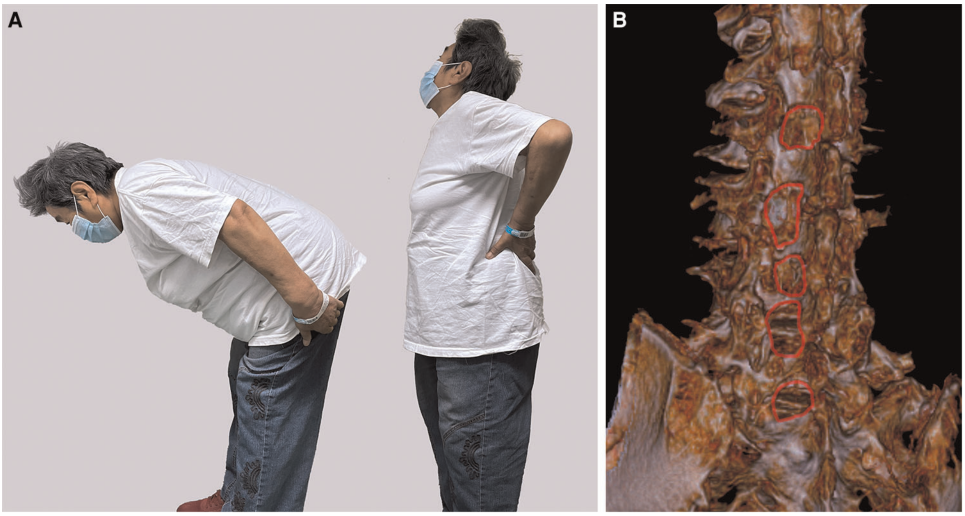

FIGURE 4 | The patient achieved favorable flexion and extension of the back with little pain (**A**). Regions of bone resection after the two-stage procedure (red circles) (**B**).

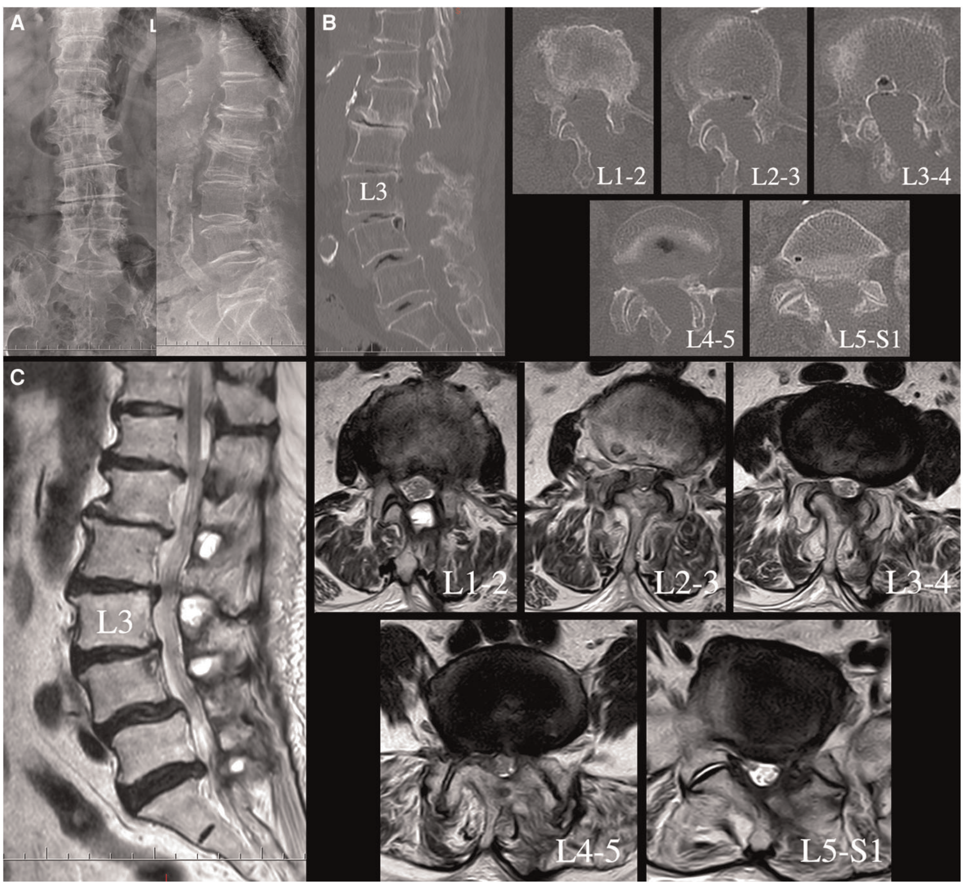

FIGURE 5 | The lumbar X-ray radiograph of 1-year follow-up demonstrating all surgical segments remained stable (**A**). Lumbar CT of 1-year follow-up showing the bony structure changes of surgical segments (**B**). Sagittal and axial T2-weighted lumbar MRI revealing satisfactory decompression of lumbar canal from L1-2 to L5-S1 (**C**).

patient had no obvious degenerative spinal deformity or serious back pain. All her symptoms had developed as a result of compression of nerve roots and cauda equina. Staging the procedures can reduce the duration of each process, which is beneficial for the postoperative recovery of elderly patients. The range of bone resection in conventional ULBD mainly involves the partial unilateral lamina and internal cortex of the contralateral lamina. In this patient, bone resection involved the ventral side of the superior articular process due to decompression of the nerve root in the lateral recess. This procedure is also widely used in the full endoscopic version of ULBD surgery (10). Our experience with this patient demonstrates that ULBD with partial facet resection minimally damages the stability of the surgical segment, and the impairment of the paravertebral muscles was relatively limited. Additionally, the patient did not complain of obvious back pain during lumbar movement.

LSS is a very common pathological condition in elderly individuals. Complicating matters is that this pathological process frequently involves two or more levels, requiring the surgeon to attempt to balance wide-range decompression and spinal stability. UBE-ULBD could provide surgeons with a good alternative to expanded laminectomy or long segmental fusion. This minimally invasive procedure has remarkable advantages in producing early ambulation, inducing less incision pain, and requiring shorter hospital stays. All these factors could reduce the risk of postoperative complications, mortality and utilization in elderly patients. Moreover, many elderly patients who have multiple comorbidities, such as hypertension, diabetes mellitus and coronary heart disease, may have more opportunities to undergo lumbar surgery with the continuing development of minimally invasive nonfusion techniques.

UBE is an emerging minimally invasive spinal technique that can be performed for a variety of lumbar degenerative diseases, including multilevel lumbar spinal stenosis. ULBD *via* UBE can achieve safe and effective decompression, which may be crucial for allowing elderly patients to complete their daily activities. We presented a case of a patient who developed multilevel LSS and underwent two-stage, five-level UBE-ULBD, achieving a favorable clinical result.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHIC STATEMENT

The studies involving human participants were reviewed and approved by Peking University Shougang Hospital Ethics Board. The patients/participants provided their written informed consent to participate in this study.

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

W-lW: conceptualization, resources, writing (original draft preparation), writing (review and editing), visualization, and project administration. S-jW: software and data collection. ZL: chief surgeon and the patient's follow-up. All authors have read and agreed to the published version of the manuscript. All authors contributed to the article and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsurg.2022.944509/full#supplementary-material.

Supplementary Video 1 | The residual left lamina of L4 under the second-stage endoscopic visualization.

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Clinical effects of unilateral biportal endoscopic decompression for lumbar posterior apophyseal ring separation

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Objective: The purpose of the study was to investigate the feasibility and effects of unilateral biportal endoscopic decompression for lumbar posterior apophyseal ring separation (PARS).

Methods: Patients with lumbar PARS who received unilateral biportal endoscopic decompression from June 2020 to September 2021 were analyzed, including 11 females and 15 males. The clinical symptoms were consistent with the imaging findings. Operation time, length of postoperative hospital stay and complications were recorded, and the clinical efficacy was evaluated by Visual Analogue Scale (VAS), Oswestry Disability Index (ODI) and modified Macnab scale at preoperative, postoperative 1, 3, 6 months and the last follow-up.

Results: Preoperative VAS scores of low back pain were (5.04 ± 1.37) and respectively decreased to (2.81 ± 0.75), (2.35 ± 0.98), (1.65 ± 0.69) and (1.15 ± 0.68) at postoperative 1, 3, 6 months and at the last follow-up, and the difference was statistically significant ($F = 127.317$, $P = 0.000$). Preoperative VAS scores of lower limb pain were (6.92 ± 1.38) and respectively decreased to (2.88 ± 1.07), (2.54 ± 1.03), (1.81 ± 0.80) and (1.00 ± 0.69) at postoperative 1, 3, 6 months and at the last follow-up, and the difference was statistically significant ($F = 285.289$, $P = 0.000$). Preoperative ODI scores were (60.47 ± 8.89) and respectively decreased to (34.72 ± 4.13), (25.80 ± 3.65), (17.71 ± 3.41) and (5.65 ± 2.22) at postoperative 1, 3, 6 months and at the last follow-up, and the difference was statistically significant ($F = 725.255$, $P = 0.000$). According to the modified Macnab criteria, the final outcome was excellent in 22 cases, good in 3 cases, fair in 1 cases. 26 patients could return to work or normal activities within 3 weeks.

Conclusions: Unilateral biportal endoscopic decompression has the advantages of clear and wide field of vision, large operating space, relatively simple need of surgical instrument and convenient and flexible operation procedure. It can achieve excellent clinical results with favorable efficacy and safety and may become a new minimally invasive endoscopic treatment for lumbar PARS.

KEYWORDS

unilateral biportal endoscopic, decompression, lumbar, posterior apophyseal ring separation, clinical effects

Background

Lumbar posterior apophyseal ring separation (PARS) is initiated in adolescents and often accompanied by lumbar disc herniation (1). Its mechanism remains unknown and different scholars have different views. The dural sac or nerve root can be compressed by herniated disc and separated bony fragment, which leads to back pain and neural symptoms among suffers (2). The disorder gradually proceeds and seriously hampers the normal life of patients. Conservative treatment is usually not satisfactory, and most of patients need surgical treatment (3).

Most patients were treated with open surgery in the past. Although the decompression was complete, there were risks of large trauma, more bleeding, spinal instability (4). When the fusion surgery was used, such as posterior lumbar interbody fusion (PLIF) or transforaminal lumbar interbody fusion (TLIF), drawbacks of the traditional fusion surgery appeared, such as adjacent segment degeneration, failed back surgery syndrome (5). Recently, with the deepening of the concept of minimally invasive spine surgery and the development of minimally invasive spine surgery techniques, percutaneous endoscpic discectomy has been used to treat this kind of disease (6). It has the advantages of less trauma, quick recovery, and no damage to paravertebral muscles and ligament. It has little impact on spinal stability and allows early out-of-bed functional exercise and reduces the occurrence of postoperative complications (7). However, the working portal and viewing portal are coaxial and the movable range of working portal is small. Due to the obstruction of joint process, pedicle, posterior margin of vertebral body, especially obstruction of high iliac crest in the L5/S1 segment, precise targeted catheterization is difficult for pertcutaneous transforaminal endoscopic discetomy. Therefore, the satisfactory decompression of the spinal canal is a challenging process. MED uses a single working channel and has the limitations of operation flexibility, operation space and poor vision of surgical field, which can easily lead to neural damage (8). Additionally, special working portal can easily lead to muscle strain injury.

Unilateral biportal endoscopic (UBE) technique utilizes two portals to complete the decompression, which are not coaxial. Viewing portal is used to expose the surgical field with arthroscopy and continuously rinse to keep the field clear, and the working portal is used for neural decompression through the posterior interlaminar approach, which is similar to traditional posterior open surgery (9). One of the advantages of this technique is that the two percutaneous portals are separated from each other and do not interfere with each other. Without portals limitation, endoscopic and surgical instruments can be moved freely and the whole operation is convenient and flexible (10). All directions and parts of the spinal canal can be explored. This technique can not only reach the goal of minimally invasive spine surgery, but also obtain the similar decompression effect close to open surgery, which is a supplement to the existing endoscopic technology (11).

This paper summarized 26 cases with lumbar PARS who were treated with UBE technique, and discussed the application and clinical efficacy of UBE technique in the treatment of lumbar PARS.

Materials and methods

Patient information

A retrospective analysis was performed on 26 patients treated with UBE technique for lumbar PARS in the authors' hospital from June 2020 to September 2021. The inclusion criteria were as the following: (1) Imaging examination (CT and MRI) confirmed lumbar disc herniation with PARS, the symptoms and signs were consistent with imaging and the responsible segment was single; (2) Neurogenic claudication or radicular leg pain with or without back pain; (3) Conservative treatment is poor or recurrent attacks; (4) The patients received unilateral biportal endoscopic decompression.

Exclusion criteria were as the following: (1) segmental instability; (2) lumbar spinal stenosis; (3) lumbar spondylolisthesis; (4) surgery history of targeted segment; (5) infectious history of lumbar spine; (5) Calcified lumbar disc herniation; (6) History of mental illness.

The study was approved by our institutional review board and the informed consent was obtained from all patients.

Surgical procedures

Patients preparation

All cases were performed by single surgeon. After induction of general anesthesia, patients are positioned prone with the abdomen free and the spine flexed to open the interlaminar space.

Placement of endoscopic portals

After level confirmation is conducted under the C-arm fluoroscopic guidance, two portals are made 1 cm parallel to midline of spinous process and 1.0 cm above and 1.0 cm below the center of the target level. The proximal portal is about 6 mm to introduce the arthroscope and the distal portal is about 10 mm to place the surgical instruments. The fascia perpendicular to the skin is incised to prevent the obstruction of water flow during surgery. The distance between both portals allows the surgeon to perform the triangulation technique with complete freedom of the surgical tool. The primary dilator is then inserted into the two portals through the paraspinal muscles without any separation till it is docked over the lamina surface and then it is uesd to separate bluntly and push aside the overlying soft tissue step by step to form a visual surgical field.

Insertion of the endoscope and preparation of the surgical field

The endoscopic cannula and trochar are introduced through the endoscopic portal till they are docked over the superior lamina. The irrigation fluid is initiated and the trochar is removed to wash out the blood and the endoscope with 30° lens is introduced through the cannula. The irrigation fluid used is isotonic saline to avoid tissue edema. Then the radiofrequency probe is used to clean the remaining soft tissues or muscles over the lamina and ligamentum flavum (**Figure 1A**).

Laminotomy and ligamentum flavum removal

When the ligamentum flavum of the target interlaminar space and inferior edge of superior lamina are completely exposed (**Figure 1B**), the arthroscopic burr is used to thin out ispilateral lamina (**Figure 1C**), which is followed by laminectomy by Kerrison punch to complete a

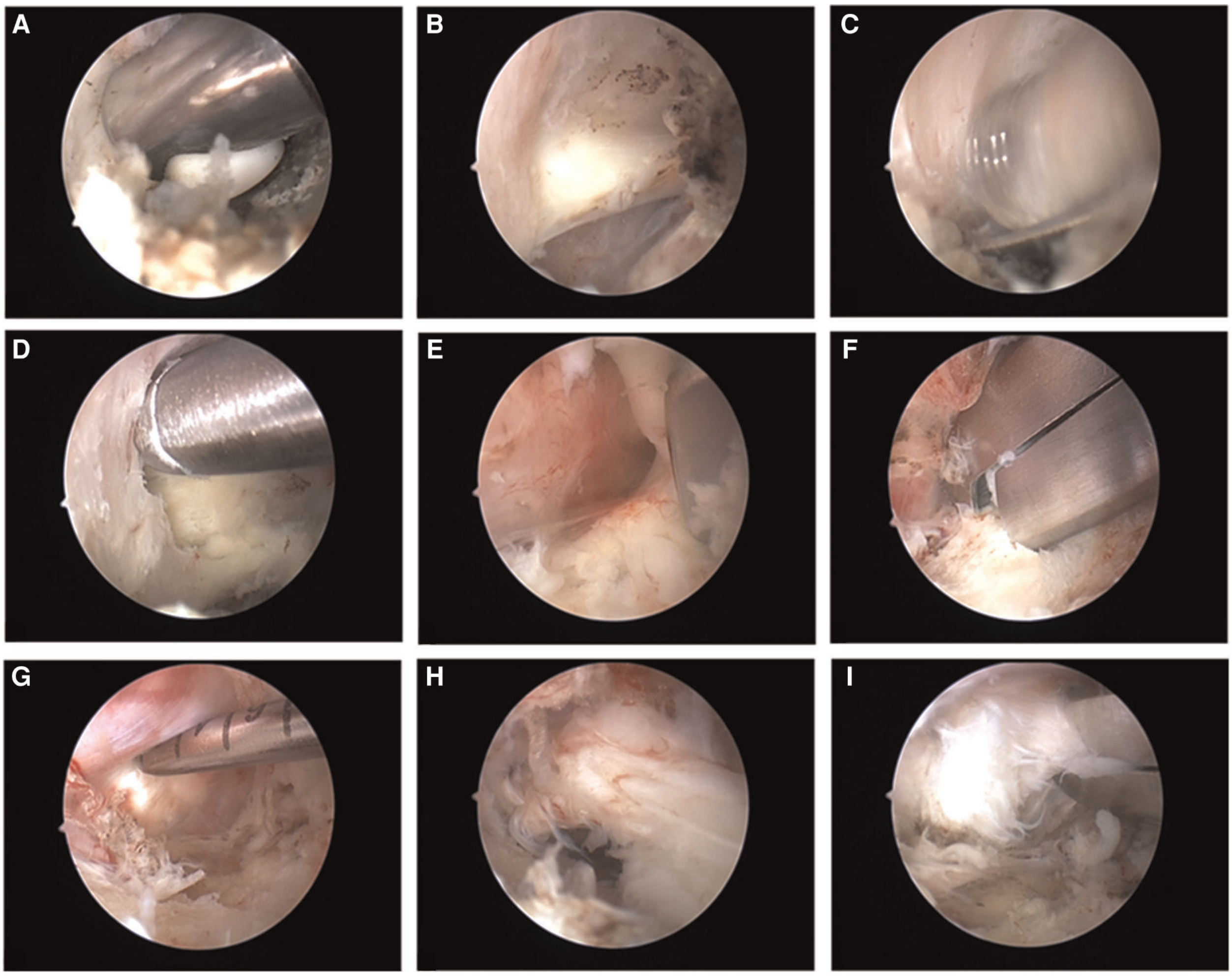

FIGURE 1
Intraoperative processes. (A) The radiofrequency probe is used to clean the remaining soft tissues or muscles over the lamina and ligamentum flavum; (B) The ligamentum flavum of the target interlaminar space and inferior edge of superior lamina are completely exposed; (C) The arthroscopic burr is used to thin out ispilateral lamina; (D) Kerrison punch is used to complete a hemilaminotomy until the upper edge of deep part of ligamentum flavum is free; (E) The ligament is peeled down in caucal direction and is removed using the Kerrison punch; (F) Kerrison punch is used to undercut the facet down to the medial wall of the pedicle; (G) The adhesion between the nucleus pulposus and the surrounding soft tissue is separated by a probe; (H) The herniated nucleus pulposus is removed by using forceps; (I) Kerrison punch and forceps are used to remove the separated bony fragment of vertebral body.

hemilaminotomy until the upper edge of deep part of ligamentum flavum is free (Figure 1D). After ensuring that the plane between ligamentum flavum and dura is free from adhesion, the ligament is peeled down in caucal direction and is removed using the Kerrison punch (Figure 1E).

Decompression

After identification of the nerve root adjacent to the dural sac, the spinal canal is explored according to direction of nucleus pulposus herniation. According to the needs, forceps or drill are used to enlarge lamina window. We prefer to undercut the facet down to the medial wall of the pedicle (Figure 1F). This work allows for the discectomy to be conducted with less nerve root retraction in addition to achieving lateral recess decompression. However, attention should be paid to protect the facet joint structure to avoid excessive damage to the spinal stability. After the herniated nucleus pulposus is found, the adhesion between the nucleus pulposus and the surrounding soft tissue is separated by a probe (Figure 1G). After assistant retracts dural sac or nerve root using an L-type nerve retractor through the working portal, the surgeon uses forceps to remove the herniated nucleus pulposus (Figure 1H). Annulotomy could be performed using a microknife if it is required. Then the surgeon needs to adjust the working position and explore the targeted intervertebral space. Any remnant fragments of the herniated disc need to be removed. We prefer to use Kerrison punch and forceps to remove the separated bony fragment of vertebral body (Figure 1I). The procedure is completed after conforming the complete decompression and freely movement of nerve root. It is not necessary to remove the separated bony fragment completely to avoid retracting the nerve excessively if the bony fragment don't lead to nerve tissue compression.

Closure

The endoscope and instruments are moved and remaining fluid is discharged by squeezing the skin around the portals. A drainage tube is placed in all patients through the working portal to prevent hematoma formation, followed by wound closure.

Outcome measures

Operation time, length of postoperative hospital stay and complications were recorded. The clinical efficacy was evaluated by Visual Analogue Scale (VAS), Oswestry Disability Index (ODI) and modified Macnab scale at preoperative, postoperative 1, 3, 6 months and the last follow-up.

Statistical analysis

Data were statistically described in terms of mean ± standard deviation (SD), or frequencies (number of cases) and percentages when appropriate. We conducted general linear model with repeated measures to analyze the clinical efficacy before the operation and at the follow-up and we compared numerical variables between different follow-up times using Student t test. P values <0.05 were considered statistically significant. We used SPSS 22.0 (Statistical Package for the Social Science; SPSS Inc., Chicago, IL, USA) for statistical analysis.

Results

Demographic data

The patients who conform to the inclusion criteria underwent UBE technique for lumbar PARS. The study included 15 men and 11 women, with a average age of (37.27 ± 7.72) years. On the targeted levels, 7 cases were at L4/5, and 19 cases were at L5/S1.

Surgical technique-related outcome

All patients were followed up for more than 6 months, with an average of (13.27 ± 3.96) months. The operative time was (78.27 ± 18.58) minutes. The postoperative hospital stay was (4.58 ± 1.42) d.

Clinical outcomes

VAS scores of low back pain were improved after operation Preoperative VAS scores of low back pain were (5.04 ± 1.37) and respectively decreased to (2.81 ± 0.75), (2.35 ± 0.98), (1.65 ± 0.69) and (1.15 ± 0.68) at postoperative 1, 3, 6 months and at the last follow-up, and the difference was statistically significant ($F = 127.317$, $P = 0.000$). The VAS scores of lower limb pain were improved after operation. Preoperative VAS scores of lower limb pain were (6.92 ± 1.38) and respectively decreased to (2.88 ± 1.07), (2.54 ± 1.03), (1.81 ± 0.80) and (1.00 ± 0.69) at postoperative 1, 3, 6 months and at the last follow-up, and the difference was statistically significant ($F = 285.289$, $P = 0.000$). ODI scores were improved after operation. Preoperative ODI scores were (60.47 ± 8.89) and respectively decreased to (34.72 ± 4.13), (25.80 ± 3.65), (17.71 ± 3.41) and (5.65 ± 2.22) at postoperative 1, 3, 6 months and at the last follow-up, and the difference was statistically significant ($F = 725.255$, $P = 0.000$) (Table 1). According to the modified Macnab criteria, the final outcomes

TABLE 1 Clinical outcomes in different times.

Time	VAS scores (back pain)	VAS scores (lower limb pain)	ODI (%)
Preoperative	5.04 ± 1.37	6.92 ± 1.38	60.47 ± 8.89
Postoperative 1 month	2.81 ± 0.75	2.88 ± 1.07	34.72 ± 4.13
Postoperative 3 month	2.35 ± 0.98	2.54 ± 1.03	25.80 ± 3.65
Postoperative 6 month	1.65 ± 0.69	1.81 ± 0.80	17.71 ± 3.41
Final follow-up	1.15 ± 0.68	1.00 ± 0.69	5.65 ± 2.22
P value	F = 127.317, *P* = 0.000	F = 285.289, *P* = 0.000	F = 725.255, *P* = 0.000

Values are presented as mean ± standard deviation.
P < 0.05 considered as significant.

were excellent in 22 cases, good in 3 cases, fair in 1 case at the final follow-up, with an excellent-or-good rate of 96.2% (25/26).

Complications

Intraoperative dural tear occurred in 1 case. Since the breach was very small, so we didn't repair the dural sac tears. No cerebrospinal fluid leakage occurred after the operation, and no discomfort symptoms occurred after the operation. No serious complications, such as vascular and nerve injury occurred after operation. Typical cases were shown in the **Figures 2, 3**.

Discussions

Lumbar posterior apophyseal ring separation is often accompanied by lumbar disc herniation and lumbar spinal canal or lateral recess stenosis, which can cause corresponding radicular symptoms or syndrome of cauda equina. Conservative treatment is usually not effective and patients with symptoms of nerve injury need surgical treatment as soon as possible. Traditional posterior open surgery is generally considered as the standard treatment, including fenestration, hemilaminectomy, total laminectomy and fusion. Although the decompression of open surgery is complete, there are risks of large surgical trauma, excessive bleeding and spinal instability. The fusion surgery also has shortcomings, such as adjacent segment degeneration, failed back surgery syndrome.

With the development of minimally invasive concept, minimally invasive spine surgery has gradually become the mainstream. It is effective to achieve complete neurological decompression and improve clinical symptoms and quality of patients' life without affecting the stability of the lumbar spine. UBE technique achieves adequate neural decompression through posterior interlaminar approach and its principle is similar to extended interlaminar fenestration surgery. The technique uses two portals to complete the decompression. The viewing portal is used to place the endoscope with continuous irrigation, and the working portal is used to complete decompression. The absence of a common working portal for the endoscope and instruments allows for independent movement and angulation of the surgical tool, which markedly reduces the procedure's difficulty. The surgical field of the UBE technique is similar to traditional open surgery, and intraoperative procedure is more similar to open surgery. So UBE technique has a relatively easy learning curve once the surgeon gets accustomed to triangulation technique (12). UBE technique reduces the incidence of complications such as nerve injury, dural sac injury because the operation is under direct vision. The technique can use ordinary spine instruments and move them freely through the working portal. UBE technique generally uses arthroscope as endoscope and structures under the contralateral lamina can be easily observed by a 30° endoscopic lens (13). The decompression is sufficient and effective and it has a unique advantage for decompression of spinal stenosis compared with other endoscopic technique (14). Also, the continuous irrigation serves in creating a potential working space and the water pressure created inhibits the epidural bleeding. UBE technique utilizes two portals to complete the decompression and can avoid the shortcomings occurred to traditional open surgery, including large surgical trauma, excessive bleeding, spinal instability and failed back surgery syndrome.

Our study mainly investigated the feasibility and effect of unilateral biportal endoscopic decompression for lumbar PARS. All patients successfully received complete neural decompression. VAS scores of low back pain and lower limb pain were improved after operation and remained good during the follow-up period. ODI scores were improved after operation and remained good during the follow-up period. These results showed that UBE technique could achieve good clinical effects for treatment of lumbar PARS.

It's found that lumbar PARS is often accompanied by intervertebral disc herniation. The three-dimensional reconstruction of CT is valuable in the evaluation of size, shape and position of posterior bony fragment of the vertebral body, so it's the best auxiliary method for the evaluation of posterior edge (15). MRI can further show the scope of decompression during the operation (5, 16). It is important for determine the size, position and type of posterior edge before operation and whether the bony fragment behind the vertebral body is removed or not is the key and difficult point in the treatment of lumbar PARS. It still remains controversial whether the separated bony fragment should be removed simultaneously when the decompression and discectomy are done. Some authors thought that the removal of disc alone was not sufficient enough to relieve nerve compression because the bony

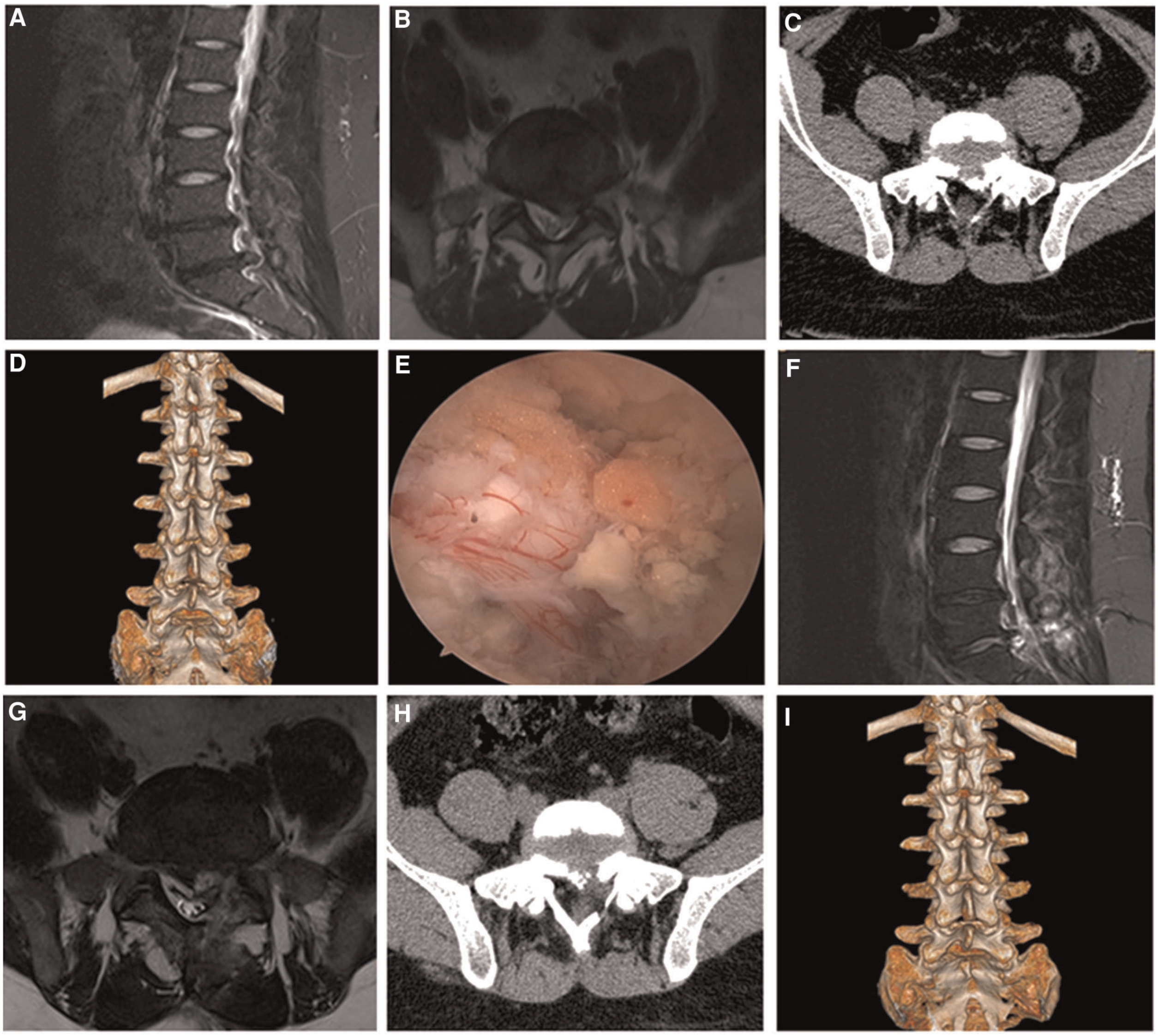

FIGURE 2
Male, 28 years old, L5/S1 lumbar disc herniation with posterior apophyseal ring separation. (A) Preoperative sagittal MR image showed L5/S1 lumbar disc herniation; (B) Preoperative axial MR image showed herniated lumbar disc compressed nerve root and dural sac; (C) Preoperative axial CT image showed separated bony fragment of vertebral body; (D) Preoperative 3D-CT image; (E) Intraoperative image after complete neural decompression; (F) Postoperative sagittal MR image revealed the complete decompression of the spinal canal; (G) Postoperative axial MR image showed the complete removal of herniated disc and bony fragment; (H) Postoperative axial CT image showed the removal of the bony fragment; (I) Postoperative 3D-CT image showed the lamina window and preservation of the facet joints.

fragment occupied the spinal space to a certain extent and triggered the symptoms more severely. They advocated the removal of the bony fragment when the decompression and discectomy were performed and reported that their clinical effects were satisfactory (17, 18). However, some authors thought that discectomy and decompression were enough (19, 20). Akhaddar et al. also supported this view and divided PARS into type I (with immobile bony fragment) /type II (with mobile fragment) and Stage A/B. They found that it was the existence of herniated disc in Type I PARS that triggered acute typical sciatica rather than the separated bony fragment, especially in Stage B and thus the removal of detached bony fragment was not necessary. On the contrary, the mobile bony fragment must be removed in Type II PARS, because the unstable bony fragment could be displaced and might damage neural structures and the clinical results were satisfactory without removal of bony fragments in 55 patients with PARS in the study (6).

In our study, the bony fragment was removed if it was not connected to vertebral body, whether it led to nerve

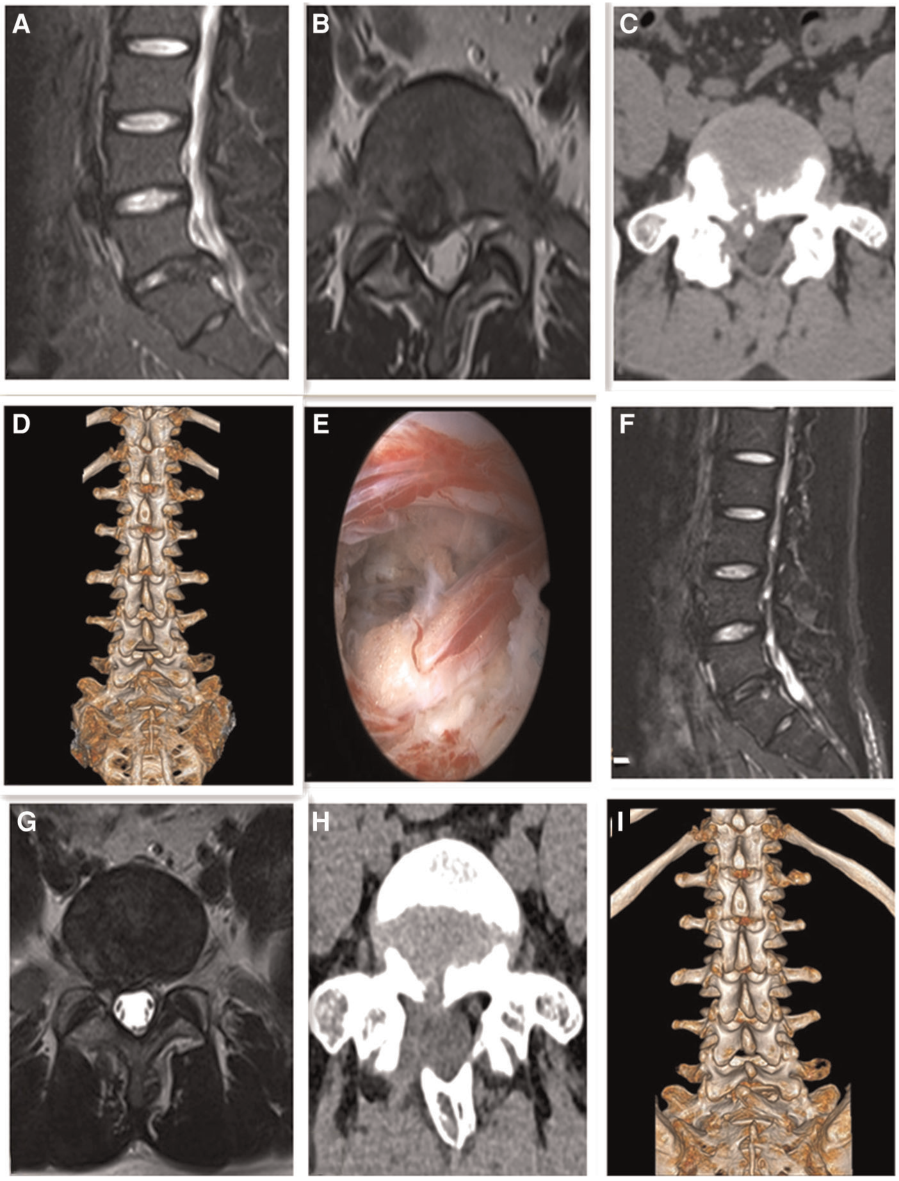

FIGURE 3
Male, 25 years old, L5/S1 lumbar disc herniation with posterior apophyseal ring separation. (A) Preoperative sagittal MR image showed L5/S1 lumbar disc herniation; (B) Preoperative axial MR image showed herniated lumbar disc compressed nerve root and dural sac; (C) Preoperative axial CT image showed separated bony fragment of vertebral body; (D) Preoperative 3D-CT image; (E) Intraoperative image after complete neural decompression; (F) Postoperative sagittal MR image revealed the complete decompression of the spinal canal; (G) Postoperative axial MR image showed the complete removal of herniated disc and bony fragment; (H) Postoperative axial CT image showed the removal of the posterior bony fragment; (I) Postoperative 3D-CT image showed the lamina window and preservation of the facet joints.

compression or not. While the bony fragment was connected to vertebral body, it did not need to be removed if it did not lead to nerve compression and the herniated nucleus pulposus should be removed completely; however, the bony fragment needed to be removed if it led to nerve root compression. After discectomy, the tension of the nerve root should be examined to see whether the compression still existed as a result of the bony fragment. Because the bony fragment is less pliable that the disc, the safe removal is of great challenge and technical manipulation. UBE technique uses two portals to complete the decompression and allows for independent movement and angulation of the surgical tool being unrestricted by the endoscope. The surgical field of the UBE technique is similar to traditional open surgery and the use of 30° endoscopic lens can easily achieve structures under the contralateral lamina. So the UBE technique can remove the bony fragment safely with reduction in the incidence of complications and the follow-up results certified it. However, there are disadvantages in the UBE technique for treatment of lumbar PARS. The surgeon needs training on baisc arthroscopic triangulation technique to master the biportal approach. UBE technique may be more invasive than percutaneous endoscopic lumbar discectomy for the treatment of lumbar PARS.

It is important for determine the size, position and type of posterior bony fragment before operation. For lateral type of lesions, unilateral decompression is conducted. While the lesions locates centrally or wider base-abroad, bilateral decompression is required. The bony fragment is removed in *en bloc* or in a piecemeal resection fashion with the use of curette, microdrill, or osteotome and Kerrison punch if necessary. In a word, the reasonable surgical plan should be made after systematic consideration according to stability, size, location of the fragment or its contributions to neurologic symptoms.

There are some limitations to our study. Firstly, this is not a multi-centered study and the size of the sample is small. Secondly, this is a retrospective study and lacks of randomized control group. Thirdly, the study still needs long-term follow up to further evaluate the clinical effects. Therefore, randomized control trials with long-term follow-up are needed to investigate the clinical benefits, especially the multi-centered study.

Conclusion

Unilateral biportal endoscopic decompression has the advantages of clear and wide field of vision, large operating space, relatively simple need of surgical instrument and convenient and flexible operation procedure. It can achieve excellent clinical effects with favorable efficacy and safety and may become an alternative minimally invasive endoscopic method for treating lumbar PARS.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Committee of the Second Affiliated Hospital of Anhui Medical University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

LJJ contributed to study conception and design, and was a major contributor in data collection, data analysis and paper writing. ZB performed data acquisition and interpretation, and also participated in paper writing. CL also perform data acquisition and interpretation. JJH and TDS assisted in drafting paper and revised it. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Risk factors for hidden blood loss in unilateral biportal endoscopic lumbar spine surgery

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Background: Unilateral biportal endoscopic (UBE) spine surgery is a minimally invasive procedure for treating lumbar disorders. Hidden blood loss (HBL) is easily ignored by surgeons because blood loss is less visible. However, there are limited studies on HBL in UBE spine surgery. This study aimed to evaluate HBL and its possible risk factors in patients undergoing UBE spine surgery.

Methods: Patients with lumbar disc herniation or lumbar spinal stenosis who underwent unilateral biportal endoscopic surgery between December 2020 and February 2022 at our hospital were retrospectively analyzed. Patient demographics, blood loss-related parameters, and surgical and radiological information were also collected. Pearson or Spearman correlation analysis was conducted to determine the association between clinical characteristics and HBL. Multivariate linear regression analysis was used to determine the independent risk factors for HBL.

Results: Fifty-two patients (17 males and 35 females) were retrospectively enrolled in this study. The mean total blood loss (TBL) volume was 434 ± 212 ml, and the mean HBL volume was 361 ± 217 ml, accounting for 77.9% of the TBL in patients who underwent UBE surgery. Multivariate linear regression analysis revealed that HBL was positively associated with operation time ($P = 0.040$) and paraspinal muscle thickness at the target level ($P = 0.033$).

Conclusions: The amount of HBL in patients undergoing UBE surgery should not be neglected. Operation time and paraspinal muscle thickness at the target level may be independent risk factors for HBL.

KEYWORDS

unilateral biportal endoscopy (UBE), hidden blood loss (HBL), minimally invasive spine surgery, lumbar disorder, risk factors

Introduction

Unilateral biportal endoscopy (UBE) is an emerging minimally invasive surgical procedure for the treatment of lumbar disorders. Spine surgery is favored by spine surgeons because of the lower rate of surgical injury, quicker postoperative recovery, and limited influence on spinal stability (1). The efficacy and safety of UBE have been confirmed in previous studies (2–5). However, the amount of blood loss is easily underestimated by spine surgeons because of continuous irrigation and the blood infiltrating into the soft tissue or remaining in the dead space of the surgical channel.

HBL was first proposed by Sehat et al. (6) and has attracted increasing attention from surgeons. HBL is common in minimally invasive spine surgeries. Jiang et al. (7) compared the clinical outcomes between UBE and percutaneous endoscopic lumbar discectomy (PELD) in the treatment of patients with lumbar disk herniation and found that the HBL volume in PELD and UBE were 30.64 ± 22.29 ml and 195.62 ± 130.44 ml, respectively. Wang et al. (8) evaluated the mean HBL volume in patients undergoing UBE surgery for lumbar degenerative diseases to be 469.5 ± 195.3 ml. Moreover, accurate evaluation of hidden blood loss (HBL) during UBE surgery is helpful for reducing perioperative complications and ensuring patient safety. However, to our knowledge, there is limited literature on HBL and its risk factors in UBE surgery for lumbar disorders. Therefore, this study aimed to estimate the amount of HBL and its risk factors in patients with lumbar disorders who underwent UBE surgery.

Patients and methods

This retrospective study was approved by the Ethics Committee of Beijing Friendship Hospital, Capital Medical University. Informed consent was obtained from all participants. Fifty-two patients diagnosed with lumbar spinal stenosis or lumbar disc herniation were included in this study from December 2020 to February 2022. The exclusion criteria were as follows: (1) age <18 years old; (2) presence of lumbar spine tumor, infection, or trauma; (3) use of anticoagulant or antiplatelet drugs; (4) presence of liver or kidney dysfunction, abnormal bleeding, or abnormal coagulation function; (5) presence of scoliosis, ankylosing spondylitis, or other spinal deformities; and (6) incomplete medical records.

Data collection

Clinical data, including sex, age, height, weight, body mass index (BMI), hypertension, diabetes, coronary heart disease (CHD), history of smoking, history of alcohol use, American Society of Anesthesiologists (ASA) classification, operation time, surgical level, and disc dissection were systematically collected.

Triglyceride (TG), serum total cholesterol (TC), low-density lipoprotein (LDL), high-density lipoprotein (HDL), hemoglobin (Hb), hematocrit (Hct), platelet (PLT), albumin (ALB), prothrombin time (PT), activated partial thromboplastin time (APTT), international normalized ratio (INR), D-dimer, and fibrinogen (Fbg) levels were recorded before surgery. Hct, ALB, Hb, PLT, and drainage levels were recorded on postoperative day 1.

The total soft-tissue thickness, subcutaneous layer thickness, and paraspinal muscle thickness at the target level were independently measured by two experienced radiologists using lumbar MRI images (**Figure 1**). The MRI measurements have demonstrated good internal consistencies with Cronbach's alpha ranging from 0.86 to 0.90.

Calculation of blood loss

Patients' blood volume (PBV) was calculated using the Nadler formula (9): $k_1 = 0.3669$, $k_2 = 0.03219$, and $k_3 = 0.6041$ for males and $k_1 = 0.3561$, $k_2 = 0.03308$, and $k_3 = 0.1833$ for females.

$$\mathrm{PBV} = k_1 \times \mathrm{Height}^3(\mathrm{m}) + k_2 \times \mathrm{Weight}(\mathrm{kg}) + k_3$$

Total blood loss (TBL) was calculated using Gross formula (10):

$$\mathrm{TBL} = \frac{\mathrm{PBV} \times (\mathrm{Hct}_{\mathrm{post}} - \mathrm{Hct}_{\mathrm{pre}})}{\mathrm{Hct}_{\mathrm{ave}}}$$

$\mathrm{Hct}_{\mathrm{pre}}$ is the Hct on preoperative day 1, $\mathrm{Hct}_{\mathrm{post}}$ is the Hct on postoperative day 1 and $\mathrm{Hct}_{\mathrm{ave}}$ is the average of $\mathrm{Hct}_{\mathrm{pre}}$ and $\mathrm{Hct}_{\mathrm{post}}$.

Thus, the HBL was calculated as follows:

$$\text{Visible blood loss(VBL)} = \text{intraoperative blood loss} + \text{postoperative drainage}$$

$$\mathrm{HBL} = \mathrm{TBL} - \mathrm{VBL}$$

Statistical analysis

Categorical variables were grouped and presented as numerical values, and continuous data were presented as mean ± standard deviation. Pearson's correlation analysis, Spearman's correlation analysis, and multiple linear regression were used to determine the factors associated with HBL, including continuous and categorical variables respectively. Statistical significance was set at $P < 0.05$. All data analyses were performed using SPSS v25.0 software (IBM Corp., Armonk, NY, United States).

Results

Fifty-two consecutive patients (17 males and 35 females) were retrospectively enrolled in this study. The demographic characteristics of the participants are summarized in **Table 1**. The mean age was 61.2 ± 14.3 (range, 26–84) years, and the mean BMI was 25.8 ± 4.3 kg/m^2. Regarding lumbar disorders, 27 patients had lumbar disk herniation and 35 had lumbar spinal stenosis. With respect to comorbidities, 27, 11, and 6 patients had hypertension, diabetes, and CHD, respectively. The mean surgery time was 132.2 ± 46.0 min. In total, 56 levels were operated, of which 2 were at L2–3, 6 at L3–4, 29 at L4–5,

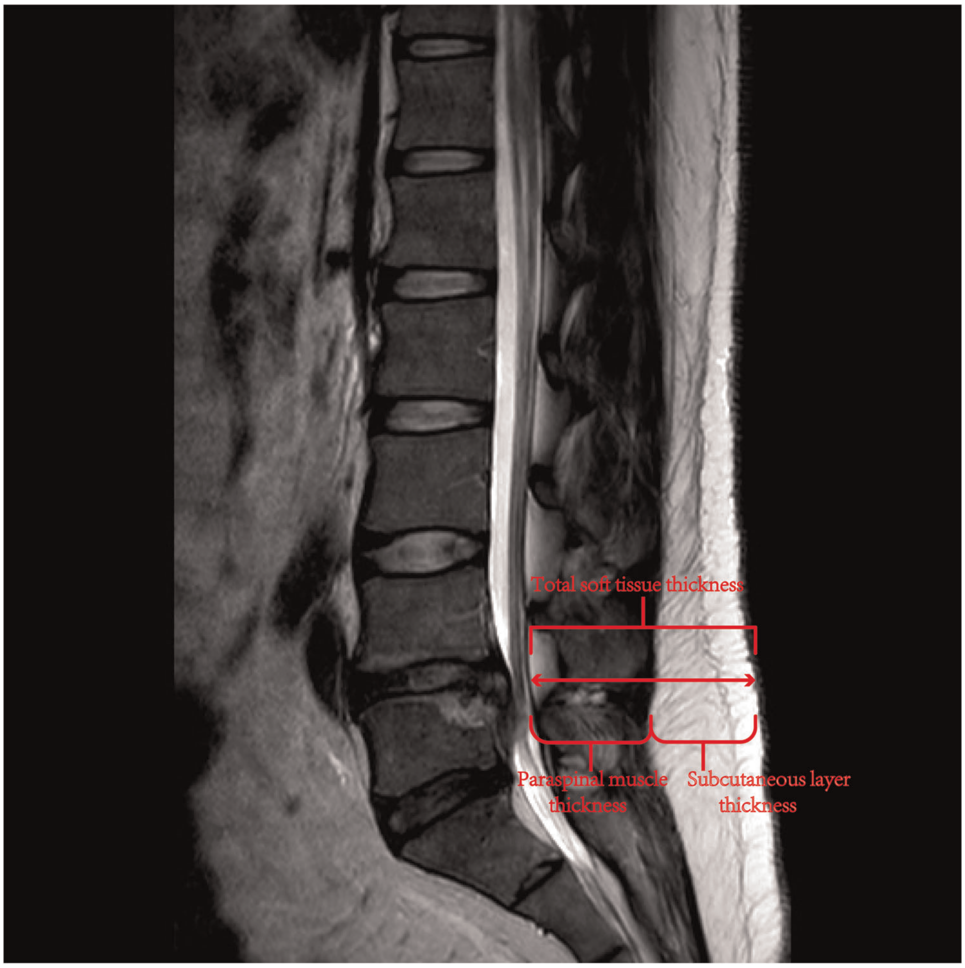

FIGURE 1
Diagram illustrating the method used to measure the thickness of total soft tissue, paraspinal muscle and subcutaneous layer at the level of L5 through sagittal view on T2-weighted MRI.

and 19 at L5–S1. Forty-eight patients underwent UBE surgery at a single level, and four patients underwent surgery at double levels. In terms of ASA classification, 2, 38, and 12 patients had a physical status classification of I, II, and III, respectively. The mean total soft tissue thickness, paraspinal muscle thickness, and subcutaneous layer thickness measured using MRI were 5.5 ± 1.1, 3.6 ± 0.6, 1.8 ± 1.0 cm, respectively. The mean PBV was 4.1 ± 0.7 L, mean TBL volume was 434.0 ± 212.0 ml, mean VBL volume was 72.5 ± 41.0 ml, mean HBL volume was 361.4 ± 216.8 ml (77.9% of the TBL). The mean amounts of Hct and Hb lost were 4.2 ± 2.0 and 11.9 ± 7.2 g/L, respectively. Postoperative Hb and Hct levels were significantly lower than the preoperative levels ($P < 0.001$ for both). Meanwhile, eight patients developed anemia (seven mild and one moderate) after UBE surgery, accounting for 15.4% of all the patients. None of the patients received perioperative transfusions. No significant difference was found in HBL between the lumbar disc herniation and lumbar spinal stenosis groups.

The Pearson and Spearman correlation analyses results are shown in **Table 2**. The analyses showed that the paraspinal muscle thickness at the target level was related to HBL ($P <$ 0.05). The following factors with $P < 0.10$ were included in the multivariate linear regression analysis to identify the independent risk factors for HBL: operation time ($P = 0.072$), paraspinal muscle thickness ($P = 0.025$), preoperative Hct level ($P = 0.055$), preoperative Fbg level ($P = 0.074$), and preoperative Hb level ($P = 0.084$), and the results showed that paraspinal muscle thickness ($P = 0.033$) and operation time ($P = 0.040$) were significant independent risk factors (**Table 3**).

Discussion

Recently, UBE surgery has shown advantages in the treatment of lumbar disorders due to the less trauma, quick postoperative recovery, and less influence on spinal stability.

TABLE 1 Patients' demographics and clinical information.

Parameters	Statistics
Total patients (*n*)	52
Sex (*n*)	
Female	35 (67.3%)
Age, year	61.2 ± 14.3
BMI, kg/m^2	25.8 ± 4.3
Height, cm	162.8 ± 8.4
Weight, kg	68.5 ± 13.4
Hypertension (*n*)	27 (51.9%)
Diabetes mellitus (*n*)	11 (21.2%)
CHD (*n*)	6 (11.5%)
Smoking (*n*)	6 (11.5%)
Drinking (*n*)	2 (3.8%)
Diseases groups	
Lumbar disc herniation	27 (51.9%)
Lumbar spinal stenosis	25 (48.1%)
Operation level	
L2–L3	2(3.6%)
L3–L4	6(10.7%)
L4–L5	29(51.8%)
L5–S1	19(33.9%)
Single-level operation (*n*)	4 (7.7%)
Double-level operation (*n*)	48 (92.3%)
Tranexamic acid (*n*)	47 (90.4%)
Lumbar disk dissection (*n*)	25 (48.1%)
ASA classification (*n*)	
I	2(3.8%)
II	38(73.1%)
III	12(23.1%)
IV	0
Surgery time, min	132.2 ± 46.0
PBV, L	4.1 ± 0.7
TBL, ml	434.0 ± 212.0
VBL, ml	72.5 ± 41.0
HBL, ml	361.4 ± 216.8
Preoperative Hb, g/L	136.0 ± 15.1
Postoperative Hb, g/L	124.0 ± 15.0
Hb loss, g/L	11.9 ± 7.2
Preoperative Hct	41.2 ± 4.3
Postoperative Hct	37.0 ± 4.2
Hct loss	4.2 ± 2.0
Preoperative ALB, g/L	38.7 ± 3.2
Postoperative ALB, g/L	34.9 ± 3.1
Alb loss, g/L	3.8 ± 2.6
Preoperative Platelet, g/L	241.6 ± 72.1
Preoperative PT, s	11.6 ± 1.1
Preoperative APTT, s	27.4 ± 3.1
Preoperative Fibrinogen, g/L	2.6 ± 0.6
Preoperative D-dimer, μg/ml	0.4 ± 0.5
Preoperative TC	4.7 ± 1.2
Preoperative TG	1.8 ± 1.7
Preoperative LDL	2.7 ± 0.7
Preoperative HDL	1.1 ± 0.3
Soft tissue thickness, cm	5.5 ± 1.1
Paraspinal muscle thickness, cm	3.6 ± 0.6
Subcutaneous layer thickness, cm	1.8 ± 1.0

BMI, body mass index; CHD, coronary heart disease; ASA, American society of anesthesiologists; PBV, patients' blood volume; TBL, total blood loss; VBL, visible blood loss; HBL, hidden blood loss; Hb, hemoglobin; Hct, hematocrit; Alb, albumin; PT, prothrombin time; APTT, activated partial thromboplastin time; INR, international normalized ratio; TC, total cholesterol; TG, triglyceride; LDL, low-density lipoprotein; HDL, high-density lipoprotein.

Although previous studies have elaborated on the complications following UBE surgery, spine surgeons have underestimated HBL in UBE surgery. Wang et al. (8) retrospectively analyzed patients who underwent UBE surgery and reported an HBL volume of 469.5 ± 195.3 ml, accounting for 57.6% of TBL. Age, number of fusion levels, ASA classification, surgery time, PBV, TBL, postoperative Hct, Hct loss, and fibrinogen level were independent risk factors for HBL. Our findings showed a mean HBL of 361.4 ± 216.8 ml, accounting for 77.9% of the TBL in patients who underwent UBE for lumbar disorders. Similar with previous studies on HBL in spine surgery (7, 8), the amount of HBL during surgery was significantly higher than that of VBL. Excessive HBL not only increases the incidence of perioperative complications but also prolongs patient recovery time. The purpose of this study aimed to explore the risk factors of HBL in UBE spine surgery. And we hope that our finding could help spine surgeons identify potential groups of patients at high risk of bleeding and pay more attention to intraoperative hemostasis and perioperative blood loss management during minimally invasive surgery, thereby reducing perioperative complications and ensuring patient safety.

Although some theories have been proposed to explain HBL, the mechanism underlying HBL has not yet been clarified. Bivariate correlation and multiple linear regression analyses were performed to determine the risk factors for HBL. Our results showed that paraspinal muscle thickness at the target level and operation time were independent risk factors for HBL. We found that the thicker the paraspinal muscle at the target level, the larger the amount of HBL. There are two possible explanations for this observation. First, muscle tissue is rich in blood supply; paraspinal muscle thickness at the target level indicated the need for longer working channels to be established during UBE surgery, increasing the wound and intraoperative bleeding. Second, paraspinal muscle tissue thickness might be related to large blood infiltration, allowing

TABLE 2 Correlation analysis between clinical factors and HBL.

Parameters	*P*	Correlation
Sex	0.435	−0.111
Age	0.638	0.067
BMI	0.736	−0.048
Height	0.825	−0.031
Weight	0.594	−0.076
Hypertension	0.241	−0.165
Diabetes mellitus	0.178	−0.190
CHD	0.672	0.060
Smoking	0.693	−0.056
Drinking	0.743	−0.047
Diseases groups	0.836	0.029
Operation level	0.803	0.037
single/double levels	0.308	0.144
Tranexamic acid	0.530	0.089
Lumbar disk dissection	0.607	0.073
ASA classification	0.139	−0.208
Surgery time	0.072	0.251
Preoperative Hb	0.084	0.220
Preoperative Hct	0.055	0.268
Preoperative ALB	0.271	0.155
Preoperative Platelet	0.543	−0.086
Preoperative PT	0.592	0.078
Preoperative APTT	0.218	−0.177
Fibrinogen	0.074	−0.255
D-dimer	0.227	−0.174
Preoperative TC	0.655	0.063
Preoperative TG	0.114	0.222
Preoperative LDL	0.713	0.052
Preoperative HDL	0.719	−0.051
Soft tissue thickness	0.274	0.155
Subcutaneous layer thickness	0.897	−0.018
Paraspinal muscle thickness	**0.025**	**0.310**
Paraspinal muscle ratio	0.593	0.076

Value in bold indicates statistical significance.
BMI, body mass index; CHD, coronary heart disease; ASA, American society of anesthesiologists; PBV, patients' blood volume; TBL, total blood loss; VBL, visible blood loss; HBL, hidden blood loss; Hb, hemoglobin; Hct, hematocrit; Alb, albumin; PT, prothrombin time; APTT, activated partial thromboplastin time; INR, international normalized ratio; TC, total cholesterol; TG, triglyceride; LDL, low-density lipoprotein; HDL, high-density lipoprotein.

more blood to penetrate the tissue space. This finding is consistent with those of previous studies on HBL in patients undergoing oblique lateral interbody fusion surgery or cervical open-door laminoplasty (11, 12). It might be important to evaluate the thickness of the paraspinal muscle at the target level of the patient using MRI before surgery. Surgeons should pay attention to the risk of excessive HBL, especially in patients with thick paraspinal muscle tissue, and achieve satisfactory hemostasis of muscle tissue as much as possible. However, the thickness of the subcutaneous layer, total soft tissue, and proportion of paraspinal muscle in the soft tissue did not show any significant relationship with HBL in this study. This may be related to the small sample size of the study. Further research is required to clarify the effects of tissue type on HBL.

Our study demonstrated that operative time was an independent risk factor for HBL. This finding is consistent with the results of previous studies (8, 13). During the UBE surgery, saline was used to irrigate and achieve good surgical vision. Continuous irrigation with a large amount of fluid flushes out the seeping blood through the soft tissue and bone surfaces. With the extension of the operation time, the blood flushed increased. Therefore, surgeons might need to be alert to the potential for excessive HBL during UBE surgery, especially if the operation time is too long. Meanwhile, a certain pressure or rapid flow of saline during irrigation might help reduce blood loss during surgery (14, 15).

The current study has some limitations. First, it was a retrospective study with a relatively small sample size and a lack of control group. Future prospective studies with larger sample sizes are required to confirm these results. Second, our study did not enroll patients undergoing fusion surgery, and the amount of TBL and related risk factors might differ from those in previous studies. Further research is required to explore the impact of spinal fusion on HBL during UBE surgery. Besides, considering that postoperative drainage might be affected by intraoperative irrigation, the calculation of VBL and HBL might be slightly biased.

Conclusion

This study showed that a large amount of HBL occurred during the UBE procedure for treating lumbar disc herniation or

TABLE 3 Multivariate linear regression analysis on risk factors of HBL.

Coefficients[a]	Unstandardized *β*	SE	Standardized *β*	*t*	*P*
Constant	−198.707	198.24		−1.002	0.321
Paraspinal muscle thickness	107.052	48.662	0.294	2.2	0.033
Operation time	1.278	0.606	0.282	2.109	0.040

[a]Dependent variable: hidden blood loss (ml).

spinal stenosis. Operation time and paraspinal muscle thickness at the target level were independent risk factors for HBL in patients with lumbar disorders who underwent UBE surgery.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Committee of Beijing Friendship Hospital, Capital Medical University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

Each author made substantial contributions to this work. SJG, HNT and QF contributed to the conception and design of the work. SJG and HNT contributed to the acquisition of study data. SJG, NA, JSL contributed to the analysis and interpretation of data. LJY, XL, NS, HM, YY contributed to the surgical technical support. All authors have drafted the work or substantively revised it. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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A comparative study of single and double incision for L4/5 and L5/S1 double-level percutaneous interlaminar lumbar discectomy

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Objective: This study aims to investigate the clinical outcome of single and double incision for double-level percutaneous interlaminar lumbar discectomy
Methods: A retrospective analysis was performed involving patients with L4/5 and L5/S1 double-level lumbar disc herniation who received percutaneous interlaminar lumbar discectomy (PEID) in our hospital from January 2017 to December 2020. These enrolled patients were divided into single- and double-incision groups, with 25 patients in each group. We compared the incision length, operation time, fluoroscopy times, and length of hospital stay between the two groups. Meanwhile, the postoperative visual analogue scale (VAS), Oswestry Disability Index (ODI), Japanese Orthopedic Association score (JOA), and modified MacNab standard were used to evaluate the outcomes of the patients within the two groups.
Results: It showed that the single-incision group performed better than double-incision group in incision length, operation time, and fluoroscopy times ($P < 0.001$). The VAS score, JOA score, and ODI index in the two groups were significantly decreased at the time points of postsurgery, 1 month after surgery, and the last follow-up ($P < 0.01$), but there was no statistical significance between the two groups involving above parameters ($P > 0.05$). At the last follow-up, the excellent and good rates of MacNab efficacy in the two groups were 92% and 88%, respectively, but no significant difference was observed between the two groups ($P > 0.05$).
Conclusion: Both the single- and double-incision approaches are effective and safe for managing L4/5 and L5/S1 double-level LDH. Single-incision PEID for treating L4/5 and L5/S1 double-segment lumbar disc herniation has advantages of less trauma, fewer intraoperative fluoroscopy times, and shorter operation time, as compared to double-incision PEID. However, the operation of double-segment LDH through a single laminar incision is difficult, the learning curve is steep, and professional skill is highly required. Importantly, the surgical indications should be strictly grasped.

KEYWORDS
single/double incision, interlaminar approach, adjacent double lumbar disc herniation, endoscopic spinal decompression, minimally invasive spine surgery

Introduction

Lumbar intervertebral disc herniation (LDH), a common degenerative disease of the lumbar spine, usually occurs at a single level (1). It was mainly presented with the clinical symptom of lumbar and leg pain, seriously affecting patients' daily life (1, 2). In the clinic, we find that it is not rare for young patients to develop double-level LDH, while patients who fail to receive stepwise conservative treatment always need further surgical interventions (3, 4). Lumbar discectomy is the traditional treatment for LDH, but it has some disadvantages, such as difficulty in operation skills and resection of normal structures, including skeletal tissue (5, 6). With the continuous development of minimally invasive spinal techniques, percutaneous endoscopic interlaminar discectomy (PEID) and microendoscopic discectomy (MED) have been widely used in clinical practice (7, 8). Compared with traditional surgery, PEID and MED are characterized by less trauma, less bleeding, faster recovery, and less impact on lumbar stability. Despite the rapid development of PEID, its efficacy in the management of symptomatic double-level LDH remains controversial (9–11). The rate of double-level lumbar disc herniation is relatively low, and the open lumbar discectomy or double-incision PELD is mostly used. Recently, we found that the single-incision translaminar approach for L4/5 and L5/S1 double-segment LDH can also achieve a satisfactory effect, but there is no consensus on which approach is better. Therefore, we aim to compare the clinical outcomes of single- and double-incision PEID for treating L4/5 and L5/S1 double-level LDH.

Materials and methods

Patients

The following inclusion criteria are applied: (1) ipsilateral lumbar disc herniation in L4/5 and L5/S1, two adjacent levels, as confirmed by computed tomography (CT) and magnetic resonance imaging (MRI); (2) definite history of lumbar and leg pain with neurological symptoms and signs; (3) symptoms and signs consistent with the images; (4) failure of conservative treatment for more than 3 months; and (5) at least 12 months of follow-up data available. The exclusion criteria are as follows: (1) patients with cauda equina syndrome or progressive neurological impairment requiring emergency surgery; (2) with spinal instability and spinal canal stenosis; (3) nonadjacent level of LDH; (4) patients with cephalic overdissociation of L4/5 nucleus pulposus and caudal overdissociation of L5/S1 nucleus pulposus; and (5) previous surgery involving the lumbar spine, concomitant somatic, or psychological conditions, such as uncontrolled myocardial ischemia, diabetes, spinal tumor, fracture, or infection.

According to the criteria, 50 patients with adjacent double-segment LDH (L4/5 and L5/S1) who received two-level PEID surgery in our hospital from January 2017 to December 2020 were enrolled. The patients were divided into a single-incision group (25 patients) and a double-incision group (25 patients). The patients were informed of the advantages and disadvantages of the two surgical options. Meanwhile, they were instructed that there was no sufficient evidence-based medicine showing which surgical option was better.

Surgical technique

Both groups were performed by the same surgical team. In the single-incision group, after successful general anesthesia, the patient was prone on the operating table, C-arm fluoroscopy was positioned in the middle of the L5 vertebral body, and L5/S1 and L4/L5 intervertebral spaces were marked. An incision of about 6 mm was made at the midpoint of the gap. The angle was adjusted to puncture into the L4/L5 intervertebral space, and a blunt dilator was inserted before placing a working sheath. After the dilator was removed, an endoscope was placed in the external working sheath. The ligamentum flavum was cut diagonally and layer by layer in 3–5 mm to expose the spinal canal contents. Part of the transparent adipose tissue was removed to reveal the dural sac, and the endoscope channel and external working sheath were adjusted to explore the nerve root position. During the operation, a radiofrequency ablation electrode was used to stop bleeding. The disc was exposed after the nerve root was pushed and protected. Nucleus pulposus was obtained alternately with different nucleus pulposus forceps. The L5/S1 intervertebral space was entered from the same puncture point adjustment angle, and the L5/S1 intervertebral disc was treated with endoscopic nucleus pulposus resection in the same way.

In the double-incision group, after successful general anesthesia, the patient was prone on the operating table, C-arm fluoroscopy was positioned at L5/S1 and L4/L5, respectively, and two incisions of about 6 mm in length were made in the middle of L5/S1 and L4/L5. First, L4/L5 disc nucleus pulposus was removed with the same incision. After the completion of L4/L5 discectomy, the L5/S1 intervertebral space was punctured, and endoscopic nucleus pulposus resection was performed on the L5/S1 intervertebral disc in the same way.

Clinical evaluation

Both groups were followed up for at least 12 months, with an average of 15.20 ± 2.06 months and 15.92 ± 2.64 months, respectively. The incision length, operation time, fluoroscopy time, and hospital stay were recorded. The visual analogue scale (VAS) was used to evaluate the low back and leg pain, and the Oswestry disability index (ODI) was used for the evaluation of the functional disability. Both VAS and ODI were collected at preoperation, 1-month postoperation, 3-month postoperation, and the last follow-up time. The modified MacNab efficacy standard was applied to evaluate the final outcome of patients, which were divided into excellent, good, fair, and poor.

Statistical analysis

Statistical analysis was performed using SPSS (Statistical Package for Social Sciences) version 21.0 (IBM SPSS, Chicago, IL, USA) software. Continuous variables are presented as mean ± SD and compared by Student's *t*-test. Categorical data are expressed as the number (percentage) and compared by Pearson's chi-squared test. Significance was set at $P < 0.01$ or $P < 0.05$.

Results

All 50 patients were successfully operated on and had at least 12 months of follow-up (range 12–22 months). The key demographic baseline parameters and follow-up time are summarized in **Table 1**.

The operative surveys between the two groups are shown in **Table 2**. In general, significant improvements were observed in leg and back pain after surgery in both groups. Compared to that in the double-incision group, the average incision length in the single-incision group was much shorter (5.91 ± 0.68 mm vs. 11.72 ± 1.36 mm, $P < 0.001$). Moreover, the average operation time was faster (81.84 ± 15.79 vs. 94.28 ± 12.59 min, $P < 0.01$) and the average fluoroscopy time was significantly decreased (3.64 ± 1.90 vs. 7.72 ± 1.40, $P < 0.001$) in the single-incision group. Furthermore, the average length of hospital stay in the single-incision group was less than that in the double-incision group (3.48 ± 0.81 vs. 3.44 ± 0.58 days, $P = 0.810$). The results indicated that the single-incision group has a shorter incision length, faster operation time, and fewer intraoperative fluoroscopy time.

TABLE 1 Baseline patient characteristics between the two groups.

Variable	Single-incision group	Double-incision group	*P* value
N	25	25	–
Gender (M/F)	18/7	20/5	0.508
Age (year)	32.60 ± 4.74	31.32 ± 5.46	0.380
Course of disease (months)	5.88 ± 1.64	6.32 ± 1.84	0.377
Follow-up (months)	15.20 ± 2.06	15.92 ± 2.64	0.288

Values are expressed in mean ± standard deviation.

The functional improvement of the patients was satisfactory. The postoperative changes in the JOA score within the two groups are shown in **Table 3**. For the single-incision group, the mean JOA scores improved from 12.20 ± 2.12 at preoperative to 23.72 ± 3.78 at 1 month postoperatively (recovery rate 69.50 ± 18.95%), further increased to 27.08 ± 1.55 at 3 months postoperatively (recovery rate 88.63 ± 9.09%). In the double-incision group, the mean JOA scores improved from 13.26 ± 2.30 at preoperative to 23.20 ± 4.00 at 1 month postoperatively (recovery rate 65.08 ± 21.86%), further increased to 27.24 ± 1.17 at 3 months postoperatively (recovery rate 89.17 ± 7.07%). At the last follow-up, the mean recovery rates of the two groups were 93.39 ± 6.44% and 93.15 ± 5.92%, respectively. There was no statistical difference in the JOA score and associated recovery rate between the two groups ($P > 0.05$).

The postoperative scores of VAS and ODI in both groups were significantly decreased compared with those before the operation (**Table 4**). Symptoms continued to improve at different time points after surgery in both groups. There was no significant difference between the two groups involving VAS and ODI scores at different time points after surgery. At the last follow-up time, the overall excellent/good rate was 92% in the single-incision group (23/25) and 88% in the double-incision group (22/25), and there was no significant difference between the two groups (**Table 5**).

All wounds healed after the first intention. In the double-incision group, one patient developed L5/S1 segment recurrence 6 months after surgery and underwent an open lumbar discectomy according to the patient's requirements. No recurrence occurred in the single-incision group. There was no significant difference in terms of recurrence between the two groups ($P > 0.05$). All of the patients ultimately acquired back and leg pain relief.

Typical cases of the single- and double-incision groups are shown in **Figures 1, 2**. There was no dural laceration, nerve root injury, cerebrospinal fluid leakage, infection, postoperative paresthesia, or other serious complications in either of the groups.

TABLE 2 Comparison of intraoperative outcomes between the two groups.

Variable	Single-incision group	Double-incision group	*P* value
Incision length (mm)	5.91 ± 0.68	11.72 ± 1.36	<0.001
Operative time (min)	81.84 ± 15.79	94.28 ± 12.59	<0.01
Frequency of fluoroscopy	3.64 ± 1.90	7.72 ± 1.40	<0.001
Hospital stays (days)	3.48 ± 0.81	3.44 ± 0.58	0.810

Values are expressed in mean ± standard deviation.

TABLE 3 Comparison of JOA score results between the two groups.

Variable	Single-incision group	Double-incision group	*P* value
Mean JOA score			
Preop	12.20 ± 2.12	13.26 ± 2.30	0.800
1 month postop	23.72 ± 3.78*	23.20 ± 4.00*	0.639
3 months postop	27.08 ± 1.55*,**	27.24 ± 1.17*,**	0.682
Last follow-up	27.88 ± 1.09*,**,***	27.84 ± 1.11*,**	0.898
Mean recovery rate[a]			
1 month postop	69.50 ± 18.95	65.08 ± 21.86	0.449
3 months postop	88.63 ± 9.09**	89.17 ± 7.07**	0.815
Last follow-up	93.39 ± 6.44**,***	93.15 ± 5.92**,***	0.891

Values are expressed in mean ± standard deviation.
JOA, Japanese Orthopaedic Association; Preop, preoperative; Postop, postoperative.
[a]Mean recovery rate (%) = (postoperative JOA score – preoperative JOA score)/(29 – preoperative JOA score) × 100%.
*$P < 0.01$ compared to the preoperative value.
**$P < 0.05$ compared to the 1-month postoperative value.
***$P < 0.05$ compared to the 3-month postoperative value.

Discussion

Minimally invasive techniques have been widely used in treating lumbar disc herniation in the past decade. Single-incision treatment of two-segment LDH is a minimally invasive operation with a small incision, less trauma, quick effect, early ground operation, and other characteristics. In this study, both groups of patients achieved good clinical results after surgery, and the quality of life was obviously improved. In addition, the postoperative JOA score, VAS score, and ODI index were significantly lower than those before surgery. The excellent and good rates of the modified MacNab in the two groups at the last follow-up were 92% and 88%, respectively, and there was no significant difference between the two groups ($P > 0.05$), which indicated the effectiveness of these two surgical methods. In our study, no nerve root injury, cerebrospinal fluid leakage, infection, and postoperative lower limb paresthesia occurred in the two groups, and the results showed that these two minimally invasive surgical methods have high safety and few complications. Single-incision endoscopic spinal treatment of two-segment LDH through an interlaminar approach can reduce the incision length, radiation frequency, and operation time compared with double-incision treatment, and the single-incision treatment is more aesthetic than double-incision treatment.

TABLE 4 Comparison of VAS and ODI score results between the two groups.

Variable	Single-incision group	Double-incision group	*P* value
Mean VAS score			
Preop	7.04 ± 1.13	7.20 ± 1.00	0.599
1 month postop	1.92 ± 1.08*	2.12 ± 0.93*	0.485
3 months postop	1.20 ± 0.91*,**	0.84 ± 0.80*,**	0.145
Last follow-up	0.40 ± 0.65*,**,***	0.28 ± 0.54*,**,***	0.480
Mean ODI score			
Preop	70.24 ± 4.05	70.08 ± 3.70	0.612
1 month postop	24.08 ± 4.45*	22.16 ± 4.47*	0.135
3 months postop	17.04 ± 3.96*,**	15.92 ± 4.02*,**	0.326
Last follow-up	9.92 ± 2.86*,**,***	9.84 ± 3.36*,**,***	0.928

Values are expressed in mean ± standard deviation.
VAS, visual analogue scale; ODI, oswestry disability index scores.
*$P < 0.01$ compared to the preoperative value.
**$P < 0.05$ compared to the 1-month postoperative value.
***$P < 0.05$ compared to the 3-month postoperative value.

TABLE 5 Modified MacNab criteria results.

Variable	Single-incision group	Double-incision group	*P* value
Modified MacNab			
Excellent	20	19	
Good	3	3	
Fair	2	2	
Poor	0	1	
Excellence/good rate (%)	92	88	0.795

The health effects of fluoroscopic radiation are also of concern to surgeons and patients (12). Compared with single incision, double incision requires multiple catheterizations. However, once the puncture quantity is increased, it is inevitable to increase the number of fluoroscopies, which also increases the operation time and radiation exposure to doctors and patients. Radiation exposure has been linked to an increased risk of cancer, cataract, and cardiovascular disease (13, 14). Therefore, a single incision can effectively reduce the number of fluoroscopy and surgical time, reducing the radiation exposure of doctors and patients.

The most common cause of failure in minimally invasive or endoscopic spine surgery is incomplete excision or intraoperative complications (15–17). In the double-incision group, a patient with recurrent pain in the lower extremity was discharged after a second operation. There were no serious complications such as dural injury in both groups. Surgical puncture is the difficulty of operation but also the key point for the successful completion of the operation in handling double segments by single incision. The laminar

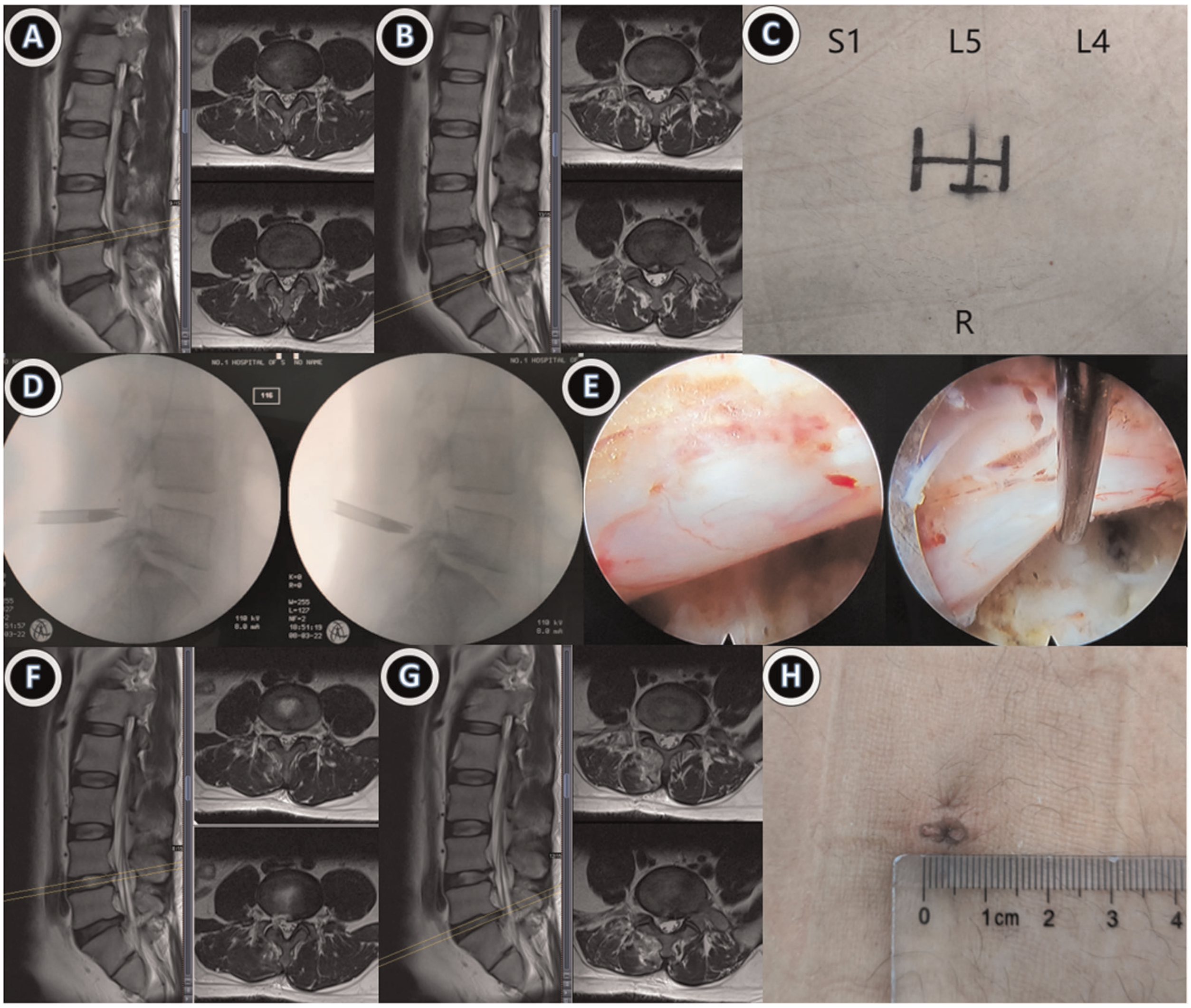

FIGURE 1
Case 1: A 38-year-old male patient with ipsilateral disc herniation at L4/5 and L5/S1. Endoscopic double-segment discectomy was performed through a single-incision and interlaminar approach. (A,B) Preoperative lumbar MRI suggested disc herniation at L4/5 and L5/S1 levels; (C) preoperative single-incision design; (D,E) intraoperative double interstitial working tubes were successively placed for nuclear pulposus excision, and the nerve root relaxation was observed under a microscope; (F,G) MRI review at 1 month after surgery suggested that the protrusion was completely removed; (H) Postoperative incision was about 7 mm, and MRI re-examination 3 months after surgery showed no further protrusion.

space of L5/S1 is larger than that of L4/5, and the puncture point could be slightly closer to L4/5 due to the need to remove the part bone of the facet and lower edge of the lamina (18). The surgeons should accurately determine the location of nerve roots during operation to avoid nerve root injury. If the disc is adherent to the nerve root or the dural sac, the disc should not be released forcibly. If necessary, open surgery should be performed (19). The nucleus pulposus tissue that can be removed should be removed as far as possible; otherwise, with the postoperative activities of the patient, the residual nucleus pulposus is easy to shift again and cause compression, resulting in disease recurrence. One incision should be used as far as possible, but it should be based on the intraoperative situation. A single incision should not be forced; otherwise, it may lead to incomplete decompression (15). Double incision usually facilitate better working pipe placement and decompression. Single-incision treatment for two-segment LDH increases the probability of nerve root injury during puncture, so a single incision cannot be forced in two-segment surgery. In addition, a single incision is not suitable for bilateral lumbar disc herniation. Not only can surgeons understand the type of disc herniation through preoperative imaging tests such as x-rays, CT scans, and MRI but also they can understand the feasibility of endoscopic surgery (20). The degree of disc herniation, degree of migration, severity of adhesion, risk of dural tear, the

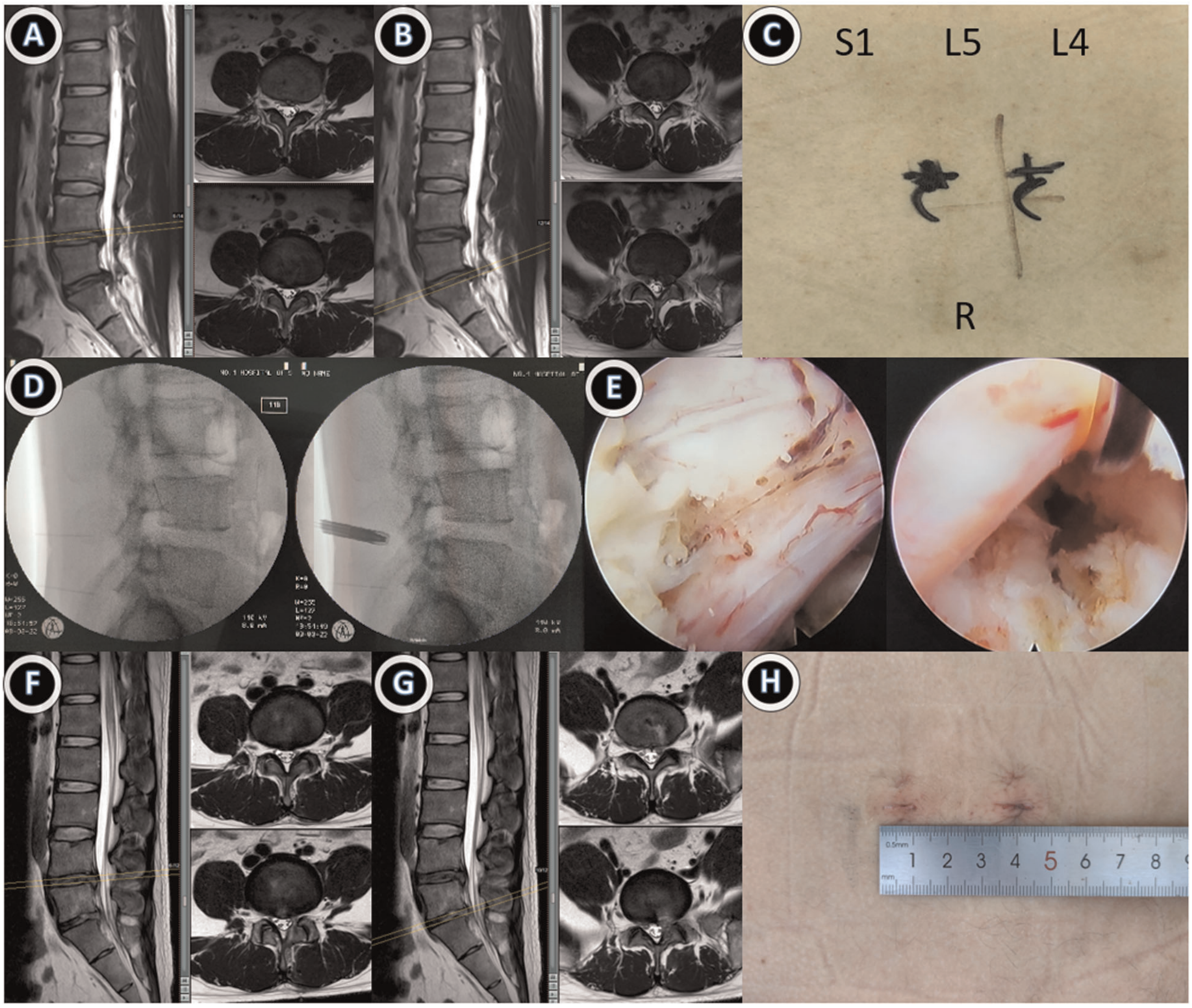

FIGURE 2
Case 2: A 28-year-old male patient with ipsilateral disc herniation at L4/5 and L5/S1. Endoscopic double-segment discectomy was performed with double incision through an interlaminar approach. (A,B) Preoperative lumbar MRI suggested disc herniation at L4/5 and L5/S1 levels; (C) preoperative double-incision design; (D,E) intraoperative double interstitial working tubes were successively placed for nuclear pulposus excision, and the nerve root relaxation was observed under a microscope; (F,G) MRI review at 1 month after surgery suggested that the protrusion was completely removed; (H) Postoperative incision was about 16 mm, and MRI re-examination 3 months after surgery showed no further protrusion.

softness of the herniated disc, and concurrent spinal stenosis should be assessed. In addition, the use of a single incision to deal with double intervertebral disc increases the difficulty of operation, so the operator needs to strictly grasp the indications and try to use a single incision for the treatment of two-level disc herniation on the basis of mastering the two-level incision (21, 22).

In conclusion, the endoscopic percutaneous interlaminar approach by single incision for the treatment of two-level lumbar disc herniation is feasible and safe. Compared with double incision, single incision exerts less trauma, shorter incision, and faster postoperative recovery. However, due to the difficulty of operation, it is necessary to strictly grasp the surgical indications and possess certain experience in single-segment endoscopic surgery. Postoperative functional exercise guarantees a curative effect. In the future, the indications of endoscopic percutaneous interlaminar approach will be further expanded, and precision will be the inevitable trend.

The study has some limitations. First, the study was not a double-blind randomized controlled trial. Surgeons and patients have different perceptions of treatment and prognosis, which may influence outcome assessment. Second, the surgeon's preference for surgical technique may also influence the outcome. Finally, this study was a single-center study with a short follow-up period. The comparison of postoperative clinical efficacy of LDH requires high-quality multicenter and long-term follow-up studies.

Conclusion

In conclusion, the single-incision approach has more advantages in operation time, incision length, and fluoroscopic time but exerts no difference in terms of JOA, VAS, and ODI scores or postoperative complications as compared to the double-incision approach.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee of the First Affiliated Hospital of Soochow University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

KC, HC, and KZ contributed to conception and design of the study; YT wrote the first draft of the manuscript; HM and JZ organized the database; YT, ZL, and HL performed the statistical analysis; XZ, ZQ, and HY ensured the accuracy of the data and analysis. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Current Status and research hotspots in the field of full endoscopic spine surgery: A bibliometric analysis

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Purpose: We aimed to comprehensively analyze the current status, hotspots, and trends in full endoscopic spine surgery (FESS) research using bibliometric analysis and knowledge domain mapping.

Methods: The Web of Science database was used to screen FESS-related articles published between January 1, 1993 and June 10, 2022. The evaluation involved the following criteria: total number of articles; H-index; and contributions from countries/regions, institutions, journals, and authors.

Results: A total of 1,064 articles were included. Since 2016, there have been a significant number of publications in the field of FESS. The country/region contributing the largest number of articles was China (37.8%), followed by South Korea (24%), the United States (16.1%), Japan (5.7%), and Germany (5.1%). South Korea (35) had the highest H-index, followed by the United States (27), China (22), Japan (21), and Germany (20). World Neurosurgery (15.7%) published the largest number of FESS-related articles. However, among the top 10 most cited articles, six were published in *Spine*. The author who contributed the most was S.H. Lee (5.4%), and the largest number of contributions in this field originated from Wooridul Spine Hospital (South Korea; 6.1%). Notably, six of the 10 most published authors in this field were from South Korea. Of the top five productive institutions, three were from South Korea. The keywords with the strongest citation bursts in the field of FESS were "lumbar spine," "discectomy," "interlaminar," "surgical technique," "follow-up," "excision," "thoracic spine," and "endoscopic surgery." The 10 clusters generated in this study were: "endoscopic discectomy" (#0), "thoracic myelopathy" (#1), "recurrent lumbar disc herniation" (#2), "low back pain" (#3), "cervical vertebrae" (#4), "lumbar spinal stenosis" (#5), "transforaminal lumbar interbody fusion" (#6), "radiation exposure" (#7), "management" (#8), and "lumbar spine" (#9).

Conclusion: Global research on FESS is mostly concentrated in a few countries/regions and authors. South Korea has made the largest contribution to the field of FESS. Based on the most cited keyword bursts and clusters, the focus of FESS research was found to include its indications, management, and applications.

KEYWORDS

bibliometric, citespace, full endoscopic spine surgery, research trends, visualization

Introduction

In recent years, percutaneous full endoscopic spine surgery (FESS) has gradually been adopted by spine surgeons owing to the following advantages: minimal invasiveness, highly effective features, increasing amount of attention from patients, and gradual expansion of its indications (1–4). The reason for the rapid development of this technology is that, compared with traditional open spine surgery, FESS does not involve massive destruction of muscle tissue, there is no need for the destruction of synovial joints and vertebral plates, and it lessens the distraction of nerve roots and dural sacs which ensures maximum stability of the spinal segment and reduces the occurrence of long-term pain and discomfort due to spinal instability and other complications (5–7). After decades of development, the use of FESS has gradually expanded from simple lumbar disc herniation (DH) to lumbar spinal stenosis and instability treatment; from lumbar to cervical and thoracic spine treatment; from pure decompression to endoscopic-assisted fusion techniques; and from the treatment of degenerative spine diseases to that of spinal trauma, infection, deformity, and tumors (8–11). With the widespread popularity of FESS, the amount of research in this field is increasing.

Bibliometric studies are commonly used to quantitatively evaluate published research and to forecast future trends in scientific research. These studies combine mathematical and statistical methods and usually aim to identify research field components, which may include authors, institutions, countries/regions, and journals. The goal of these studies is to reveal a bibliometric structure that illustrates the network between research components and contributes to the knowledge structure that is built on topic clusters related to the research field (12). By obtaining vast amounts of data in the form of knowledge maps, researchers may gain valuable insight into the trajectory of discipline growth and frontier tendencies in the field of interest. Researchers may use this method to dive deeper into research patterns and to better identify research hotspots. The findings may also be used in future research and decision-making.

Bibliometrics has been applied widely in the analysis of scientific research in various fields (13–15). Since the authors published their first bibliometric study (16) on FESS (data collected through July 2018), many FESS studies have been updated worldwide. In particular, with the recent development of biportal endoscopic spine surgery and full endoscopic spinal fusion surgery, the indications for the application of FESS have become broader, and many studies have been published on these techniques. Therefore, in this study, we aimed to perform a comprehensive assessment of the scientific research in the field of FESS worldwide through an up-to-date quantitative and qualitative analysis of the existing literature.

Materials and methods

Sources of data

All data were obtained from the Web of Science (WoS) Core Collection database. We searched the WoS database for articles published between January 1, 1993, and June 10, 2022. The following keywords were used to search the database: "percutaneous endoscopic spine surgery," "percutaneous endoscopic spinal surgery," "endoscopic cervical discectomy," "endoscopic cervical foraminotomy," "endoscopic cervical decompression," "endoscopic cervical interbody fusion," "endoscopic thoracic discectomy," "endoscopic thoracic decompression," "endoscopic lumbar discectomy," "endoscopic lumbar laminotomy," "endoscopic lumbar foraminotomy," "endoscopic lumbar decompression," and "endoscopic lumbar interbody fusion." The terms "microendoscopic spine surgery," "laparoscopic," "thoracoscopic," and "endonasal" were excluded.

Data analysis

Two independent observers assessed the articles extensively based on their titles and abstracts. Disagreements were discussed and assessed by a third party. All the articles were collected and exported as plain-text files for recordkeeping and examining the cited references. The title, authors, abstract, funding, keywords, references, and other pertinent analytical information were included in each bibliographic record.

The quantity of research production was determined by the number of published articles, whereas the quality of research output was determined by the H-index and citations.

CiteSpace (Chaomei Chen, Drexel University, USA), was used to perform the bibliometric research on the data in this study (17). We used CiteSpace to identify the top authors, institutions, and countries/regions, as well as the research cooperation linkages that existed between these categories. A co-citation network analysis of authors, institutions, countries/regions, and references was performed to further investigate the research cooperation linkages. A co-word network analysis of keywords was undertaken to acquire cutting-edge information and examine trends. The frequency of the occurrence of a keyword or reference across time was denoted by co-citation relationships.

The size of nodes in a visual network diagram represents the degree of co-occurrence or citation frequency. The node connection represents the relationship between co-occurrence and co-citation. The thickness of the linkages and length between nodes reflect how closely countries/regions, institutions, and writers collaborate. The lines represent the connections between the nodes and their colors represent the year of publication.

Our research was essentially descriptive. Without statistical analysis, the quantity and ratio (percentage) of each indicator show the distribution and evolving trends in terms of different years, countries/regions, institutions, journals, and authors.

Results

Publication outputs

From January 1, 1993, to June 10, 2022, 1,549 articles were screened, and after a detailed review by two authors, 1,064 articles were finally identified as meeting the inclusion criteria. Among these, 940 were original articles, and 124 were review articles.

More than 99.5% (1,059/1,064) of the articles were published in English, followed by in German (two articles), Czech (one article), French (one article), and Portuguese (one article). From 1993 to 2015, there was a period of modest development in terms of the number of publications. Following a surge in 2016, the number of publications increased significantly, reaching 211 in 2020, which is more than 100 times the number in 1993 (Figure 1). Additionally, the 1,064 articles were cited 13,404 times.

Analysis of countries/regions

The research articles on FESS were published across 49 countries/regions (Table 1). China had the highest number of publications (37.8%, 402/1,064), followed by South Korea

TABLE 1 Top 5 countries that contributed to research publications in the FESS field.

Rank	Country	Number	%	H-index
1	China	402	37.8	22
2	South Korea	256	24.0	35
3	USA	171	16.1	27
4	Japan	61	5.7	21
5	Germany	54	5.1	20

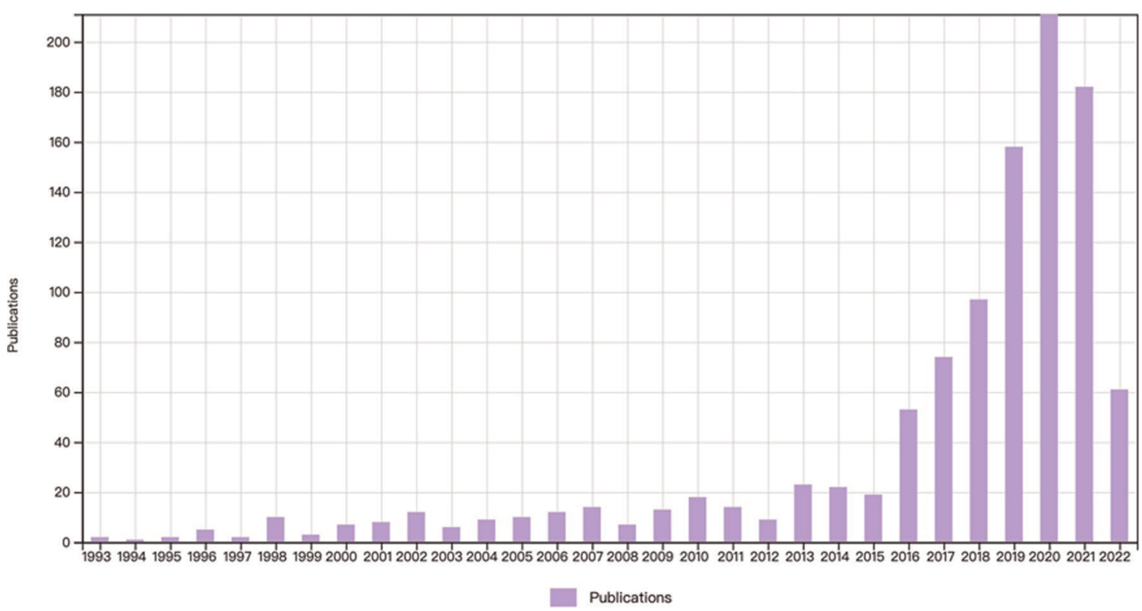

FIGURE 1
The annual trends of publications and citations.

(24%, 256/1,064), the United States (16.1%, 171/1,064), Japan (5.7%, 61/1,064), and Germany (5.1%, 54/1,064). Together, these top five countries published 88.7% of all FESS-related articles. To identify relevant signals, a co-occurrence map (Figure 2) was drawn to help researchers in detecting the cooperation linkages. There was a paucity of international collaborations among key nations in the field of FESS. Table 1 also shows the H-indices in the top five countries. South Korea had the highest H-index (35), followed by the United States (27), China (22), Japan (21), and Germany (20).

Analysis of institutions

Table 2 ranks the institutions in terms of the number of published FESS-related articles. Wooridul Spine Hospital had the largest number of published articles (65 publications, 6.1%), followed by Brown University (57 publications, 5.4%), Catholic University of Korea (44 publications, 4.1%), Nanoori Hospital (43 publications, 4.0%), and TongJi University (41 publications, 3.9%). Among the top five productive institutions, three are in South Korea, one in China, and one in the United States. Figure 3 depicts the extent to which the institutions collaborate on FESS.

Analysis of journals

Table 3 lists the top 10 journals based on the number of articles published in the field of FESS. Of the 1,064 FESS-related articles, most were published in *World Neurosurgery* (167 articles, 15.7%), followed by *Pain Physician* (67 articles, 6.3%), *Medicine* (45 articles, 4.2%), *Neurospine* (38 articles, 3.6%), *Spine* (36 articles, 3.4%), *European Spine Journal* (28 articles, 2.6%), *BMC Musculoskeletal Disorders* (28 articles, 2.6%), *Journal of Neurosurgery: Spine* (27 articles, 2.5%), *Biomed Research International* (25 articles, 2.4%), and *Acta Neurochirurgica* (23 articles, 2.3%). It was found that nearly half (45.6%) of the FESS-related articles were published in the top 10 most prolific journals. It is reasonable to presume that

TABLE 2 Top 5 productive institutions in the FESS field.

Rank	Institution (Country)	Number	%
1	Wooridul Spine Hospital (South Korea)	65	6.1
2	Brown University (USA)	57	5.4
3	Catholic University of Korea (South Korea)	44	4.1
4	Nanoori Hospital (South Korea)	43	4.0
5	TongJi University (China)	41	3.9

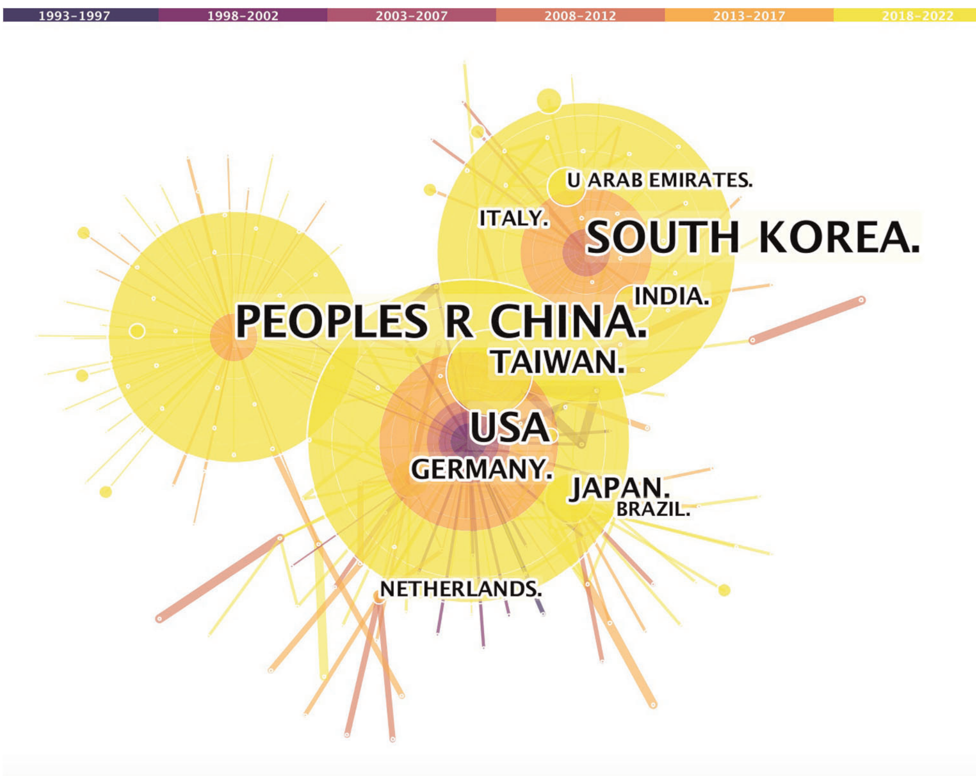

FIGURE 2
Co-operation of productive countries/regions.

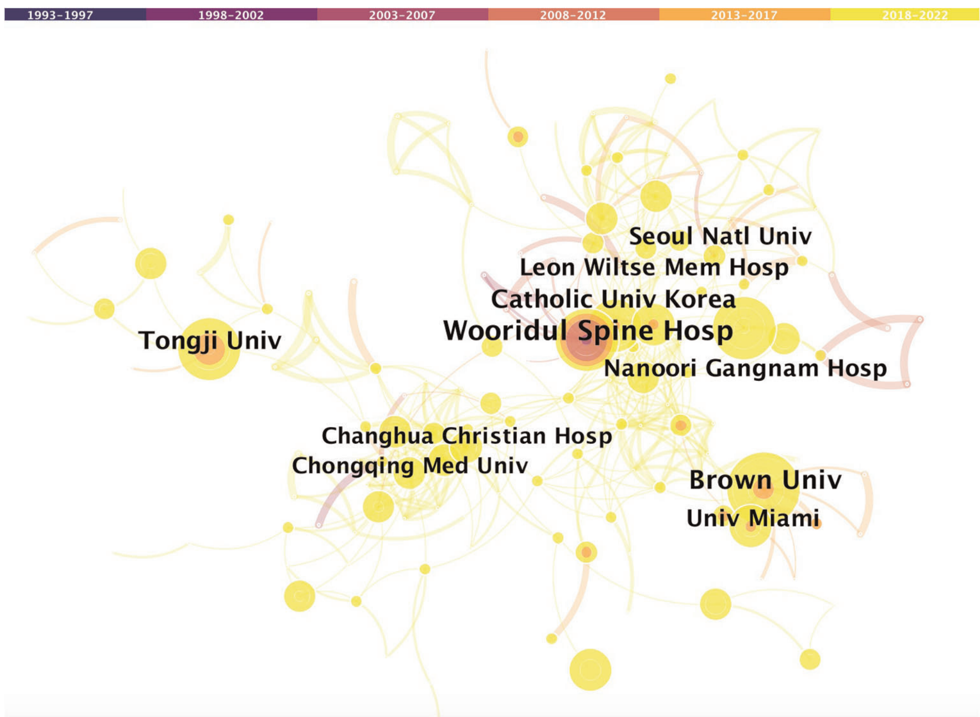

FIGURE 3
Co-operation network of productive institutions.

TABLE 3 Top 10 journals in the FESS field.

Rank	Journals	Number	%
1	World Neurosurgery	167	15.7
2	Pain Physician	67	6.3
3	Medicine	45	4.2
4	Neurospine	38	3.6
5	Spine	36	3.4
6	European Spine Journal	28	2.6
7	BMC Musculoskeletal Disorders	28	2.6
8	Journal of Neurosurgery: Spine	27	2.5
9	Biomed Research International	25	2.4
10	Acta Neurochirurgica	23	2.3

these journals are the mainstays of publication in the field of FESS and that they are more open to accepting FESS-related articles.

Analysis of funding

The National Natural Science Foundation of China contributed the most financial support to FESS research, with 67 grants.

Analysis of authors

Nearly 3,000 authors contributed to publishing the 1,064 FESS-related articles. Table 4 lists the top 10 most productive authors. S.H. Lee published the most articles (57 publications, 5.4%), followed by A.E. Telfeian (47 publications, 4.4%), J.S. Kim (42 publications, 3.9%), Y. Ahn (42 publications, 3.85%), I.T. Jang (41 publications, 3.85%), S. Ruetten (31 publications, 2.9%), H.S. Kim (30 publications, 2.9%), M.Y. Wang (29 publications, 2.7%), M. Komp (26 publications, 2.4%), and C.K. Park (26 publications, 2.4%). It is noteworthy that six of the 10 most published authors in this field were from South Korea. Figure 4 depicts the author cooperation network and further analysis showed a strong connection between these authors. It can be seen that authors who worked in the same country or who were co-authors of a study are linked in the bibliography.

Analysis of references

Table 5 lists the most cited publications in the field of FESS. The most cited article was by A.T. Yeung (USA), with a total of 429 citations. Five of the 10 most cited articles were from South Korea, and the remaining four were from Germany. Of the 10

TABLE 4 Top 10 productive authors in the FESS field.

Rank	Author	Number	%	Affiliation
1	S.H. Lee	57	5.4	Department of Neurosurgery, Wooridul Spine Hospital, Seoul, South Korea
2	A.E. Telfeian	47	4.4	Department of Neurosurgery, Rhode Island Hospital, The Warren Alpert Medical School of Brown University, Rhode Island, USA
3	J.S. Kim	42	3.9	Department of Neurosurgery, Seoul St. Mary's Hospital, The Catholic University of Korea, Seoul, South Korea
4	Y. Ahn	41	3.85	Department of Neurosurgery, Gil Medical Center, Gachon University, Incheon, South Korea
5	I.T. Jang	41	3.85	Department of Neurosurgery, Nanoori Hospital, Seoul, South Korea
6	S. Ruetten	31	2.9	Department of Spine Surgery and Pain Therapy, St. Anna-Hospital Herne, University of Witten/Herdecke, Herne, Germany
7	H.S. Kim	30	2.8	Department of Neurosurgery, Nanoori Hospital, Seoul, South Korea
8	M.Y. Wang	29	2.7	Department of Neurological Surgery, University of Miami Miller School of Medicine, Miami, Florida, USA
9	M. Komp	26	2.4	Department of Spine Surgery and Pain Therapy, St. Anna-Hospital Herne, University of Witten/Herdecke, Herne, Germany
10	C.K. Park	26	2.4	Department of Neurosurgery, Leon Wiltse Memorial Hospital, Suwon, South Korea

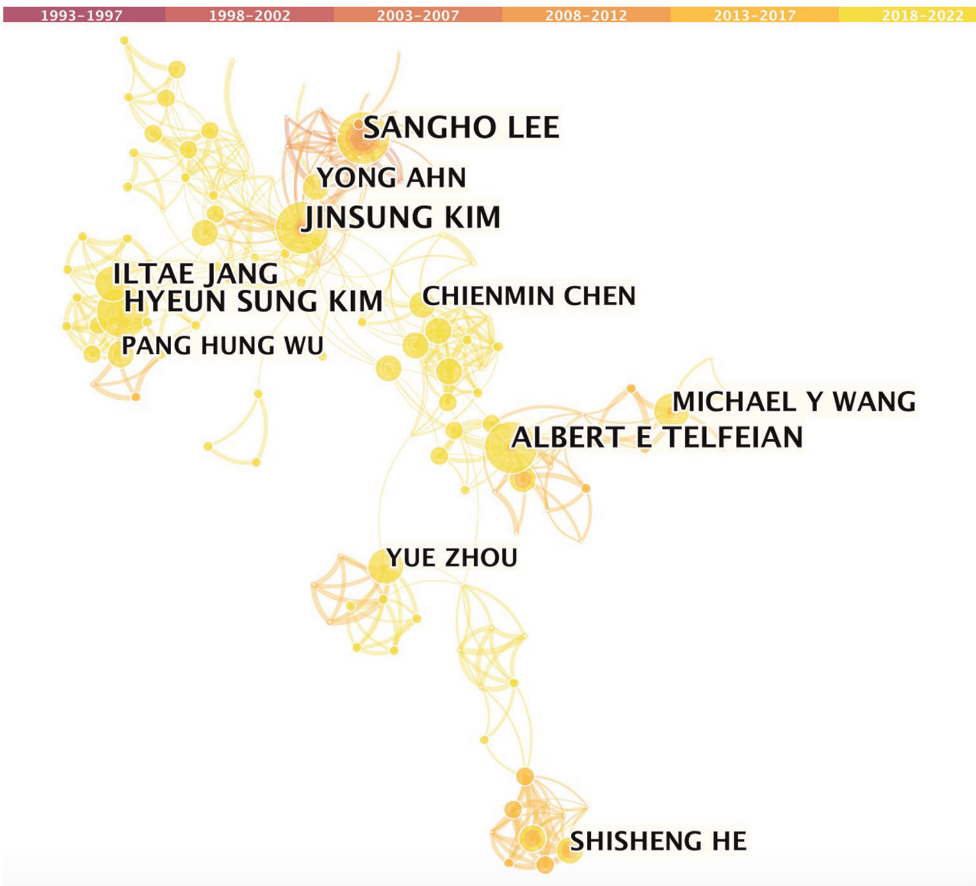

FIGURE 4
Co-operation network of productive authors.

most cited articles, S. Ruetten contributed to three and six were published in *Spine*.

In the co-citation display analysis, the distance between references reveals the link between them in terms of co-citations. **Figure 5** shows a network diagram of the cited references, which illustrates the co-citation relationships of the references. The most frequently cited article in reference lists was authored by K.C. Choi et al. (2016) (18); followed by articles authored by D.H. Heo et al. (2017) (19), J.H. Eun et al. (2016) (20), H.S. Kim et al. (2017) (21), and M. Komp et al. (2015) (22).

TABLE 5 Top 10 cited articles in the FESS field.

Rank	Title	Year	Author	Journal	Citations
1	Posterolateral endoscopic excision for lumbar disc herniation - Surgical technique, outcome, and complications in 307 consecutive cases	2002	A.T. Yeung et al.	*Spine*	429
2	Transforaminal posterolateral endoscopic discectomy with or without the combination of a low-dose chymopapain: A prospective randomized study in 280 consecutive cases	2006	T. Hoogland et al.	*Spine*	193
3	Percutaneous endoscopic lumbar discectomy for recurrent disc herniation: Surgical technique, outcome, and prognostic factors of 43 consecutive cases	2004	Y. Ahn et al.	*Spine*	184
4	Use of newly developed instruments and endoscopes: full-endoscopic resection of lumbar disc herniations *via* the interlaminar and lateral transforaminal approach	2007	S. Ruetten et al.	*Journal of Neurosurgery: Spine*	181
5	A new full-endoscopic technique for the interlaminar operation of lumbar disc herniations using 6-mm endoscopes: Prospective 2-year results of 331 patients	2006	S. Ruetten et al.	*Minimally Invasive Neurosurgery*	150
6	Percutaneous endoscopic approach for highly migrated intracanal disc herniations by foraminoplastic technique using rigid working channel endoscope	2008	G. Choi et al.	*Spine*	148
7	An extreme lateral access for the surgery of lumbar disc herniations inside the spinal canal using the full-endoscopic uniportal transforaminal approach-technique and prospective results of 463 patients	2005	S. Ruetten et al.	*Spine*	146
8	Percutaneous endoscopic lumbar discectomy for migrated disc herniation: classification of disc migration and surgical approaches	2007	S. Lee et al.	*European Spine Journal*	142
9	Percutaneous endoscopic interlaminar discectomy for intracanalicular disc herniations at L5-S1 using a rigid working channel endoscope	2006	G. Choi et al.	*Neurosurgery*	134
10	Operative failure of percutaneous endoscopic lumbar discectomy: A radiologic analysis of 55 cases	2006	S.H. Lee et al.	*Spine*	133

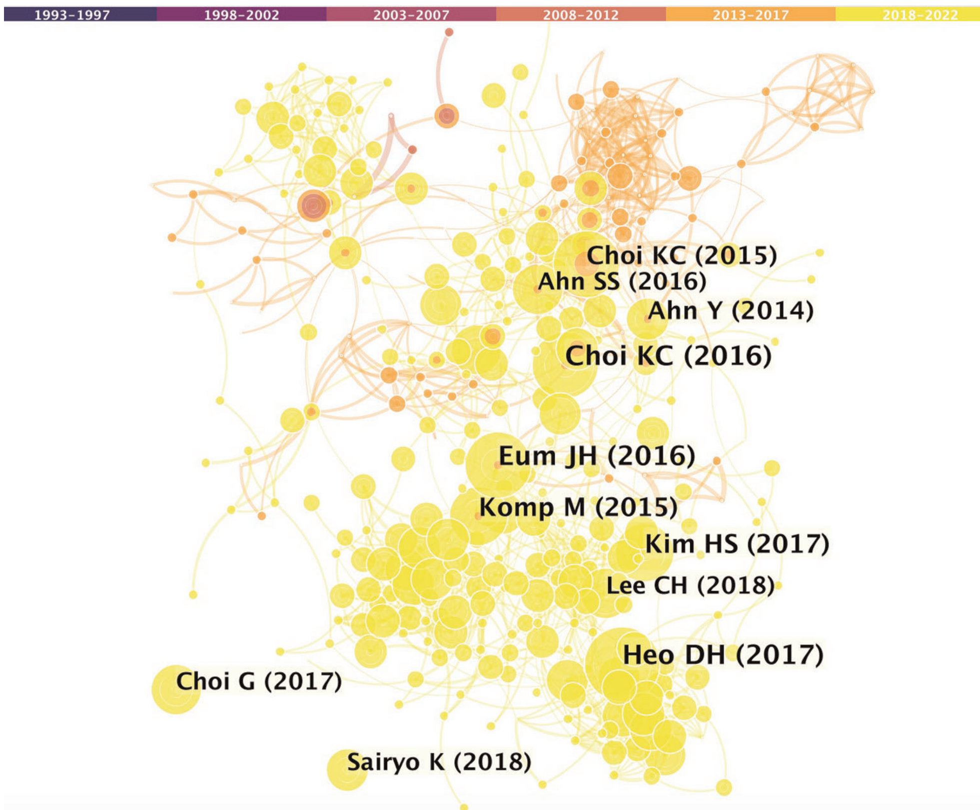

FIGURE 5
Co-operation network of cited references.

Analysis of keywords and research hotspots

Keywords can accurately describe the topic under consideration. Summarizing high frequency and highly emerging terms in a publication can aid in describing research hotspots and trends. **Figure 6** presents the top 20 keywords with the strongest citation bursts. The red bars represent the time and interval of keyword occurrence. The strongest citation burst keywords in the field of FESS were "lumbar spine," "discectomy," "interlaminar," "surgical technique," "follow-up," "excision," "thoracic spine," and "endoscopic surgery."

Keyword clustering collects words and phrases with obvious domain features and groups them into clustering objects, uses original feature extraction algorithms for text classification in order to perform domain clustering of words, and obtains generic and specific domain words by controlling the influence of word frequency. **Figure 7** presents the 10 clusters generated in this study: "endoscopic discectomy" (#0), "thoracic myelopathy" (#1), "recurrent lumbar DH" (#2), "low back pain" (#3), "cervical vertebrae" (#4), "lumbar spinal stenosis" (#5), "transforaminal lumbar interbody fusion" (#6), "radiation exposure" (#7), "management" (#8), and "lumbar spine" (#9). Serial numbers were sorted by cluster size, and the field was carefully divided into several groups.

Discussion

The current study used the WoS database and CiteSpace software to perform a bibliometric analysis of 1,064 articles on FESS published in approximately the last 30 years. The growth route from 1993 to the present was divided into two phases: 1993–2015, which was a period of gradual development, and 2016–the present, which was a period of rapid development. For decades, a great number of spine surgeons have been fascinated by the merits of FESS and have pushed for further development of this technique. Many researchers have dedicated their lives to this specific field of study and have made several significant scientific discoveries.

The surge in the number of FESS-related publications occurred in 2016. A possible reason for this is the large number of spinal endoscopic surgeons that have been trained by many spinal endoscopy-related societies around the world since 2010. Through the efforts of these groups, endoscopic spine surgery is becoming an increasingly important aspect of spine surgery and can be applied to most spinal conditions. With several additional years of practice and case accumulation, the first results began to be seen in 2016, as evidenced by a significant increase in the number of publications. Further, the development of biportal endoscopic spine surgery and full endoscopic spinal fusion procedures has greatly increased the number of spinal endoscopy publications.

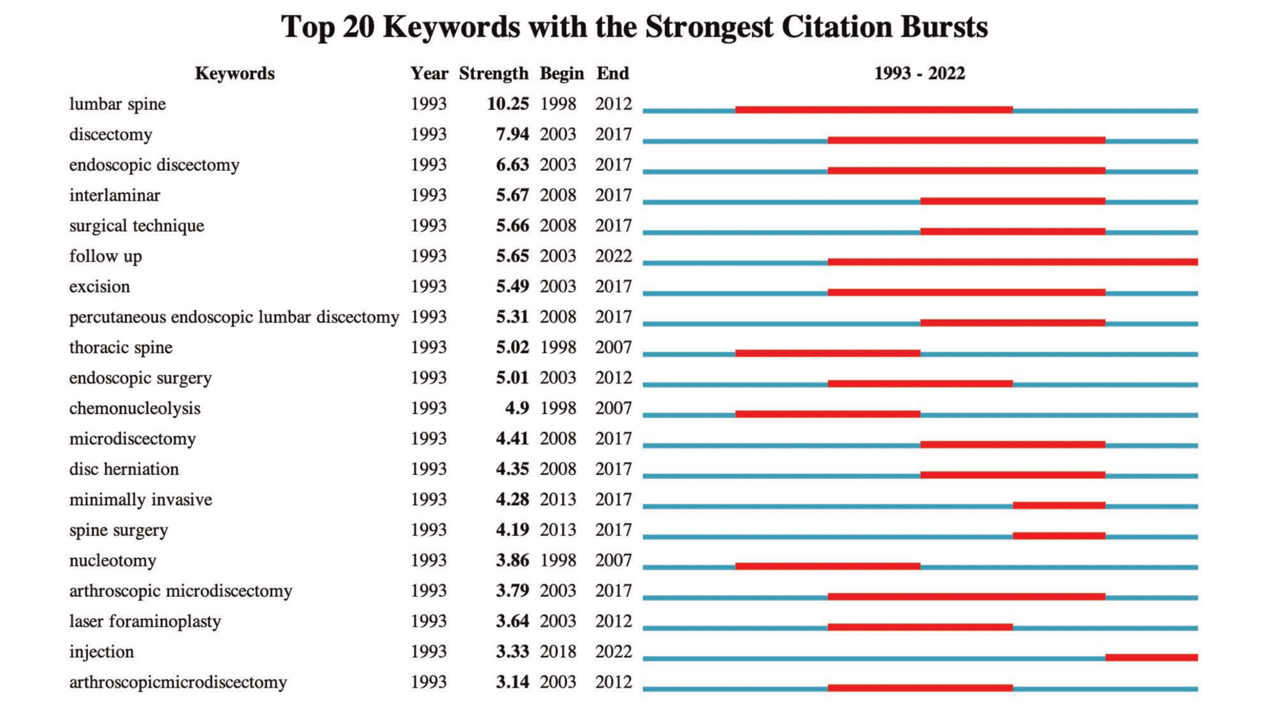

FIGURE 6
Top 20 keywords with the strongest citation bursts.

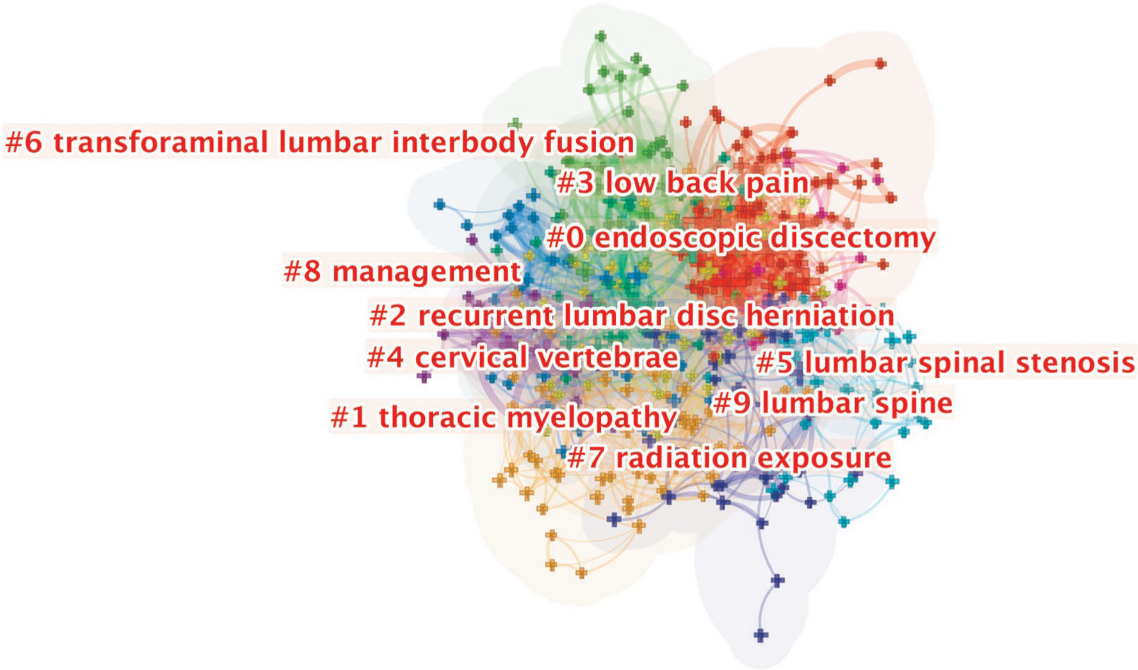

FIGURE 7
The clustering of keywords.

Distribution analyses of countries/regions, institutions, and authors may aid in increasing collaboration and worldwide cooperation in the field of FESS. The authors discovered that the top five countries published 88.7% of all articles, implying that global FESS-related research findings were concentrated within a few countries/regions. The top five productive countries in the field of FESS were represented by the top five research institutes, three of which were in South Korea. Like in the case of other medical specialties, most of the key FESS-related research findings are uncovered by a few large countries/regions. National endoscopy-related publication outputs are provided by one or more of these national institutions. In addition, when specific authors at these institutions are examined closely, it can be found that only one or two surgeons on the team perform the bulk of the primary research. Differences in scientific output between countries/regions are multifactorial and are mainly caused by socioeconomic factors, overall research capacity, national expenditure in scientific research, and population size differences (23, 24). Furthermore, country/region level variances in specialized training in the field of endoscopic spine surgery have influenced the development of FESS techniques. Asian surgeons in China, South Korea, and Japan use spinal endoscopes more often in clinical practice and appear to perform spinal endoscopic procedures with a higher level of self-reported competence. In contrast to North America and Europe, where surgeons are still unclear about when to perform these advanced endoscopic operations, endoscopic spine surgery training appears to be more organized in Asia.

In the current study, we found that China had the largest number of publications in the field of FESS. In particular, the number of publications in China has increased dramatically over the last five years. This may be because China has an inherent demographic advantage as well as a comparable advantage in recruiting patients with spinal disorders. Moreover, China is one of the countries with the largest number of spine specialists. Their surgical and writing skills are gradually improving, thereby further increasing the output of publications (25). Furthermore, rapid economic growth has contributed to an increase in the funding allotted to the medical field and a corresponding increase in research output. Sponsorship in terms of research funding has also been significant. With 67 grants, the National Natural Science Foundation of China made the largest investment in FESS research. The number and quality of publications directly reflect the growth of the field of FESS. South Korea had the second highest number of publications after China. In addition, of the top five productive institutions, three were from South Korea. Nevertheless, among all the countries/regions contributing to the field of FESS, the H-index of published papers was the highest in South Korea. This demonstrates that the quality of research in the field of FESS is assured in the case of institutions or authors originating from South Korea. Despite being a pioneer in many biological sciences, the United States is not a leader in FESS research and had fewer publications than China or South Korea. In addition, the publication quality in the United States is also lower than that in South Korea. This may be because of the health insurance system or other economic factors. Most insurance companies in the United States do not provide adequate reimbursements for FESS. These factors may hinder the further development of FESS techniques. Additionally, the use of FESS is steadily rising in other countries/regions, such as India, Brazil, and Canada, although fewer articles may have been published because of a lack of publishing incentives. Moreover, none of the top 10 most cited articles were from China. The author of the most cited paper was A. T. Yeung from the United States. Five of the 10 most cited articles were from South Korea, and the remaining four were from Germany. This finding proves that Germany's influence in the field of FESS should not be underestimated. It can be summarized that FESS originated in Europe and the United States, while it has flourished in China, South Korea, and Japan.

It is worth noting that six of the top 10 most published authors in this discipline originate from South Korea. Further investigation revealed a clear link between these authors and they were listed as co-authors in several studies. This association has also been observed in the case of other studies. This may be characterized as a calculated and advantageous strategy.

Journal analysis may help researchers in selecting an appropriate channel for paper submission. The journal *World Neurosurgery* (15.7%), has published the largest number of FESS-related articles. In addition, of the top 10 most cited papers, six were published in *Spine*. Unfortunately, none of the top 10 FESS-related research articles with the largest number of citations were published in *World Neurosurgery*. This implies that the articles published in *Spine* may be more impactful. In addition, the FESS-related articles published in the top 10 journals accounted for 45.6% of all published FESS-related articles. These journals may be more accepting of FESS-related studies. Concurrently, articles published in these journals are more likely to be noticed and cited.

The analysis of keywords in the field of FESS revealed the focus, hotspots, and trends of research in the field. By analyzing keyword co-terminology, we identified the most prominent hotspots in the field over the past 30 years. Based on the top 20 keywords with the strongest citation bursts and top 10 keyword clusters, the research focus of FESS was found to include indications for the technique, perioperative management, and application of FESS in the treatment of various spinal diseases. After more than 30 years of development, FESS has become a common surgical approach for treating various spinal conditions; however, it must be used fairly and judiciously to maximize its advantages and avoid any associated concerns.

Many improvements have been made to FESS techniques, which has expanded its indications beyond lumbar DH to include cervical spondylosis, thoracic DH, chronic low back pain, spinal stenosis, and spinal infections.

FESS in cervical spinal diseases

(i) Anterior approach: The primary disease that requires full endoscopic cervical surgery is cervical DH with or without foraminal stenosis. Both anterior and posterior approaches can be used for treating cervical DH. However, the surgical path is determined by the location of DH, and cervical DH in any location, including central and paracentral DH, can be treated with anterior approach cervical endoscopy (26). The advantages of cervical endoscopic surgery include a small incision; reduced risk of hematoma, infection, and vocal cord paralysis; and decreased injury to major tissues (such as the carotid artery, trachea, and esophagus) (27, 28). Therefore, this technique is useful in elderly patients or in patients with poor tolerance to anesthesia. However, the technique has some limitations. On the one hand, the percutaneous anterior approach may destroy the nucleus pulposus and may lead to postoperative narrowing or instability of the disc space; therefore, in some cases, a transcorporeal approach (the surgeon creates a safe channel from the anterior to the posterior edge of the cervical vertebrae, through which the discectomy is performed) can be used instead to achieve reduced disc destruction (29, 30). On the other hand, this technique is not suitable in cases of disc stenosis or severe calcification.

(ii) Posterior approach: The main targets of posterior endoscopic cervical foraminotomy or discectomy are herniated discs or foraminal stenosis when the primary lesion is located lateral to the spinal cord (31). The main indications for posterior approach cervical endoscopy are as follows: lateral herniated or paracentral herniated cervical DH and unilateral cervical foraminal stenosis combined with intractable cervical radiculopathy (32). According to a previous randomized trial, in cases with appropriate indications, posterior approach cervical endoscopy can be an effective alternative to traditional open surgery (33).

FESS for thoracic spinal diseases

According to the literature, FESS resulted in favorable clinical outcomes when used to treat thoracic DH, thoracic spinal stenosis, and ossification of the yellow ligament of the thoracic spine (34, 35). Establishing good working access is a key step in percutaneous endoscopic posterolateral access thoracic discectomy, and with the help of three dimensional (3D) computed tomography navigation, bony access and precise localization of the lesion can be better established (36). The full endoscopic technique has a magnifying effect on visual field and uses radiofrequency coagulation for securing small vessels and bleeding points during surgery to ensure a clear field of view which enables precise excision of the lesion, reduces damage to the surrounding soft tissues and bony structures, and effectively prevents postoperative complications, such as postoperative adhesions and spinal instability.

FESS for lumbar spinal diseases

(i) Transforaminal FESS is the most representative endoscopic procedure and is widely used. The basic concept underlying this technique is gaining access to the disc lesion directly through the Kambin triangle while preserving the normal anatomic tissue, which can be performed under local anesthesia and can reduce adjacent segmental lesions. The initial indication is simple lumbar DH. With the development of endoscopic techniques and instruments, their practical applications have expanded to include migrated, recurrent, and even partially calcified DH (37, 38). Furthermore, in recent years, many reports on transforaminal FESS for treating lateral recess or foraminal stenosis have been published (39, 40).

(ii) Interlaminar FESS was initially developed to treat herniated discs at L5-S1 because a transforaminal approach is difficult in patients with high iliac crests and because there is sufficient space between the laminae at the L5-S1 level to perform decompression while preserving the paravertebral muscles and most of the laminae (41). In the treatment of lumbar spinal stenosis, the transforaminal interlaminar approach is suitable in patients with lateral recess stenosis and central canal stenosis, and decompression can be performed bilaterally with a unilateral approach in patients with central canal stenosis with intermittent claudication as the main symptom (42, 43). Foraminal DH, extreme posterolateral DH, and DH with segmental instability are contraindications for interlaminar FESS (44).

(iii) In addition, the use of special approaches, such as translaminar (45), transpedicular (46), and transiliac (47) approaches, during full endoscopic techniques has been reported.

Full endoscopic spinal fusion surgery

Endoscopic advances have been clearly demonstrated in decompression surgery, and in recent times, endoscopic fusion procedures have been frequently reported (48, 49). Full endoscopic spinal fusion surgery is a minimally invasive technique that is one of the landmarks in the advancement of spinal endoscopic technology; it has led to the development of comprehensive endoscopic spinal fusion procedures with more delicate and precise surgical techniques (50, 51). Under the same premise followed in the case of indications for lumbar fusion surgery, the recent clinical efficacy of this procedure has been satisfactory. Recently, some researchers have attempted to perform a full endoscopic anterior cervical decompression and fusion procedure (52, 53). However, this procedure still has a steep learning curve, long initial surgical time, and a high complication rate. To complete the surgery in a safer, more efficient, and minimally invasive manner, many specialists have improved and innovated the surgical techniques, accesses, and instruments.

Biportal endoscopic spine surgery

The concept underlying unilateral biportal endoscopic spine surgery is similar to that involved in arthroscopic surgery, in which two different channels placed in the endoscopic system are used along with the working channel (54). The endoscopic channel is used to advance a 0° or 30° endoscope in order to obtain a surgical field of view, while the instrument channel is used for surgical instrument access. The surgical approach is similar to that used with microendoscopic systems; however, it involves the use of saline as a medium, flexible use of instruments, operation of most instruments with existing open surgical tools, a shorter learning curve than that associated with single-portal endoscopes, performance of most procedures under general anesthesia, use of various instruments for assistance, and free handling of instruments (55, 56). 3D endoscopy is also used to obtain depth-of-field surgical images (57). Compared with single-portal endoscopy, biportal endoscopy is slightly more disruptive to the spinal anatomy but is more efficient in decompression. Therefore, many clinicians use this technique for multilevel spinal decompression and fusion (58–60).

Limitations

First, this bibliometric study was limited to published resources retrieved from the WoS database. Second, because bibliometric data evolve, indexing delays may have resulted in minor variations in search results. Third, regardless of merit, publications with repeated titles or titles not directly relevant to FESS may have been deleted owing to selection bias. Finally, because only papers from approximately the past 30 years were included, valuable publications from earlier years may have been omitted. Despite these limitations, our data provide information on the features of FESS-related investigations as well as on the trends in the citation of published articles.

Conclusions

A bibliometric approach was used to analyze the quantity and quality of FESS-related publications and research hotspots. According to our study, the number of FESS-related publications has increased significantly since 2016. Most publications on FESS are limited to a few countries/regions and institutions. China has the highest number of publications, while South Korea has the highest impact as assessed by the H-index. However, the contributions of the United States, Japan, and Germany should not be overlooked. The author who contributed the most was S.H. Lee, and the largest number of contributions to this field originated from Wooridul Spine Hospital. *World Neurosurgery* published the largest number of FESS-related articles, but the articles published in *Spine* may be more impactful. Based on the most cited keyword bursts and clusters, the focus of FESS research was found to include its indications, management, and applications.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

Ethics statement

This is a review study, so ethics committee approval was not required.

Author contributions

G.X.L. drafted the manuscript; M.T.Z. performed the investigation; V.K. performed data curation; P.L. interpreted the data and performed software analysis; C.M.C. conceptualized and designed the study B.S.H. helped with manuscript revision. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Percutaneous full-endoscopic uniportal decompression for the treatment of symptomatic idiopathic lumbar spinal epidural lipomatosis: Technical note

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Background: Lumbar spinal epidural lipomatosis (SEL) is a rare condition characterized by an excessive accumulation of adipose tissue within the spinal canal, compressing the dura sac and/or nerve roots. When conservative treatments fail and clinical symptoms progress quickly and seriously, surgical decompression should be considered. With the rapid development of endoscopic armamentaria and techniques, the pathological scope that can be treated by percutaneous endoscopic spine surgery is ever expanding.
Objective: In this paper, the authors describe a patient with lumbar spinal epidural lipomatosis who was treated with a percutaneous full-endoscopic uniportal decompression surgery successfully. This article aims to validate the feasibility of percutaneous full-endoscopic uniportal decompression for the treatment of symptomatic idiopathic spinal epidural lipomatosis *via* interlaminar approach.
Methods: We describe a case of a 69-year-old man with a 10-year history of low back pain, intermittent claudication, and bilateral leg neuropathic pain. He was diagnosed with lumbar epidural lipomatosis, which did not respond to conservative therapy. After a comprehensive evaluation, he underwent percutaneous endoscopic spine surgery to remove hyperplastic adipose tissue and decompress nerve roots and dura sac.
Results: The patient was treated with a percutaneous full-endoscopic uniportal decompression surgery successfully. After the procedure, his leg pain decreased and his walking capacity improved. There were no surgery-related complications, such as cerebrospinal fluid leakage, incision infection, etc.
Conclusions: The case with SEL was successfully treated with a percutaneous full-endoscopic uniportal surgery, which has the advantages of excellent presentation of anatomical structures, expanded field of vision, less surgical-related trauma, and bleeding. The key point of the procedure is to release and cut off the bands which divide the epidural space into small rooms filled with excess adipose tissue.

KEYWORDS
spinal epidural lipomatosis, percutaneous, minimally invasive surgery, uniportal, full-endoscopic

Introduction

Percutaneous endoscopic spine surgery has been evolving rapidly these years with the development of endoscopic philosophy, technology, and equipment (1, 2). Consequently, the indications of endoscopic spine surgery are ever expanding, from the initial lumbar intervertebral disk disease to other types of pathologies located in the whole spinal column (3, 4). The obvious advantages of working-channel endoscopic spinal surgery include the reduction of the surgical corridor, avoiding soft tissue and muscular stripping, minimizing bony resection, as well as obtaining excellent visualization (1, 2, 4).

Since Lee et al. first reported a case of spinal epidural lipomatosis (SEL) in 1975 (5), more and more studies on this disease have been retrieved in the literature (6–12). SEL is defined as an abnormal accumulation of adipose tissue in the epidural space within the spinal canal resulting in compression to the spinal cord and/or cauda equina. Clinical manifestations of SEL in lumbar include low back pain, lower extremity weakness, lower extremity numbness, and neurogenic intermittent claudication, which are identical to that of degenerative lumbar stenosis. The treatment measures of SEL include conservative therapy and surgical decompression. Although there is still no clear consensus on the treatment of SEL, the approach to patients with SEL should initially be conservative involving weight reduction and endocrine therapy (13, 14). Surgery interventions should be considered when conservative treatments fail and clinical symptoms deteriorate rapidly (14). As for the surgical methods, extensive laminectomy and excision of the adipose tissue are the most commonly used options (15). So far, there has been no report to treat lumbar lipomatosis using the percutaneous uniportal full-endoscopic technique. In this report, we describe a case of lumbar epidural lipomatosis, which was successfully treated with percutaneous uniportal full-endoscopic surgery (**Figure 1**). The objective of this article is to validate the feasibility of the approach and describe several operative pearls based on our experience.

Materials and methods

The study was conducted in accordance with the guidelines of the 1964 Declaration of Helsinki and was approved by the ethics committee of Zhongshan Hospital, Fudan University (Institutional Review Board approval number 2021-042), as well as Minhang Hospital, Fudan University (Institutional Review Board approval number 2021-037-01X). The patient signed informed consent forms for the surgery procedure.

History and examination

A 69-year-old male patient (weight, 70 kg; height, 172 cm; body mass index, 23.66 kg/m^2) presented with a 10-year history of low back pain, neurogenic intermittent claudication, and bilateral leg radicular pain. He could walk no more than 100 m and daily activities were severely affected. His VAS score for leg pain was 8/10. He denied any history of endocrine and metabolic diseases and steroid use. Physical and neurologic examinations showed that the dorsiflexor strength of bilateral ankles and great toes was grade 4. Besides, the physical examination also indicated that there was numbness accompanied by a decrease in temperature, touch, and pinprick sensation in the skin of the bilateral sole and calf. His numbness, pain, and walking capacity did not respond to conservative treatment measures, including physical therapy, weight control, and oral medications. He did not receive an epidural steroid injection.

His lumbar dynamic x—ray radiographs did not show any instability. Lumbar magnetic resonance imaging (MRI) and computed tomography (CT) reconstruction revealed abnormal deposition of epidural adipose tissue in the spinal canal, which compressed the nerve roots and thecal sac, especially at the L4–5 and L5–S1 levels (**Figure 2**). He was diagnosed with idiopathic lumbar spinal epidural lipomatosis. In accordance with the MRI grading by Borré et al. (16), the current state of the patient was classified as grade III.

Endoscopic instruments

The endoscopic surgical system Delta (**Figure 3**) (Joimax GmbH, Karlsruhe, Germany) was applied to perform the surgery, including an endoscope (15° angle), endoscopic sheaths, basket forceps, endoscopic punches, nucleus pulposus clamp, etc. The radiofrequency probe (Trigger-FlexR Bipolar System, Elliquence LLC, Baldwin, NY, USA) was used to ablate soft tissue and control bleeding. The endoscopic high-speed diamond burr (Primado P200-RA330, NSK-Nakanishi International, Co., Ltd., Osaka, Japan) was utilized to grind bones.

Operative technique

The operation was performed under general anesthesia. The patient was placed in a prone position on a radiolucent surgery table with appropriate flexion (**Figure 4**). The posterior approach was used to perform the decompression and debulk at L4–5 and L5–S1 levels.

Lumber 4–5 segment was performed firstly. After the patient was routinely sterilized and draped. A 10 mm stab

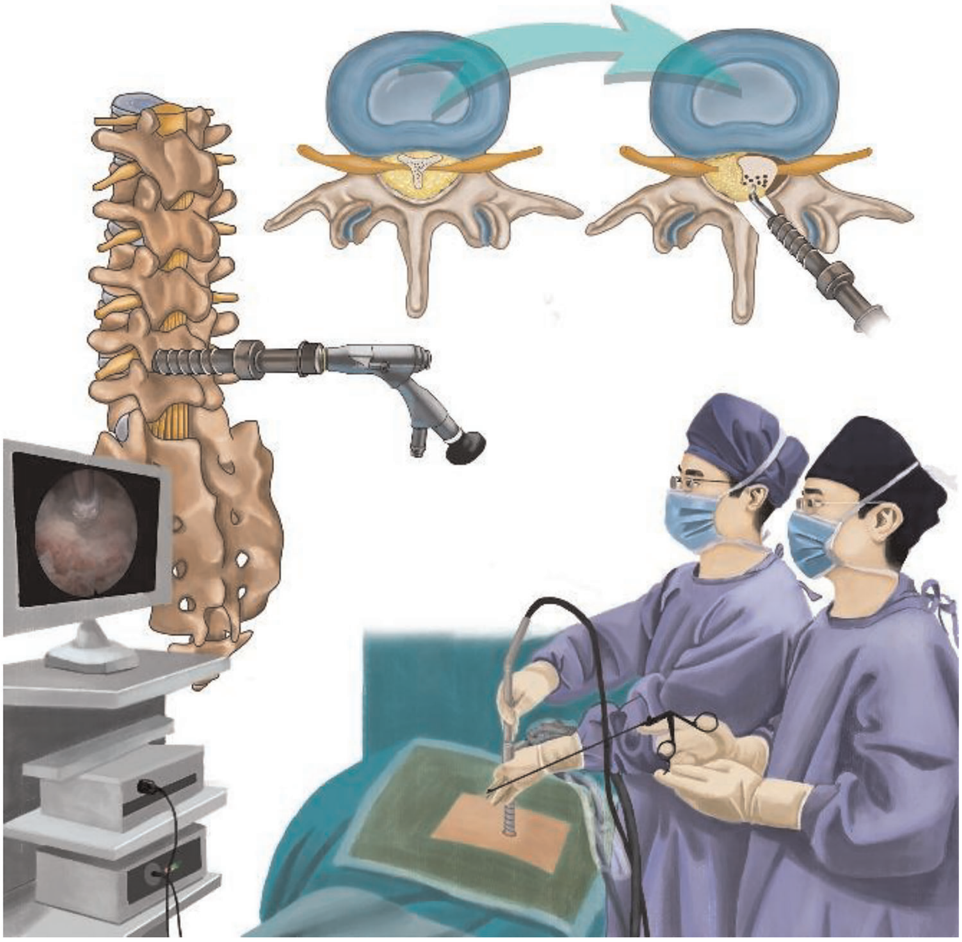

FIGURE 1
Illustration showing the percutaneous full-endoscopic uniportal decompression for the treatment of spinal epidural lipomatosis.

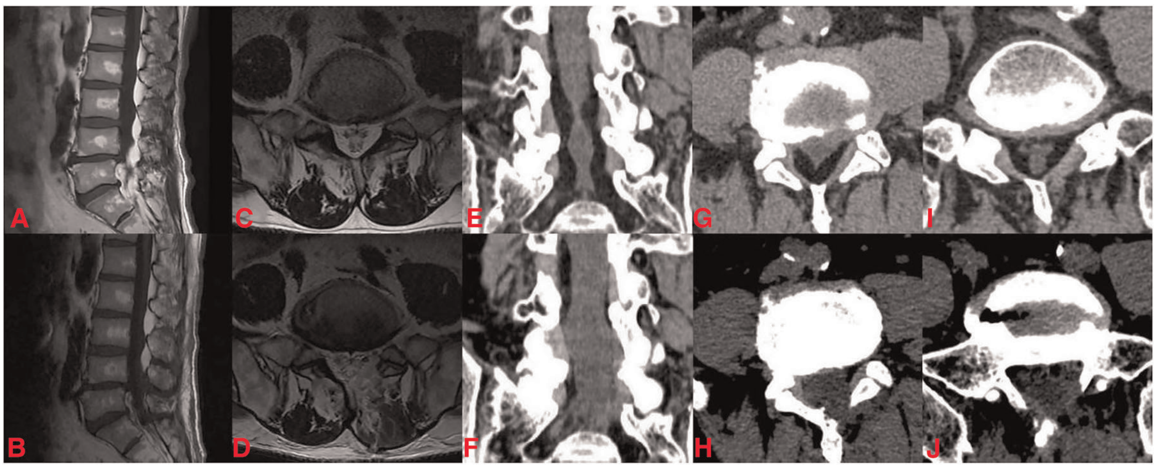

FIGURE 2
The preoperative and postoperative imaging data of the patient. Preoperative (A) and postoperative (B) sagittal MRI image; preoperative (C) and postoperative (D) axial magnetic resonance imaging (MRI) image at the L5–S1 level; preoperative (E) and postoperative (F) coronal CT; preoperative (G) and postoperative (H) axial CT at L4–5 level; preoperative (I) and postoperative (J) axial CT at the L5–S1 level.

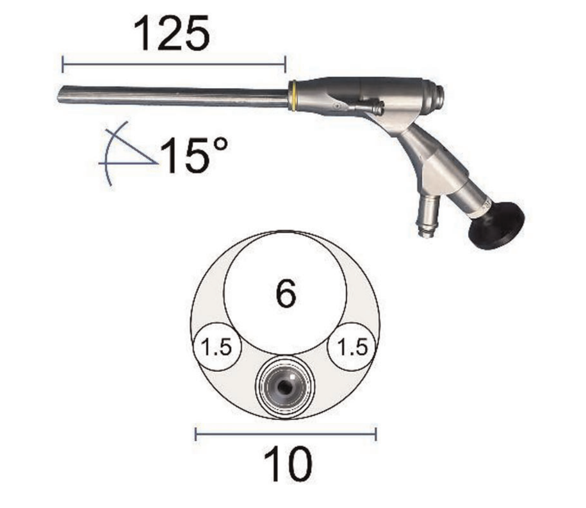

FIGURE 3
Illustration showing endoscopic surgical system Delta (Joimax GmbH, Karlsruhe, Germany) scope profile, including outer diameter, working channel, working length, and angle.

FIGURE 4
The patient was positioned in the prone position on a radiolucent surgery table with hips and knees in slight flexion and hands appropriately oriented at the sides of the head.

wound was made in the skin and a pencil-like rod was introduced to touch the bone (left L4–5 articular) under fluoroscopic guidance. The paravertebral muscles and fascia were dilated gradually by soft-tissue-dilators. Then, the 10 mm delta working cannula with oblique mouth was inserted. The position of the working cannula was verified with fluoroscopy in anteroposterior and lateral positions (**Figure 5A, B**). Finally, the endoscopic surgical system was introduced and all the subsequent steps were performed under constant irrigation with endoscopic visualization.

After the soft tissue was cleared using the radiofrequency probe, the left L4 lamina, L5 lamina, and ligamentum flavum between L4 and L5 could be identified under endoscopy. The ipsilateral partial laminotomy (L4 lower part and L5 upper part), as well as partial facet joint resection, were performed using a 3.5 mm endoscopic diamond bur and endoscopic Kerrison Rongeur (**Figure 6A**). The outer layer of ligamentum flavum was removed with a rongeur to expose the inner layer, which was tightly attached to the inner surface of the lamina, especially on the cephalic side (**Figure 6B**). The inner layer of ligamentum flavum was retained *in situ* in this step to prevent bleeding. Then, the base of the spinous process was shaved to facilitate that the working cannula can be inserted toward the contralateral side (**Figure 6C**). Contralateral bony decompression could be achieved using a diamond bur between the undersurface of the lamina and the ligamentum flavum (17). The enthesis of the inner ligament was detached and at last, the whole ligamentum was resected. At the same time, epidural excess fatty tissues were identified (**Figure 6D**). It should be noted that abundant bands were found not only between the dura sac and inner ligament, but also between the dura mater and the nerve root (**Figures 6E,F**). These bands divided the epidural space into small rooms filled with excess fat. The bands were cut off and most of the fatty tissues were removed. At the end of the operation, decompression of bilateral traversing nerve roots, as well as pulsation of the thecal sac were confirmed (**Figure 6G**). The skin incision was closed with one stitch. The same surgical technique was used for the adjacent affected level (L5–S1 level).

Results

After the procedure, his leg pain decreased and his walking capacity improved. One day postoperatively, the pain decreased sufficiently with 2/10 on VAS. There were no surgery-related complications, such as cerebrospinal fluid leakage, incision infection, etc. During the follow-up, 3- and 12-month postoperatively, the VAS scores were 2/10 and 1/10 points. He was able to walk 500 m without obvious numbness and pain in his lower limbs at the last follow-up. Postoperative MRI and CT scans indicated the successful decompression of the neural structure at the L4–5 and L5–S1 levels (**Figure 2**).

Discussion

Under physiologic conditions, the epidural fat tissue in the spine canna is thought to serve as a cushion for nerve structures. However, the excessive accumulation of fat tissue, which is referred to as SEL, can cause compression damage to the spinal cord and cauda equina. As a result, patients with SEL often develop neurological symptoms, such as sensory and

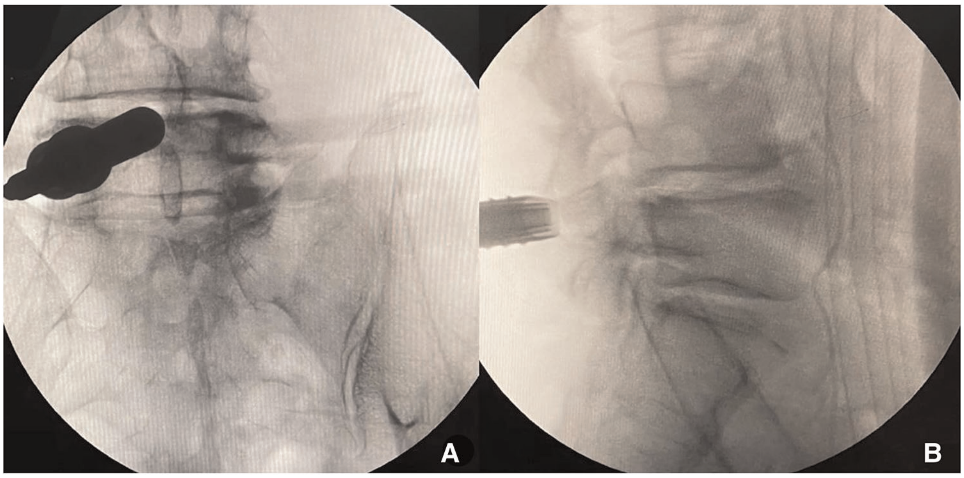

FIGURE 5
The position of the working cannula was verified with fluoroscopy in anteroposterior and lateral position (L4–5).

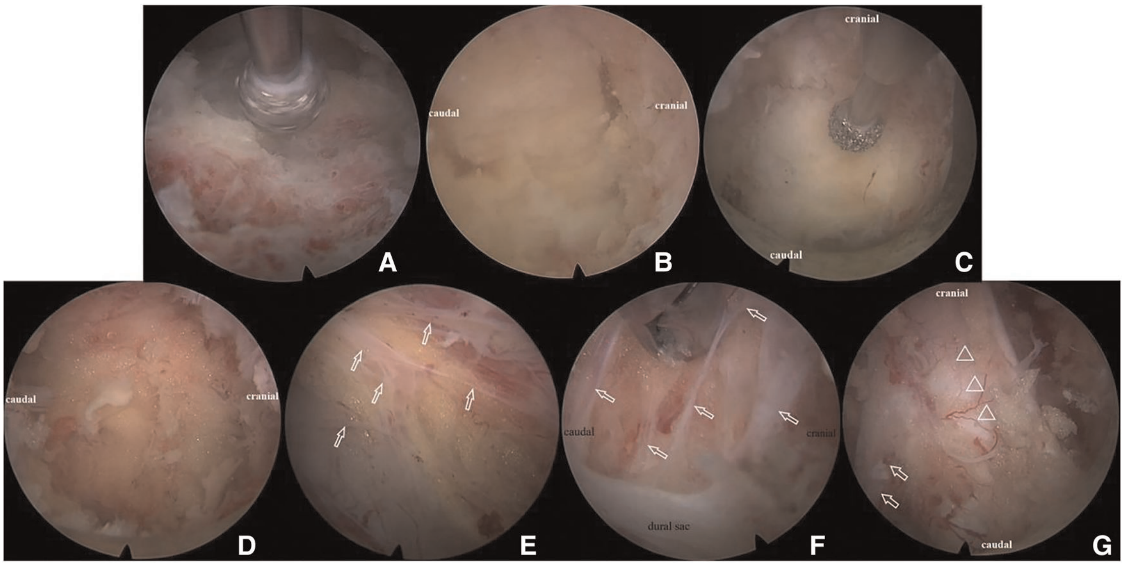

FIGURE 6
Illustration of percutaneous full-endoscopic uniportal decompression procedures for the treatment of lumbar spinal epidural lipomatosis. (A) The inter lamina window was expanded using diamond bur; (B) the cranial and caudal end of the ligamentum flavum was identified; (C) the base of the spinous process was shaved with diamond bur without removal of the ligamentum flavum; (D) epidural excess fatty tissues were exposed; (E) bands (white arrow) between dural sac and ligamentum flavum; (F) bands (white arrow) between the dura mater and the nerve root; (G) decompression of the dural sac (triangle) and bilateral traversing nerve root (white arrow).

motor disturbance, claudication, lower back pain, and radiculopathy (14). The pathogenesis of SEL may include the following disease states: endogenous steroid hormonal disease, long periods of exogenous steroid use, surgery-induced, obesity, and idiopathic disease (18, 19). Malone et al. reported a rate of 6.26% for symptomatic SEL in their population, with an incidence rate of 2.5% per year (9). Thus, it can be seen that SEL seems to be more than people originally thought. The patient we presented in this report had difficulty in walking less than 50 m, leg weakness, and sensory loss in L4, L5, and S1 distribution. He had no history of endocrine diseases and steroid use. Therefore, he was diagnosed with idiopathic SEL.

For this idiopathic SEL patient, with clinical symptoms have been deteriorating progressively, surgical treatment should be considered (14). Although there is no consensus about surgical methods, laminectomy with excision of the hypertrophic fatty tissues is considered the mainstay (6, 12, 14, 20, 21). However, the traditional laminectomy and microsurgery of excision of the hypertrophic fatty tissue need a wide incision, significant paravertebral muscle stripped, and bone dissection for adequate visualization, which can result in postoperative pain and slow recovery (22). During the past three decades, percutaneous endoscopic spine surgery has evolved dramatically with the development of endoscopic equipment and techniques. As a result, the indications of endoscopic spine surgery are ever expanding, from the initial lumbar disc disease to other types of pathologies located in the whole spine column (4). The obvious advantages of percutaneous working-channel endoscopic spine surgery are as follows: reduction of the surgical corridor, avoiding muscular dissection, reduction of bony resection to prevent iatrogenic instability, close observation to obtain excellent visualization, and reduction of bleeding under water perfusion pressure (4). In the operation of this case, we used Delta endoscopic surgical system with a larger manipulation channel (diameter of 1 cm) than the previous traditional endoscopy (**Figure 3**). This character facilitated us to use larger sizes of endoscopic Kerrison punches in the procedure, in which the size of the rongeur bite part can be up to 5 mm. Hence, the ligamentum flavum and its enthesis are convenient to be removed (17). Owing to this, the efficiency of surgery was greatly enhanced. The operation duration was within 2 h for two segments (L4–5, L5–S1) in this case. Kang et al. reported that the biportal endoscopic technique had been used to achieve successful neural decompression for symptomatic SEL (22). It is indeed a minimally invasive technique possessing the traits of percutaneous spinal endoscopy, such as close observation and clear field of vision under water irrigation. Compared with this technique, our uniportal technique had less damage to soft tissue because we neither need two skin incisions and two ports nor need to remove part of the muscle and muscle fascia to make room for the procedure and continuous irrigation. In this case, our experience has proved that the full endoscopic uniportal technique is fully suitable for decompression treatment for SEL.

In addition, compared with microscopic channel surgery, our endoscopic surgery has great strengths to manipulate the opposite side lesion. The outer working cannula can be inserted toward the contralateral side using sub-spinous process space. The camera's eye with 15 view angles can be put closer to the opposite side lesion, providing high-definition images on a video monitor for the operator (4, 22). Therefore, it makes the removal of excessive adipose tissue safer and easier, facilitating the reduction of the possibility of dura tear and neural damage.

Thanks to the high-definition vision of endoscopy, we had an interesting discovery during the operation. We found that there were many bands among the dura, ligamentum flavum, and nerve roots in the epidural space (**Figures 6E,F**). These bands separated the epidural space into multitudinous small spaces, and the hyperplastic adipose tissue was bound in these small spaces. It can explain why although adipose tissue is soft, it causes compression of the nerve roots and dura sac (**Figure 7**). In this case, the thecal sac has a striking stellate appearance on lumbar axial imaging. Kuhn et al. named this configuration as the "Y-sign" which is characteristic of lumbar SEL (23). The stretch action of these bands may interpret the "Y-sign." During the operation, cutting off these bands to eliminate the stretch action is very important to release the compression of the sac and nerve roots. Cutting off these bands also makes it easier to remove fatty tissues and reduces bleeding and dura involvement. Frank reported an endoscopic suction technique for the treatment of idiopathic epidural lipomatosis (24). In his article, he noted that sharp microsurgical techniques should be used in the area that the fat was well vascularized and adherent to the dura. Otherwise, suction of adipose tissue is insufficient to achieve success. Our experience verified that in current uniportal full-endoscopy technology, all the procedures can be accomplished in a single channel.

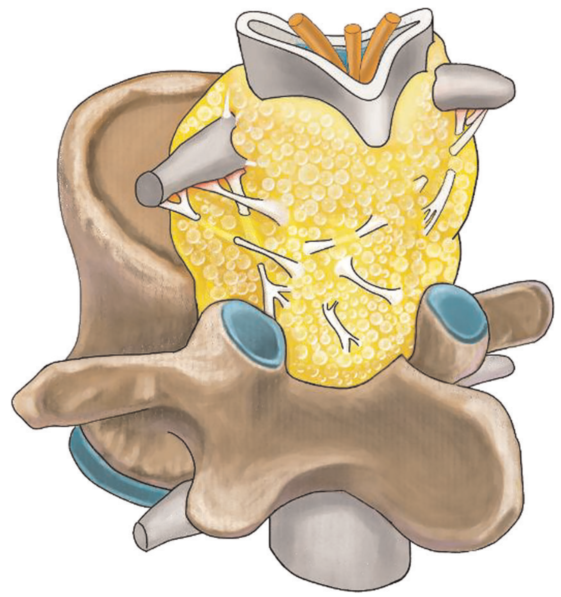

FIGURE 7
Illustration showing mechanisms of compression of the nerve roots and dura sac in spinal epidural lipomatosis.

Limitations

To our knowledge, we reported the first use of percutaneous uniportal full-endoscopic decompression for the treatment of lumbar SEL disease. The limitation of this article is obvious, which is a case report without enough follow-up time.

However, this article aims to validate the feasibility of percutaneous full-endoscopic uniportal decompression for the treatment of symptomatic idiopathic spinal epidural lipomatosis. We believe that it can be used as a reference for other doctors who are going to employ this technique.

Conclusion

The case with SEL was successfully treated with a percutaneous full-endoscopic uniportal surgery, which has the advantages of excellent presentation of anatomical structures, expanded field of vision, less surgical-related trauma, and bleeding. The key point of the procedure is to release and cut off the bands which divide the epidural space into small rooms filled with excess adipose tissue.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

Ethics statement

Written informed consent was obtained from the individual (s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

All authors have read and approved the final submitted manuscript. The following is the author's contribution: YY and YJ contributed to research design, acquisition, FX and LY analysis and interpretation of data; YM and CL analyzed and measure the radiological outcomes; YY drafted the manuscript and revised it critically. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Mapping knowledge structure and themes trends in unilateral biportal endoscopic spine surgery: A bibliometric analysis

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Background: The numerous benefits of unilateral biportal endoscopic (UBE) spine surgery have attracted the attention of many researchers, and a considerable number of relevant clinical studies have been published. However, global research trends in the field of UBE have received little attention. The purpose of this study was to apply bibliometric method to analyze the UBE-related publications to obtain an overview of the research trends in the field of UBE, as well as research hotspots and trends.
Methods: Web of Science database was searched for articles published until January 31, 2022. CiteSpace was used to analyze the data, which provided graphical knowledge maps. The following factors were applied to all literature: number of publications, distribution, h-index, institutions, journals, authors, and keywords.
Results: Seventy-three articles were identified. Since 2019, there has been a significant increase in the number of UBE-related publications. The country with the largest number of articles was South Korea (72.6%), followed by China (9.6%), Japan (4.1%), and Egypt (4.1%). South Korea had the highest h-index (16), followed by China (2), Japan (1), and Egypt (1). Leon Wiltse Memorial Hospital was the organization that produced the most papers (12 publications). Heo DH was the most productive author (16 papers) and was the most cited author (35 times). *World Neurosurgery* published the most papers on UBE (23.3%). The main research hotspots were spinal diseases, decompression, complications, learning curve, and interbody fusion. In addition, the recent concerns were "learning curve," "interbody fusion," "management," and "dural tear."
Conclusions: The quantity of publications on UBE research will increase, and South Korea being the major contributor and most prominent country in this field. The findings of our study will provide researchers with practical information on the field of UBE, and identification of mainstream research directions and recent hotspots.

KEYWORDS
unilateral biportal endoscopic, biportal endoscopic spine surgery, bibliometric analysis, visualization, research trends

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Introduction

With the accelerating trend of aging in society and changes in people's lifestyle and work style, the incidence of lumbar spinal diseases is gradually increasing. For patients requiring surgical treatment, traditional open surgery is highly traumatic and has many complications, and microendoscopic techniques have certain complications that do not fully meet the requirements of patients (1). The unilateral biportal endoscopic (UBE) technique is an emerging clinical treatment tool with the advantages of a wide surgical field of view and large operating space, which can be implemented *via* the interlaminar or transforaminal approach and successfully applied in treating various spinal surgical diseases (2–4). As a minimally invasive surgery, it combines the advantages of open surgery and traditional minimally invasive surgery, preserving the paravertebral muscles while operating under high-definition vision, reducing damage to the paravertebral bones, joints, and ligaments, with the advantages of less postoperative pain and early return to normal activities, and is therefore widely used in treating various spinal disorders (5–7).

As a new technique, UBE has attracted the attention of many researchers and a large number of clinical studies have been published recently. A bibliometric analysis can provide clinical researchers with practical information, including the influential countries/regions, journals, institutions, and authors in the field (8). In addition, bibliometrics helps comprehend a topic's underlying knowledge, current research hotspots, and research trends (9).

Therefore, this bibliometric study aims to analyze the published UBE-related literature to obtain an overview of the current status and trends of UBE research and to provide recommendations and suggestions for the development of related research in the future.

Materials and methods

Search strategy

Because this was a retroactive assessment of public data, no institutional committee permission was necessary. Publications were gathered from the Web of Science (WoS) Core Collection (Thomson Reuters, New York, NY, USA), which is the world's biggest academic database and has been frequently used in bibliometric research.

The publications were evaluated until January 31, 2022. The following terms were searched: "biportal endoscopic spine surgery," "unilateral biportal endoscopic surgery," "UBE," "BESS," and "two portal endoscopic spine surgery." Only original articles, reviews, and case reports were accepted; letters, editorial materials, and corrections, as well as unpublished and non-English studies, were excluded from this study. In addition, documents on unrelated topics were excluded. Two researchers independently reviewed and chose the publications. Any disagreements were resolved through third-party discussions until consensus was reached.

To conclude the bibliometric investigation, we deployed CiteSpace to construct data tables and visual knowledge graphs for interpretation. CiteSpace is essentially built on the concept of co-citation analysis and pathfinder network scaling to evaluate the literature in a certain field so that users may discover significant advances and knowledge turning points in the discipline's history (10).

Our quantitative studies were based on the number of publications each year, nations/regions, the h-index (a legitimate and trustworthy measure for academic assessment), institutions, journals, authors, citations, and keywords. In the present study, CiteSpace was used to conduct a cooperative analysis of regions, institutions, and authors; to perform the impact of scientific journals; to analyze the top 10 most cited documents; and to identify the top 10 keywords with the strongest citation bursts. The node connection represented a relationship of cooperation, co-occurrence, or co-citation in the network maps. The links in the visualization knowledge maps between nodes reflected the cooperative ties. The thickness of the linkages and the distance between the nodes showed the extent to which prominent nations/regions, institutions, and writers collaborated.

Data examination

All data were gathered and entered into Microsoft Excel 2021 (Microsoft). CiteSpace was used to quantify data, display cooperation networks in various layouts, and create a term timeline.

Results

Annual trend and current situation

Initially, the WoS database contained 89 articles on the subject of UBE. Seventy-three publications were chosen after manual screening. The number of publications in the field of UBE rapidly rose in the past 3 years (**Figure 1**). In 2020, 23 articles were published; this number was the most in a single year in the previous decade. The number of publications about UBE is steadily rising, indicating that more attempts and explorations in UBE are being made.

Analysis of countries/regions

In the field of UBE, 10 countries have conducted studies throughout the study period (**Table 1**). South Korea

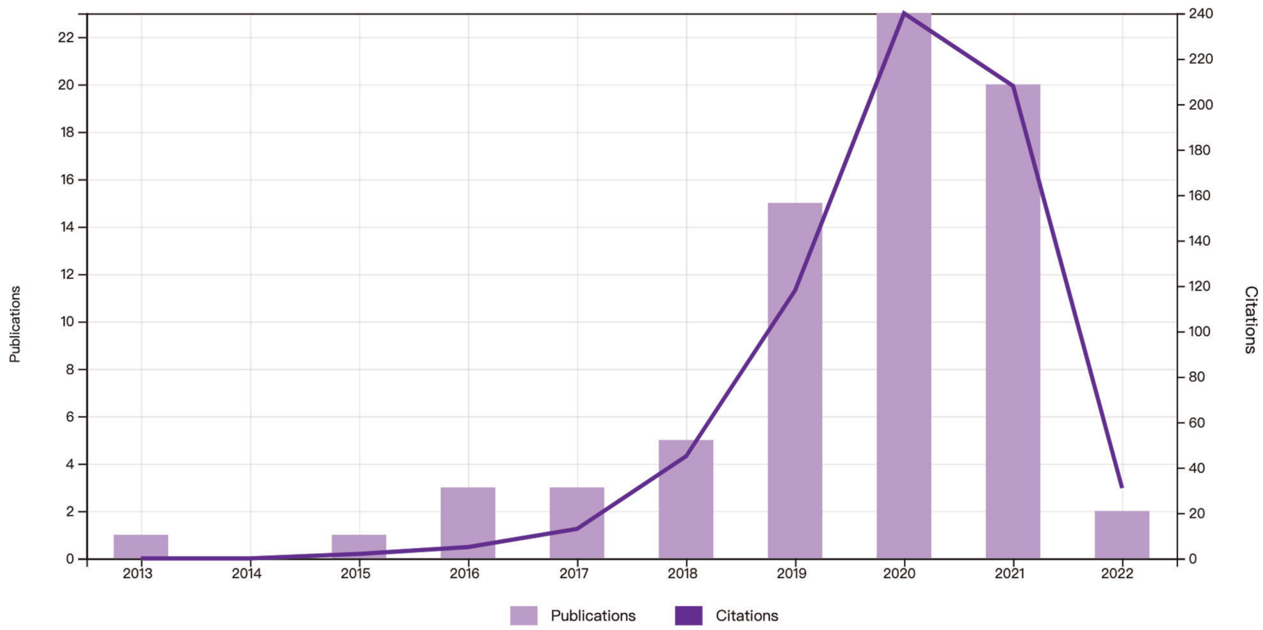

FIGURE 1
The annual trends of publications.

TABLE 1 The most productive countries/regions contributed to research publications in the field of unilateral biportal endoscopic spine surgery.

Rank	Country	Number	Percentage	h-Index
1	South Korea	53	72.6	16
2	China	7	9.6	2
3	Japan	3	4.1	1
4	Egypt	3	4.1	1

produced the most publications (53 of 73, 72.6%), followed by China (7 of 73, 9.6%), Japan (3 of 73, 4.1%), and Egypt (3 of 73, 4.1%). South Korea has the highest h-index at 16, followed by China (2), Japan (1), and Egypt (1). The map of the country's network had 40 nodes and 40 links (Figure 2).

FIGURE 2
Co-operation network of the productive countries/regions.

Analysis of institutions

Table 2 shows the most productive institutions in the field of UBE. Of the 73 publications, Leon Wiltse Memorial Hospital published 12 articles (16.4%), followed by Hallym University, which published 10 articles (13.7%); Himchan Hospital, which published seven articles (9.6%); and Himnaera Hospital, Seoul Bumin Hospital, and Yonsei University, which published seven articles (9.6%). The institution network map has 81 nodes and 139 connections (Figure 3).

Analysis of journals

UBE was featured in 25 scientific journals during the research period. *World Neurosurgery* published the most articles regarding UBE (17 articles, 23.3%) (Table 3), followed by *Acta Neurochirurgica* (9 articles, 12.3%), *Journal of Orthopaedic Surgery and Research* (5 articles, 6.8%), *Neurospine* (5 articles, 6.8%), and *Spine Journal* (5 articles, 6.8%). Articles published in these essential journals received more attention and therefore were referenced more frequently.

TABLE 2 The most productive institutions in the field of unilateral biportal endoscopic spine surgery.

Rank	Institution	Number	Percentage
1	Leon Wiltse Memorial Hospital	12	16.4
2	Hallym University	10	13.7
3	Himchan Hospital	7	9.6
4	Himnaera Hospital	7	9.6
5	Seoul Bumin Hospital	7	9.6
6	Yonsei University	7	9.6

FIGURE 3
Co-operation network of the productive institutions.

TABLE 3 Top 5 productive journals in the field of unilateral biportal endoscopic spine surgery.

Rank	Journal	Number	Percentage
1	World Neurosurgery	17	23.3
2	Acta Neurochirurgica	9	12.3
3	Journal of Orthopaedic Surgery and Research	5	6.8
4	Neurospine	5	6.8
5	Spine Journal	5	6.8

Analysis of authors

Heo DH was the most productive author in the field of UBE (Table 4), publishing 16 articles (21.9%); Choi DJ published 11 articles (15.1%), Park CK published 10 articles (13.7%), Chung HJ published 9 articles (12.3%), and Park HJ wrote 9 articles (12.3%). The cited author network's map has 263 nodes and 1,080 linkages (Figure 4). The most frequently cited author (35 times) was Heo DH, followed by Eum JH (26 times), Kim JE (25 times), Choi DJ (22 times), and Choi KC (18 times).

TABLE 4 Top 5 productive authors in the field of unilateral biportal endoscopic spine surgery.

Rank	Author	Number	Percentage	Affiliation
1	Heo DH	16	21.9	Leon Wiltse Memorial Hospital, South Korea; Seoul Bumin Hospital, South Korea
2	Choi DJ	11	15.1	Himnaera Hospital, South Korea
3	Park CK	10	13.7	Leon Wiltse Memorial Hospital, South Korea
4	Chung HJ	9	12.3	Seoul Bumin Hospital, South Korea
5	Park HJ	9	12.3	Hallym University, South Korea

Analysis of references and citations

The top ten most cited articles are presented in Table 5. An article's highest and lowest numbers of citations were 74 and 22, respectively. Nine of the top 10 most cited articles were from South Korea, whereas the remaining article was from Egypt. Heo DH has four articles on this list. Three articles were published in *World Neurosurgery* or *Neurosurgical Focus*, respectively. The network map of the references mentioned has 181 nodes and 744 linkages (Figure 5). The top 5 most frequently referenced article was Eum JH et al. (2016) (26 times), followed by Heo DH et al. (2017) (18 times), Choi DJ et al. (2016) (15 times), Kim SK et al. (2018) (13 times), and Choi CM et al. (2016) (12 times).

Analysis of keywords and research hotspots

Keyword lists can effectively discover research hotspots and provide research assistance. Bigger nodes in the keyword co-occurrence map had larger keyword weights. Shorter distances between nodes suggested stronger connections between those nodes. Thicker lines indicated a higher frequency of two words being mentioned together. As shown in Figure 6, the main research hotspots were as follows: spinal diseases, decompression, complications, learning curve, and interbody fusion.

"Keyword bursts" were an indication of research frontier themes throughout a certain period. Figure 7 shown the top 10 keywords with the strongest citation bursts in the UBE field. The red bar corresponded to the time of keyword appearance and duration of presence. The recent concerns were "learning curve," "interbody fusion," "management," and "dural tear."

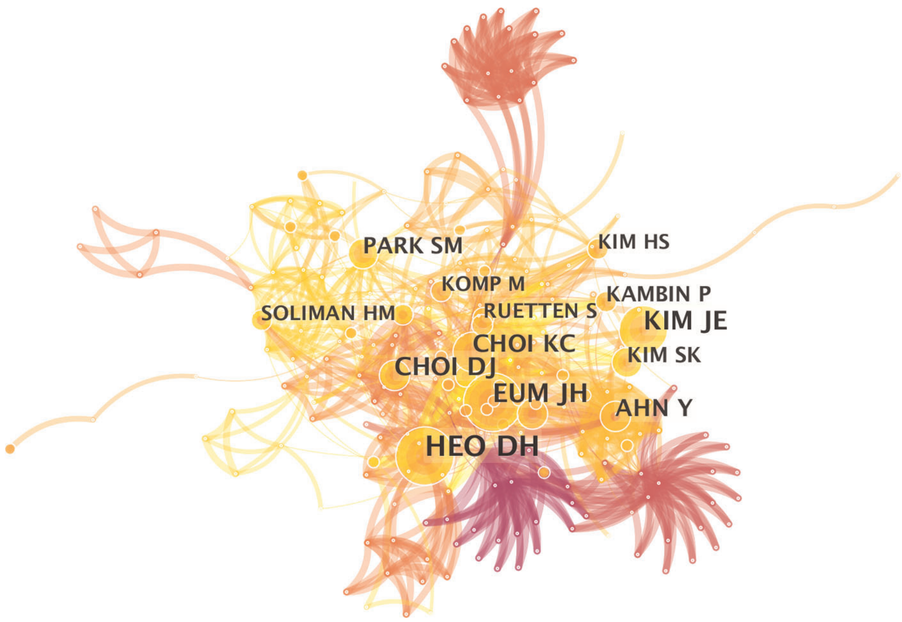

FIGURE 4
Co-operation network of the cited authors.

TABLE 5 Top 10 cited articles in the field of unilateral biportal endoscopic spine surgery.

Rank	Title	Author	Journal	Year	Citation
1	Percutaneous biportal endoscopic decompression for lumbar spinal stenosis: a technical note and preliminary clinical results	Eum JH et al.	Journal of Neurosurgery-Spine	2016	74
2	Fully endoscopic lumbar interbody fusion using a percutaneous unilateral biportal endoscopic technique: technical note and preliminary clinical results	Heo DH et al.	Neurosurgical Focus	2017	68
3	How I do it? Biportal endoscopic spinal surgery (BESS) for treatment of lumbar spinal stenosis	Choi CM et al.	Acta Neurochirurgica	2016	36
4	Irrigation endoscopic decompressive laminotomy	Soliman HM et al.	Spine Journal	2015	36
5	Comparison of surgical invasiveness between microdiscectomy and 3 different endoscopic discectomy techniques for lumbar disc herniation	Choi KC et al.	World Neurosurgery	2018	31
6	Can percutaneous biportal endoscopic surgery achieve enough canal decompression for degenerative lumbar stenosis? Prospective case-control study	Heo DH et al.	World Neurosurgery	2018	30
7	Learning curve for lumbar decompressive laminectomy in biportal endoscopic spinal surgery using the cumulative summation test for learning curve	Park SM et al.	World Neurosurgery	2019	27
8	Comparative analysis of three types of minimally invasive decompressive surgery for lumbar central stenosis: biportal endoscopy, uniportal endoscopy, and microsurgery	Heo DH et al.	Neurosurgical Focus	2019	26
9	Clinical results of percutaneous biportal endoscopic lumbar interbody fusion with application of enhanced recovery after surgery	Heo DH et al.	Neurosurgical Focus	2019	23
10	Biportal endoscopic versus microscopic lumbar decompressive laminectomy in patients with spinal stenosis: a randomized controlled trial	Park SM et al.	Spine Journal	2020	22

Discussion

UBE is a percutaneous endoscopic technique that uses two channels, one for endoscopy and one for instrumentation, which is the major difference from the traditional single-portal endoscopic technique (11, 12). The UBE procedure is mainly used for endoscopic treatment of spinal stenosis, cervical spondylosis, thoracic spine lesions, and degenerative lesions of the lumbar spine (13–15). Since two channels are used, the operating instruments are not limited in size; thus, the UBE technique is an efficient technique among various minimally invasive spine techniques, and the treatment results are as thorough as those of open surgery, with certainty of efficacy, less trauma, and faster recovery (16, 17).

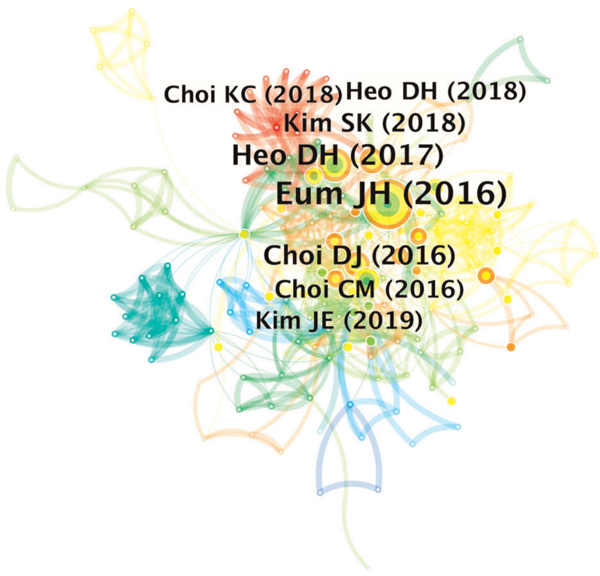

FIGURE 5
Co-operation network of the cited references.

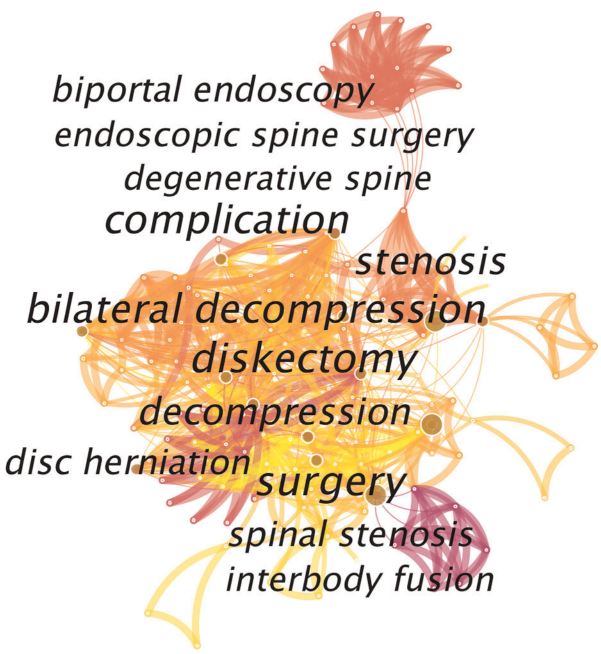

FIGURE 6
Co-operation network of the keywords.

Additionally, traditional single-portal endoscopic techniques can address a small percentage of spinal stenosis cases, a large percentage of which are not operable, and the UBE technique with unilateral dual access can better address cases of spinal stenosis. The UBE technique is complementary to the single-portal endoscopic technique and can be used for partial vertebral instability and minor slippage, as well as for endoscopic spinal fusion, which has a broader range of indications (12).

The merits of the UBE technique have brought more attention to spine surgeons, as evidenced by the increase in clinical studies in recent years. To confirm the comprehensiveness of the publications, we conducted a bibliometric study of publications in the WOS database. Our results will provide researchers with practical information on the field of UBE, and identification of mainstream research directions and recent hotspots.

This study found a consistent increase in the quantity of UBE-related publications recently, particularly after 2019. This pattern demonstrates that UBE research is advancing quickly and has piqued the interest of the worldwide medical community. South Korea is the most productive country in the UBE field and has published the most articles and is home to almost all influential authors. Moreover, nine of the top 10 most cited articles were from South Korea. Early scholars, represented by Dr. Kambin, developed the percutaneous spinal endoscopy technique, followed by their predecessors, such as De Antoni DJ and Osman SG, who laid the theoretical and practical foundation for the “unilateral biportal spinal endoscopy” technique. Although the studies by De Antoni DJ and Osman SG have inspired some operators to trace their concepts and findings, this group of operators has embarked on a path to continue exploring dual-channel spinal endoscopy techniques. In the next decade, the unilateral biportal endoscopic technique will enter a period of rapid development driven by Korean spine surgeons, and many improvements were made, as follows: (1) changing the patient’s position from lateral to prone; (2) starting to use radiofrequency, which improved the efficiency of handling soft tissue; (3) further expanding the indications for the procedure, adding spinal disk herniation, spinal stenosis, spondylolisthesis, and fusion (cervical-thoracic-lumbar spine can be applied); and (4) formalizing the procedure as UBE. The contribution of Korean doctors to the inheritance, pioneering, and development of the UBE technique has made them well known internationally. This has led several spine surgeons to go to South Korea for further training and study.

According to the network map, countries/regions, institutions, and authors were all somewhat connected; however, the map shows a weak relationship, indicating a lack of cooperation between countries/regions and institutions. International academic cooperation between countries/regions and institutions must be strengthened. This technique may benefit all countries/regions and institutions.

World Neurosurgery, *Acta Neurochirurgica*, *Journal of Orthopaedic Surgery and Research*, *Neurospine*, and *Spine Journal* were the top five journals that have published the most UBE-related articles, suggesting that these journals are more friendly to the publication of UBE-related articles. The 10 most cited

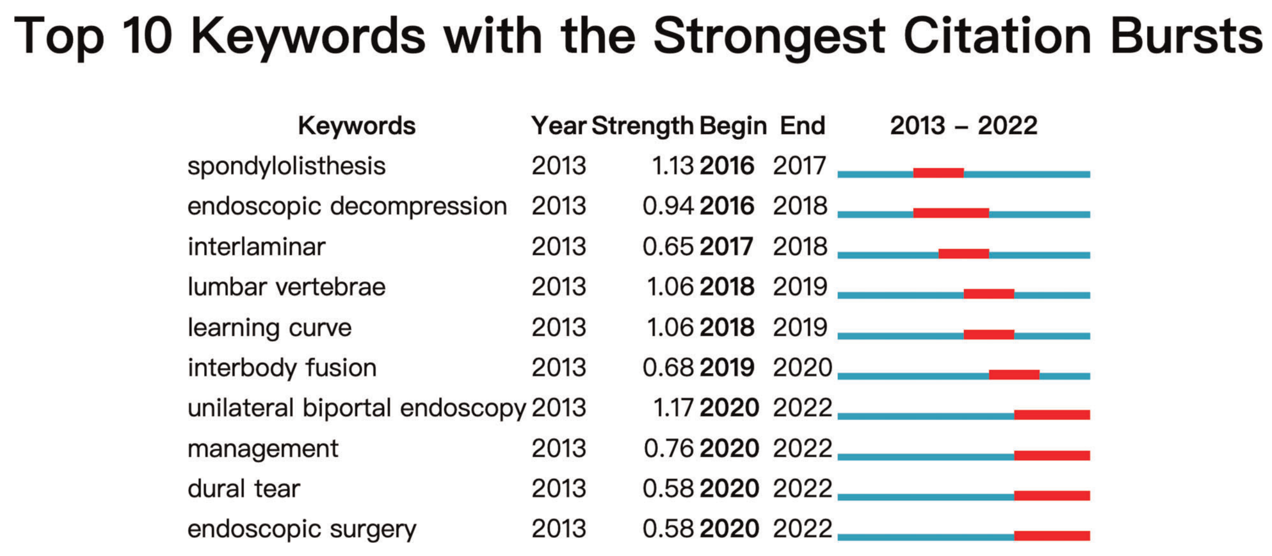

FIGURE 7
Top 10 keywords with the strongest citation bursts.

articles were from the aforementioned journals, with *World Neurosurgery* and *Neurosurgical Focus* being the top two journals. These journals represented the core journals in the field of UBE and should be followed to track relevant research trends.

Keywords not only represent the research focus and hotspots in a field, but also allow the discovery of research trends through keywords. According to top 10 keywords with the strongest citation bursts, the focus of UBE research includes the use of UBE in treating various lumbar spine diseases, prevention and treatment of complications, interbody fusion, and learning curve. UBE has recently evolved as a prominent lumbar surgical method; however, it must be used with objectivity and prudence to maximize its advantages and avoid its risks.

The UBE technique has more obvious technical advantages than the one-portal endoscopic surgical method. First, the UBE technique provides a larger and more open field of view under the mirror because the UBE procedure has a dual channel: one side of the main mirror is under 0°, the mirror field of view is 360° visible. Second, the grasping forceps and biting forceps used are thicker and have larger openings, which can remove the protruding nucleus pulposus faster and easier (18). The third reason is that the UBE technique can be visualized and the learning curve is relatively simple, especially if the surgeon can operate a one-portal endoscopic surgery or has experience in microscopic surgery. In addition, if the fusion is done under the endoscopy, the UBE technology can be visualized throughout the operation, and interbody cage placed directly under visualization, which greatly reduces the issue of intraoperative localization and radiation. In contrast, the single-portal technique for placing interbody cage is not visualizable and has a higher number of intraoperative localizations (19–21). A recent meta-analysis (6) has reported no significant differences in visual analog scale scores for the legs, Oswestry Disability Index scores, complications, or fusion rates between UBE interbody fusion and conventional lumbar interbody fusion surgery. Notably, the UBE interbody fusion surgical technique had considerably lower postoperative visual analog scale values for back pain than the traditional lumbar interbody fusion surgery. Furthermore, UBE interbody fusion took a longer operating time than traditional lumbar interbody fusion surgery but resulted in much less blood loss (6).

The most common complications of UBE were dural tears and hematomas, which were consistent with the findings of a previous systematic study (22, 23). A rupture in the dura is a serious issue. Endoscopic surgery may be converted to microsurgery in situations of large-scale dura ruptures. Small intraoperative durotomies can be sutured using sealant materials (TachoComb or TachoSil), and the patient should be restrained (3). The most important step in lowering the occurrence of this technical issue is to keep the operation field free by preventing epidural bleeding. A high magnification of the surgical field combined with continuous saline irrigation can be used to decrease epidural hematoma. When we started removing the flavum or conducting laminectomy, we needed to ensure that there was enough water flow and bleeding control, especially on the contralateral side (24). If all other measures fail to halt the bleeding, lowering the diastolic blood pressure to approximately 100 mmHg may be effective in certain cases (24). When raising the height of the saline bag or compressing it to raise the saline pressure, using a specialized pressure pump is advised. Moreover, high-pressure irrigation is not recommended because it may increase

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intracranial pressure and may delay surgical recovery. Water pressure should be maintained between 4.41 cm H_2O (2.41 mmHg) and 31.00 cm H_2O (22.83 mmHg) during UBE to avoid iatrogenic damage (25). Furthermore, preoperative anticoagulant use, female sex, elderly age, intraoperative water infusion pump use, and surgery involving higher bone manipulation were risk factors for epidural hematoma following UBE (26, 27).

Limitations

To guarantee fairness and thoroughness and provide powerful data, we did a comprehensive literature search in the WoS datable. Despite its impressive characteristics, this study has a few flaws. First, this bibliometric analysis only included published articles from the WoS Core Collection database, which inevitably led to some useful literature not included in this study. Second, different search time points may have caused differences in the search results, especially in the number of citations. Third, for some recently published articles, the short time of publication leads to low citation counts, which may affect the total number of citations and h-index of the literature.

Conclusions

According to our results, there was a dramatic increase in the number of UBE-related publications since 2019. Most of the UBE-related research institutions and researchers are from South Korea. Heo DH is the most contributing author, and Leon Wiltse Memorial Hospital has the largest contribution in this field. *World Neurosurgery* and *Neurosurgery Focus* represented the core journals in the field of UBE and should be followed to track relevant research trends. The main research hotspots in the field of UBE were the use of UBE in treating various lumbar spine diseases, prevention and treatment of complications, interbody fusion, and learning curve.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

Author contributions

MTZ conceptualized or designed of the work; KL performed software; BSH supervision; CMC interpreted of data; GXL has written the original article. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

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Da Vinci robot-assisted laparoscopic retroperitoneal debridement for lumbar septic spondylodiscitis: A two-case report

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The anterior approach is one of the widely used surgical treatments for lumbar spondylodiscitis, but it has the disadvantages of large trauma and a high incidence of complications. Our experiences suggested that the laparoscopic retroperitoneal approach could be effective to overcome those disadvantages of the anterior approach. Herein, we report two cases of successfully treated lumbar pyogenic spondylodiscitis using a robot-assisted laparoscopic retroperitoneal approach. The technique utilizes a robot that allows a laparoscopic retroperitoneal approach while offering excellent high-definition images of three-dimensional vision. After the operation, both patients achieved good formation and fusion of the vertebrae. Preliminary evidence suggests that the robot-assisted laparoscopic retroperitoneal approach may be feasible for the treatment of lumbar spondylodiscitis.

KEYWORDS
robotics, laparoscopy, pyogenic spondylodiscitis, lumbar spine, Da Vinci surgical system®

Introduction

Pyogenic spondylodiscitis refers to the infection of intervertebral discs, cartilage endplates, and adjacent vertebrae (1). Surgical treatments of lumbar spondylodiscitis mainly include anterior and posterior approaches (1). The advantages of the anterior approach include debridement under direct vision, ensuring the removal of necrotic tissue, and effectively protecting the anterior lumbar vascular as well as other important structures, while preservation of posterior column integrity is conducive to stability after spinal surgery (2). However, trauma and high incidence of complications are two obvious disadvantages of the anterior approach (2–4). Our previous experience suggests that retroperitoneal endoscopy can effectively reduce the trauma of the anterior approach and improve the operative effect (5). Moreover, robots may be ideal surgical assistants in spinal surgery as they can achieve superior levels of precision. Multiple studies have shown that the robot-assisted technique is more accurate than the conventional method in spine surgery (6, 7). Based on the cognition above, we performed two robot-assisted laparoscopic retroperitoneal procedures for the treatment of lumbar pyogenic spondylodiscitis, which are reported as follows.

Case reports

This study was approved by the institutional review board at the authors' institution. Written informed consent was obtained from each subject. Further, these subjects and/or their families were informed that data from the cases would be submitted for publication, after which they gave their consent. This study was conducted in accordance with the principles of the Declaration of Helsinki and with the laws and regulations of China.

Case 1

The patient, a 78-year-old man, was admitted to the hospital because of lumbar pain. Two months before admission, the patient had suffered from lumbar pain without any precipitating cause, and it became obvious during nighttime, aggravated after activity. There was no fever, lower limb–radiating pain, or other symptoms. Symptomatic treatment in the local hospital did not improve the symptoms. Physical examination revealed lower lumbar spinous process tenderness and percussion pain. Lumbar spine flexion, extension, and lateral flexion were limited. There was no abnormal muscle strength and muscle tension in both lower extremities. The straight leg raising test was negative, as also the Babinski sign. The patient had a history of diabetes for 5 years and was treated with oral hypoglycemic drugs.

A routine blood test showed WBC 12.61×10^9/L, ESR 16 mm/h, and CRP 7.75 mg/L. The T-SPOT test was negative. No abnormalities were found upon the tumor series examination. Lumbar spine x-ray showed L1/2 intervertebral disc destruction; lumbar CT three-dimensional reconstruction showed lesions in the L1/2 vertebral body, intervertebral disc, and surrounding soft tissue lesions, the results from lumbar MRI scan for L1/2 vertebral body, intervertebral disc, and surrounding soft tissue were considered to show infectious lesions (**Figures 1A,B**).

A robot-assisted laparoscopic retroperitoneal approach procedure was performed. General anesthesia was performed by using tracheal intubation, ambulatory blood pressure was monitored by using arterial intubation, and dynamic CO_2 partial pressure was monitored. The patient lay on the right lateral decubitus using the Trendelenburg position with low head and low foot. The Da Vinci XI Surgical System (Intuitive Surgical, Sunnyvale, CA, USA) was placed on the head side of the patient, with the medial axis aligned to the retroperitoneal space (**Figure 2**). The placement of the working channel was planned before operation (**Figure 1C**). After routine disinfection and towel laying, the upper two transverse fingers of the iliac spine in the middle axillary line were taken as the A point to create the lens arm channel. The skin was cut about 1.5 cm longitudinally, the muscular layer and lumbar fascia were separated bluntly, and the retroperitoneal space was separated bluntly by using the fingers. A self-made air sac was inserted and injected with 600 ml of air. Then, 1 cross finger under 11 ribs and 8 cm away from point A was taken as the robotic arm channel (B point), and an 8 mm trocar for the robot was placed. The posterior line of the armpit 8 cm from the A point was taken as the C point, which was the second robotic arm channel. Point D as the auxiliary hole was between A point and C point, and a 12 mm trocar was placed. Another 12 mm trocar was placed at the A point, and CO_2 gas was added to establish the retroperitoneal air chamber after suturing the skin. The lens arm was connected to the trocar at the A point, and the two mechanical arms were connected to the trocar at the B and C points, respectively. After fixing the lens and the lens arm properly, the Maryland forceps and unipolar bending shears were fixed with the two robotic arms, respectively, and the instruments were moved into the operation area under direct vision. The peritoneum was pushed bluntly to the abdomen and the space behind the retroperitoneum was enlarged. To identify the psoas major muscle, unipolar scissors were used to separate between the psoas major fascia and peritoneum in order to expose important anterior structures of the vertebral body such as the ureter and aorta. A C-arm x-ray machine was used to guide endoscopic titanium clips to locate the diseased vertebrae, unipolar scissors were used at the anterior edge of the psoas major muscle to separate the muscle tissue and retracted psoas major muscle to expose the diseased vertebrae. Next, the paravertebral pus was cleared, the L1/2 intervertebral disc fibrous ring was cut, the necrotic nucleus pulposus and bone tissue were cleared, and local irrigation was repeated. The drainage tube was placed at the lesion through the auxiliary cannula, and the robotic arm was pulled out. L1 and L3 vertebral bodies were fixed by using a percutaneous pedicle screw system under the guidance of the C-arm. All the operative instruments are shown in **Figure 3**, which included the nucleus pulposus forceps kit, lamina rongeur kit, stripper series, curette series, endplate scraper series, and osteotome series. The length of the working section of the above-mentioned tools ranged from 25 to 35 cm, while the diameter ranged from 5 to 10 mm. These parameters ensured that the above-mentioned surgical instruments could pass smoothly through the 12 mm trocha.

Postoperative pathological examination showed suppurative inflammation, and pus and tissue culture were negative. The

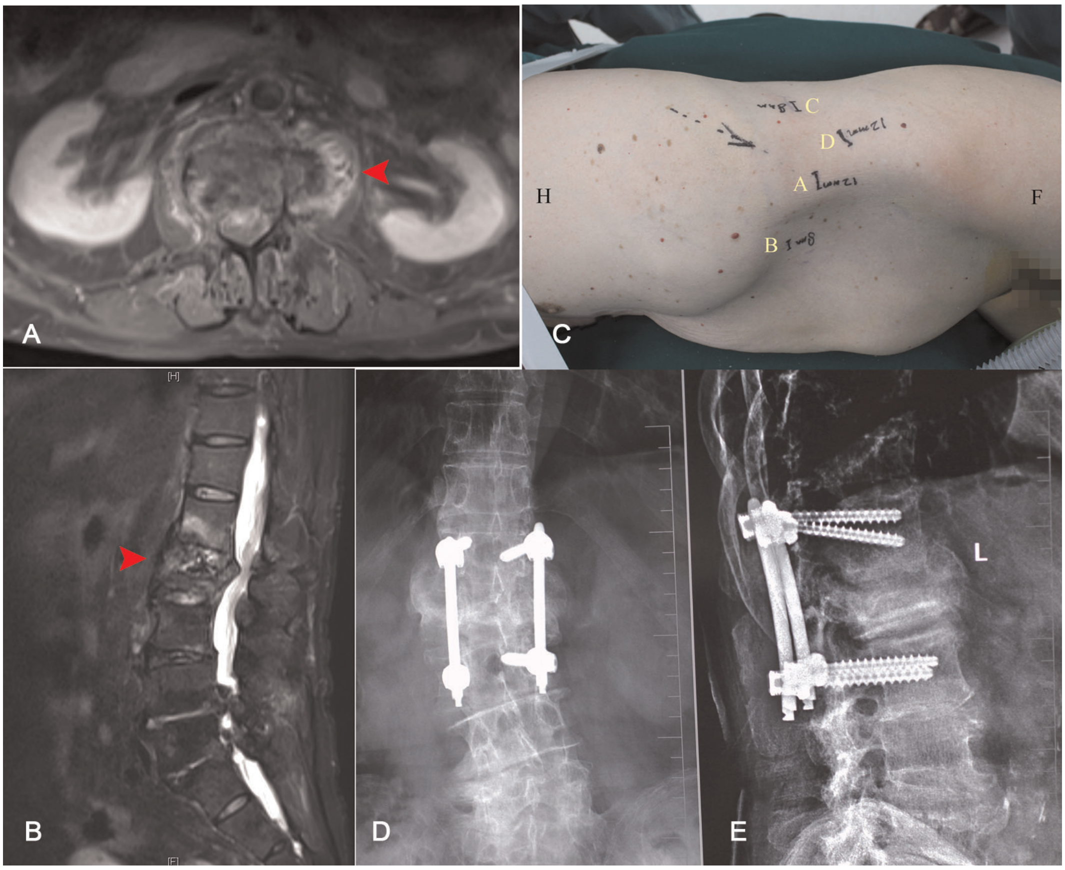

FIGURE 1
Cross section (A) and sagittal (B) T2-weighted MRI demonstrated destruction at the L1/2 intervertebral space and a partial L2 vertebral body (red arrow). The location of the working channel was planned before operation (C). Thirty months after the operation, the x-ray of the lumbar spine performed in the positive position (D) and the lateral position (E) showed the formation and fusion of the vertebrae.

patient was treated with broad-spectrum antibiotics and vacuum drainage, and the drainage tube was removed 5 days after the operation. The patient was discharged 1 week after the operation, and his lumbar pain was relieved. After discharge, the thoracolumbar scaffold and oral antibiotics were recommended for 3 months (vancomycin 15 mg/kg IV q12 h for 4 weeks and levofloxacin 500 mg PO for 8 weeks). Thirty months after the operation, x-ray examination showed intervertebral bone formation and fusion (Figures 1D,E).

Case 2

The patient, a 57-year-old woman, complained of low back pain for 20 days, and the pain was obvious during the night. Body temperature fluctuated between 37.5°C and 38.6°C.

A routine blood test showed WBC 11.03 × 109/L, ESR 53 mm/h, and CRP 45.9 mg/L. The T-SPOT test was negative. A lumbar spine MRI scan revealed infectious lesions in the L4/5 vertebral body, intervertebral disc, and surrounding soft tissues (Figures 4A,B). An operation was scheduled.

The robot was placed on the patient's caudal side, and the mid-axis aligned to the retroperitoneal space. A 15-mm incision was made 6 cm above the iliac ridge in the anterior axillary line as the A point, the retroperitoneal space was split, and an endoscope was placed. The B point and the C point were made on both 8 cm sides of the A Point to serve as mechanical arm channels. The D-point was made at L4/5 for auxiliary tools (Figure 4C). Abscess and L4/5 disc tissue were removed intraoperatively (Figures 4D,E). One-staged posterior L4-S1 pedicle screw fixation was performed. The result of postoperative tissue bacterial culture indicated Staphylococcus aureus. The antibiotic regime after the operation was vancomycin for 4 weeks and levofloxacin for 8 weeks. Lumbar x-ray 28 months after surgery showed a good internal fixation position and fusion of the L4/5 intervertebral space (Figure 4F).

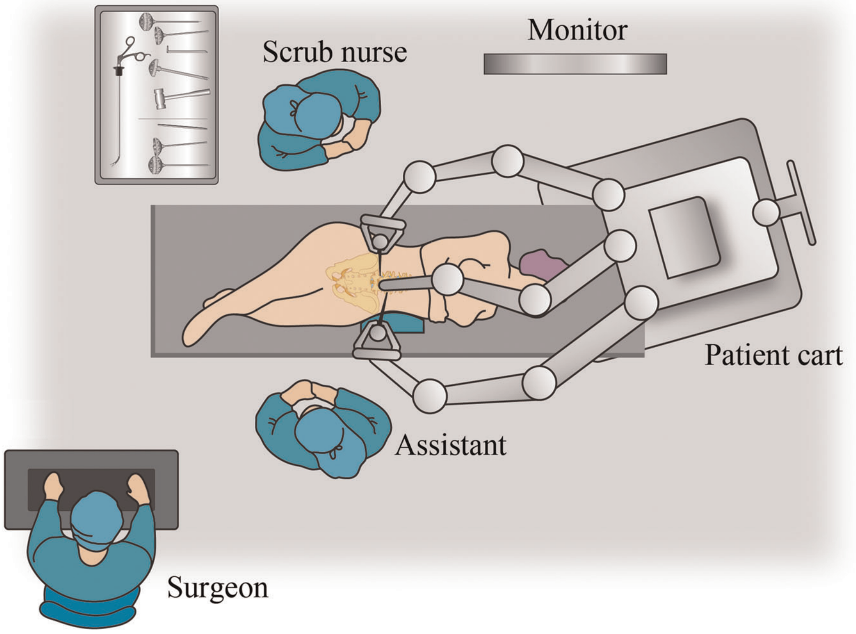

FIGURE 2
Robotic instrumentation, personnel, and operating room setup for the laparoscopic retroperitoneal approach.

Discussion

Laparoscopy technology is an important branch of minimally invasive surgery. However, its application in spinal surgery is progressing slowly. In 1991, Obenchain first used the transabdominal approach to perform anterior L5/S1 laparoscopic discectomy (8). McAfee reported retroperitoneal laparoscopic discectomy and interbody fusion in 1998 (9). In 1999, Olinger reported the retroperitoneal laparoscopic treatment of lumbar fractures that one-stage posterior pedicle screw fixation was performed, and anterior laparoscopic bone grafting and plate fixation were performed through a retroperitoneal approach (10). The lesions of these two cases were both located in the middle and anterior columns of the lumbar vertebra. This extraperitoneal approach facilitated the visualization and removal of infectious lesions as well as preventing the infection from spreading to the abdominal organs. Similarly, since 2009, laparoscopic surgery has been applied in the treatment of lumbar tuberculosis through an extraperitoneal approach. One-stage anterior debridement and bone grafting plus anterior/posterior internal fixation have achieved good results (11). Thus, laparoscopic retroperitoneal debridement is a rational strategy for treating lumbar septic spondylodiscitis located in the anterior vertebral body.

The robot system is based on laparoscopy surgery (12). It provides high-definition images of three-dimensional vision for the surgeon so that the surgeon can identify the essential anatomical structures such as the abdominal aorta, inferior vena cava, common iliac artery/vein, psoas muscle, lumbar sympathetic trunk, and superior hypogastric plexus (SHP). (13). This clear vision significantly helps surgeons to avoid injury above anatomical structures and reduce bleeding during operations. Moreover, the camera system is controlled by the robotic arm with a stable vision and a more flexible viewing angle. The level of freedom of the robotic arm and Endo-Wrist of the robot exceeds the limit of human hands, and it can perform precise movements continuously without fatigue and error during the psoas muscle separation procedure (14). In summary, the application of robots can help improve laparoscopy surgery.

In 2013, Lee et al. first reported surgery by a robot wherein the patient underwent intraperitoneal approach anterior L5/S1 discectomy plus bone grafting and internal fixation *via* laparoscopy (14). In the extraperitoneal approach, the extraperitoneal space is relatively narrow, which is not conducive to the deployment of the robotic arm, and hence there are few reports about the extraperitoneal approach of the robot (15). As mentioned above, laparoscopic retroperitoneal debridement is a rational strategy for treating lumbar septic spondylodiscitis located in the anterior vertebral body to avoid the risk of peritonitis, in contrast to the transperitoneal approach. The Da Vinci robot can further expand these advantages. Compared with conventional laparoscopy, the Da Vinci robot provides higher-resolution images of three-dimensional vision for the surgeon.

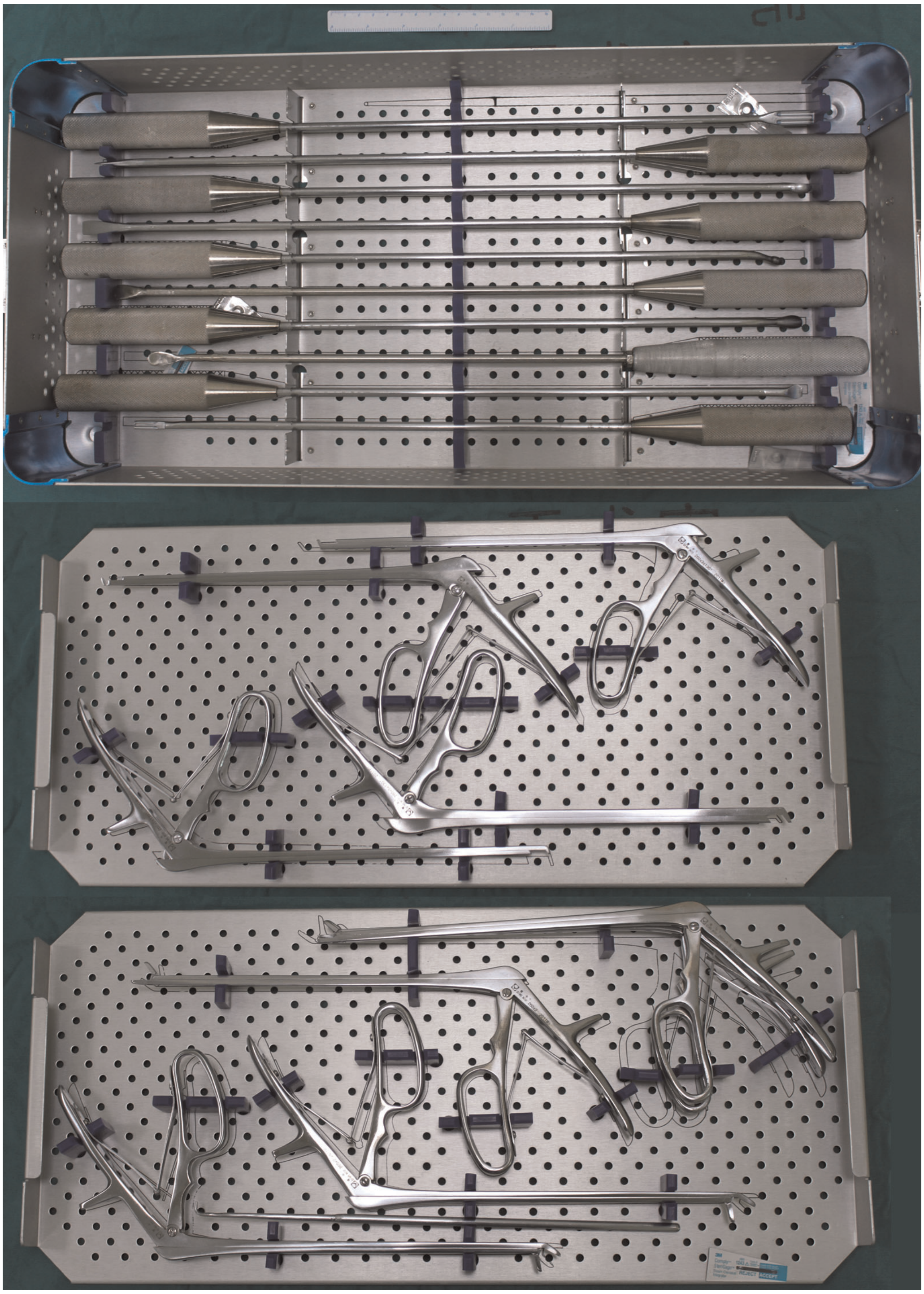

FIGURE 3
Operative instruments for robot-assisted laparoscopic retroperitoneal debridement surgery. Scale bar = 15 cm.

This is particularly important for the surgeon to clearly identify the essential anatomical structures such as the abdominal aorta, inferior vena cava, common iliac artery/vein, psoas muscle, lumbar sympathetic trunk, and superior hypogastric plexus (SHP) during the operation, since lumbar septic spondylodiscitis may make the retroperitoneal space and organs edema and adhesion which may be difficult to be identified and separated sometimes. Higher-resolution images can significantly reduce bleeding and the incidence of organ injury during operations. Moreover, the flexibility and stability of the robotic arm can

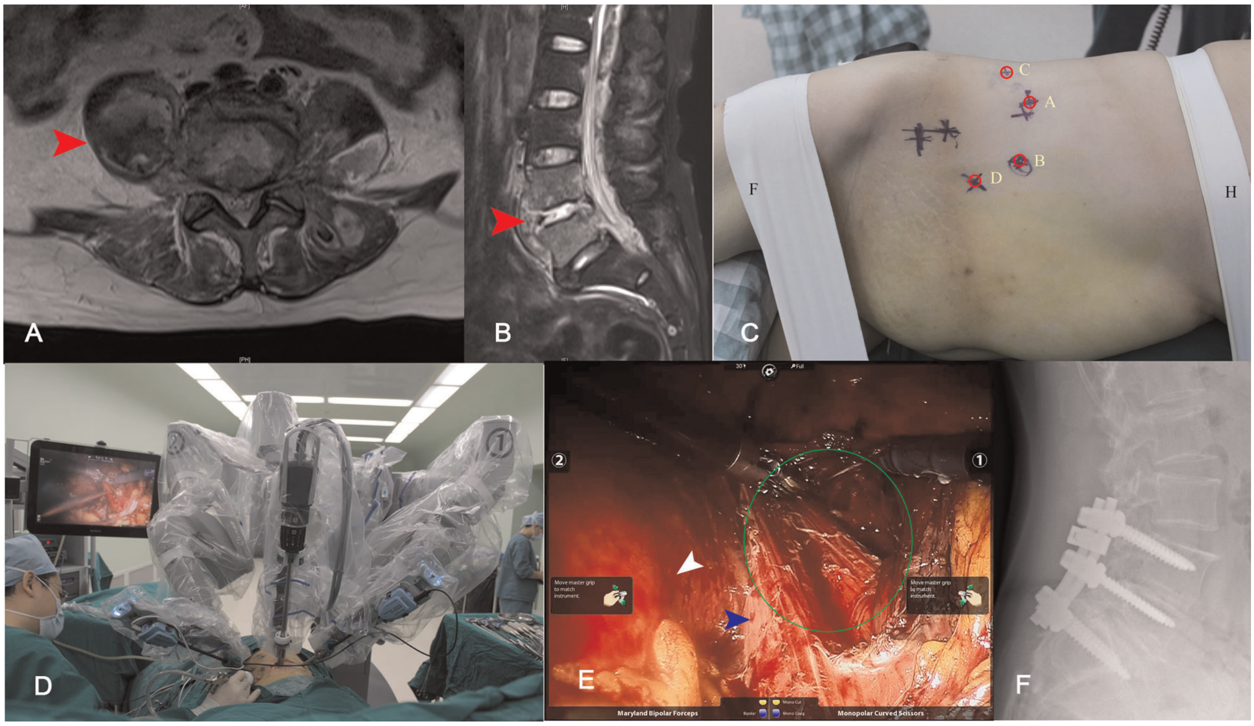

FIGURE 4
Cross section (A) and sagittal (B) T2-weighted MRI demonstrated destruction at the L4/5 intervertebral space, and a huge abscess formation at the paravertebral (red arrow). The location of the working channel was planned before the operation (C), the abscess and L4/5; the intervertebral disc tissue was removed during operation (D, E). Endoscopic view of the procedure, peritoneum (white arrow), psoas muscle (blue arrow), and abscess (green circle) (E). Twenty-eight months after operation, x-ray showed a good internal fixation position and fusion of L4/5 intervertebral (F).

further reduce the possibility of injuring vital organs as well as removing infectious lesions more effectively. Finally, we recorded the following experiences after the operations were performed successfully: (1) The space of the retroperitoneal is small, and it is easy to penetrate the peritoneum when placing point B robotic arm Trocar. When the self-made balloon expands the retroperitoneal space, 600 ml of air is injected. After removing the balloon, the peritoneum is pushed forward as bluntly as possible with the index finger, and Trocar is placed under the guidance of the index finger. (2) Obstructed by the robotic arm, the position of the assistant hole is far away from the lesion, which puts the forward higher requirement for the tool for spine surgery by laparoscopy. (3) When the location of the lesion cannot be identified during the operation, the titanium clip can be temporarily placed, the robotic arm can be removed, and the C-arm x-ray machine can be used to guide the localization in order to reduce the separation and injury of soft tissue.

At present, although this surgical technique is very efficient for soft tissue, it has limited ability for bone and other hard tissues (16). Since there are still no matching instruments for the Da Vinci robot system to handle bony structures, we have to clear the necrotic nucleus pulposus and bone tissue manually. Thus, stability and flexibility cannot be qualified during the above operative process (16). In addition, the operation cost is expensive, and the surgeon needs special training. Thus, the application value of this surgical technique in spine surgery needs further research and discussion. Moreover, developing matching instruments for the Da Vinci robot system to handle bony structures is one of our future research orientations.

Conclusion

As the number of lumbar anterior approach surgeries increased in recent years, especially in mainland China, robot-assisted surgery is still an inevitable development direction in this field. This paper shows that the lumbar operation *via* the retroperitoneal anterior approach is feasible, safe, and flexible. Given the development of manufacturing technology and the decrease in the cost related to this kind of operation in the near future, the author is optimistic about the application of robots in spine surgery.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee of Sun Yat-sen Memorial Hospital (Guangzhou, China). The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual for the publication of any potentially identifiable images or data included in this article.

Author contributions

YT supervised the project. JY, HL, and YT designed and performed the surgery. XH wrote the draft manuscript. JL and LG edited the figures. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Contralateral inclinatory approach for decompression of the lateral recess and same-level foraminal lesions using unilateral biportal endoscopy: A technical report

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Objective: Unilateral biportal endoscopic (UBE)surgery is being increasingly adopted as a minimally invasive technique. The purpose of the current study was to introduce a novel surgical technique for lateral recess and same-level foraminal decompression by the contralateral inclinatory approach with unilateral biportal endoscopy(CIA-UBE) at the lumbar level.
Methods: Between January 2020 and February 2022, 10 patients suffering from lateral recess and same-level foraminal stenosis at the lumbar level underwent UBE surgery by contralateral inclinatory approach (CIA-UBE). Magnetic resonance imaging (MRI) scans were examined after surgery to measure the cross-sectional area (CSA) of the spinal canal (CSA-SC), the CSA of the intervertebral foramen (CSA-IVF), and the CSA of the facet joint (CSA-FJ). Postoperative radiologic images using computed tomography (CT) were obtained to investigate the existence of facet joint violation. Clinical outcomes were assessed using Oswestry Disability Index (ODI) scores and visual analogue scale (VAS) scores for buttock and radicular pain.
Results: Ten levels were decompressed, and the mean age of the patients was 56.92 ± 13.26 years. The mean follow-up period was 7.60 ± 4.47 months. The average operative time was 85.14 ± 25.65 min. Postoperative CT and MRI revealed ideal neural decompression of the treated segments in all patients. CSA-IVF and CSA-FJ improved significantly, indicating good foraminal and lateral recess decompression with less damage to facet joints. Preoperative VAS and ODI scores improved significantly after surgery.
Conclusion: CIA-UBE may be an effective surgical treatment of the lateral recess and same-level foraminal stenosis at the lumbar level, which provides successful surgical decompression for traversing and exiting nerve roots with a better operative view and easier surgical manipulation. This approach may also help to maximize the preservation of the facet joint.

KEYWORDS

lumbar, UBE, foraminal and lateral recess stenosis, inclinatory, contralateral

Introduction

Lumbar lateral recess and same-level foraminal stenosis is a common disease in which degenerative changes of the vertebral column cause entrapment of traversing and exiting nerve roots (1). There are currently two major surgical treatment options for this disease: decompression with spinal fusion and decompression without fusion (2, 3). However, several disadvantages of fusion surgery, such as junctional problems, instrumental failures, pseudoarthrosis, and chronic back pain due to iatrogenic trauma, have been reported (4–6). Thus, researchers have introduced decompression without fusion using endoscopic spinal surgery (7). However, for the lateral recess and same-level foraminal stenosis, the disadvantage is that proper decompression is difficult without destroying the facet joint due to the two-level nerve roots (one nerve root at the lateral recess and another nerve root at the same level foraminal region) by endoscopic surgery.

Recently, several authors have introduced UBE surgery as a minimally invasive therapeutic option (8–10). Although UBE surgery has been developed with a wider view and more degrees of freedom, significant facet joint violations may develop after ipsilateral laminectomy, especially in areas around the lateral recess and foraminal region (11). A contralateral sublaminar approach has already been introduced in UBE surgery to preserve facet joints during decompression (12, 13). However, the current literature does no describe the contralateral inclinatory approach with unilateral biportal endoscopy at the lumbar level.

We attempted a contralateral inclinatory approach by applying a UBE surgery system to treat lumbar lateral recess and same-level foraminal stenosis pathologies. The purpose of the present study was to introduce the surgical technique of CIA-UBE and present preliminary radiologic and clinical results. To the best of our knowledge, this is the first report to describe the lumbar CIA-UBE technique at the lumbar level with patients in prone positions.

Materials and methods

Between January 2020 and February 2022, a single surgeon team performed 864 UBE surgical procedures for lumbar degenerative diseases. Among the total 864 patients, 10 patients treated *via* CIA-UBE for lumbar lateral recess and same-level foraminal stenosis were included in this study. Demographic characteristics, classification of pathologies, distribution of operation level, operative time, and surgical complications were reviewed.

The clinical results were evaluated and compared preoperatively and postoperatively using Oswestry Disability Index (ODI) and the visual analogue scale (VAS) scores for buttock and radicular pain. Pre- and postoperative radiologic images (computed tomography [CT] and magnetic resonance imaging [MRI]) were taken and compared. Preoperative CT and MRI images were examined for the extent of lateral recess and same-level foraminal compression. Postoperative CT and MRI images were recorded to evaluate the adequacy of decompression on the third day after surgery. For the morphometric analysis, the cross-sectional area (CSA) of the spinal canal (CSA-SC), the CSA of the intervertebral foramen (CSA-IVF), and the CSA of the facet joint (CSA-FJ) at the level of foraminal decompression were measured with T2-weighted MRI. CSA-SC was measured using an imaginary line encircling the area between the facet and the lamina. CSA-IVF was measured using an imaginary line around the neural foramen on the symptomatic side of the parasagittal cuts. CSA-FJ was measured using an imaginary line surrounding the facet joint at the affected foraminal compression. All areas were expressed in square millimeters (**Figure 1**).

Statistical analyses

Statistical calculations, including means and standard deviations, were obtained using SPSS version 17.0. Paired *t*-

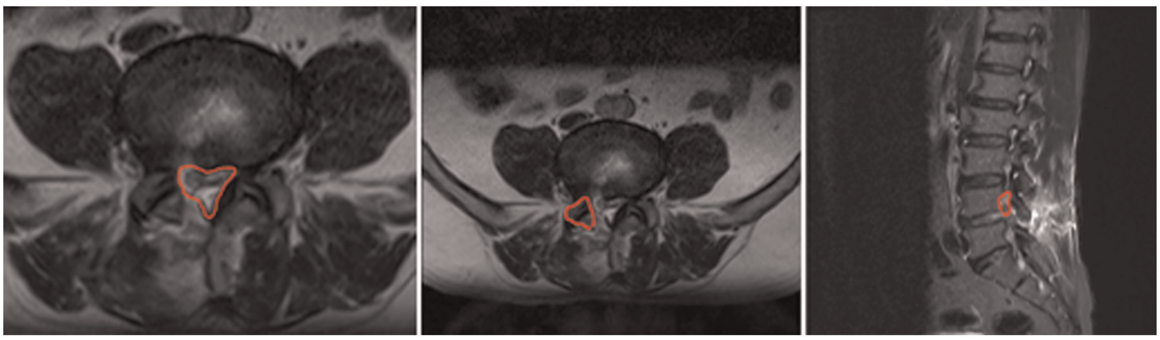

FIGURE 1
Method of the measurement of CSA-SC, CSA-IVF, and CSA-FJ.

tests were used to compare the differences in each parameter of the perioperative outcome. Statistical significance was established at a *p*-value of less than 0.05.

Indications and contraindications

CIA-UBE was indicated in the patients suffering from unilateral radiculopathy with a diagnosis of degenerative lumbar spinal stenosis at two contiguous levels (one nerve root at the lateral cress and another nerve root at the adjacent level in its foraminal region), which correlated to the neurologic distribution of pain and dysesthesia. All enrolled patients have suffered from unilateral radiculopathy with associated neurogenic claudication and have undergone all conservative measures including bed rest, physiotherapies, and medications, for a minimum of 6 weeks with no alleviation of symptoms. All patients underwent selective nerve root block, indicating that both lesions were pathologic.

The exclusion criteria were the presence of segmental instability, spinous process deviation or hypertrophy, severe kyphosis or rotatory scoliosis, central stenosis with bilateral leg pain, and patients with extraforaminal ruptured discs.

Preoperative evaluation

Patients were routinely evaluated with anteroposterior, lateral, oblique, and dynamic x-rays to assess spine alignment, disc space height, foraminal bony encroachment, and instability. Additional radiographic evaluations, such as MRI and CT, were performed to evaluate the degree of foraminal stenosis and acquire detailed information about the facet joint, such as the degree of joint hypertrophy, tropism, size and shape of the bony spur, and inclination angle of the spinous process. This allowed the surgeon to determine the amount of facet joint resection and approach angle for ideal decompression with the preservation of segmental stability.

Surgical technique

Instruments used in CIA-UBE

During the operation, we used a 30° 4-mm-diameter arthroscope (Smith & Nephew, USA), a 90° 3.75-mm radiofrequency ablator, and a 1.4-mm microablator radiofrequency probe (Bonss Medical, Jiangsu Bonss Medical Technology Company., Ltd., China). We also used instruments such as 3-mm-diameter straight and curved round burr (Guizhou Zirui Technology Co. Ltd., China), 3-mm curved curettes, and 3-mm straight and curved chisels.

Surgical procedure

Anesthesia and patient positioning

The patient was placed in a prone position with flexion on a radiolucent frame under general anesthesia. The abdomen was relaxed using an H-shaped pillow to avoid increased abdominal pressure. The entire posterior back was prepared with an antiseptic solution and draped with a waterproof surgical drape.

Skin incisions and making portals

The contralateral side means the surgeon should stand on the opposite side of the lesion, and two portals were created at the lesion side over the spinal process. If the patient had a right side lesion, the operating surgeon stood on the left side, and the procedure was performed on the right (lesion) side *via* an inclinatory operative trajectory (**Figure 2**). Under the guidance of C-arm fluoroscopy, two skin incisions were made in the vicinity of the spinous process. The first 0.5 cm-long skin incision for a cranial portal (viewing portal) was made at the level of the lower third of the upper lamina, while the other 1 cm-long skin incision for a caudal portal (working portal) was made at the level of the upper third of the pedicle of the distal vertebra on the C-arm lateral view. Both incisions were made obliquely along the multifidus muscle, and the distance between these two incisions was about 2–3 cm (**Figure 3**).

Insertion of the endoscope and preparation of the surgical field

Serial dilators were passed down along the spinous process and the lamina to dissect the back muscle and acquire operative space. After triangulation with the instruments on the margin of the superior laminar and medial points of the facet joint, the localization was confirmed with anteroposterior and lateral views (**Figure 4**). A 30° endoscope was inserted through the viewing portal, and a 1.7 m-high saline irrigation system from the operating room floor was applied to create the initial working space. Surgical instruments were inserted through the caudal working portal after inserting the cannula.

Laminotomy for making interlaminar working window

Soft tissues overlying the lamina and the ligamentum flavum were ablated to expose the bone edge in the targeted interlaminar space. After complete exposure of the medial point of the facet joint, the inferolateral portion of the upper lamina, and the superolateral part of the lower lamina, keyhole laminotomy was performed with endoscopic drills and Kerrion punches. The medial boundary of the working zone was the spinolaminar junction of the adjacent lamina. Because the proximal origin of the ligamentum flavum is Y-

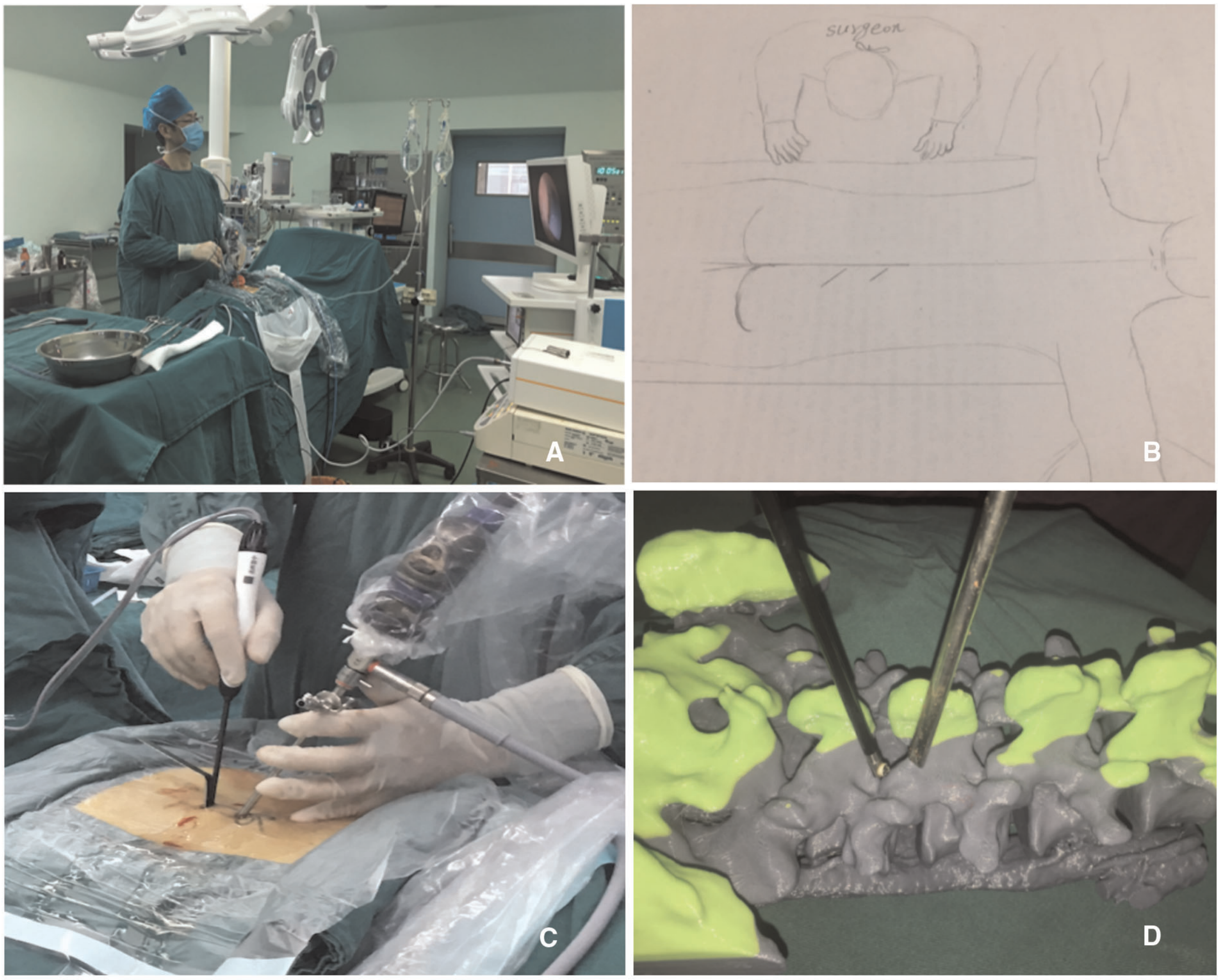

FIGURE 2
Surgeon's operative position and schematic illustration of operative setup. (A) If the patient has a right side lesion, the operating surgeon stands on the left side and the procedure is performed on the right (lesion) side *via* inclinatory operative trajectory (position for a right-handed surgeon); (B) schematic illustration of the operation setup; (C) intraoperative views of contralateral Inclinatory approach to the lesion side over the midline of spinous process and the angle of scope and instruments; and (D) inclinatory operative trajectory is simulated on the artificial lumbar spine model.

shaped, laminoplasty of the upper laminae should be extended more cranially on the lateral border until the flavum edge is freed. The laminotomy of the lower was performed until full exposure of the ligamentum flavum. The operator should try to make the keyhole wide enough for easier handling of endoscopic instruments, and the deeper ligament flavum should be preserved to protect the neural structure during drilling.

When the laminotomy of the upper and lower laminae was finished, by manipulating and tilting the endoscope, the undercutting of the medial point of the facet joint could be achieved by using a bendable 3-mm diamond burr. Thereafter, the interarticular plane of the superior articular process was revealed after the remnant thin bony eggshell was removed by a curette. After determining the medial part of SAP and the lateral recess, a thin bone osteotome, an up-curved chisel, and a Kerrison laminectomy punch can be used to cut the osteophytes and unroof the lateral recess (**Figures 5A,B**).

Flavectomy and decompression

After sufficient bony decompression and the plane between the flavum and dura was defined carefully, flavectomy by piecemeal started from the midline of the thecal sac toward the lateral and from the cranial to the caudal. The edge of the flavum ligamentum was dissected from the bone margin with a small Kerrison laminectomy punch and up-curved curettes.

After the flavum ligamentum was removed, the spinal canal, along with the lateral margin of the dural sac, was clearly seen. After the nerve root adjacent to the dural sac was identified, an attempt at further facet undercutting down to the medial wall of

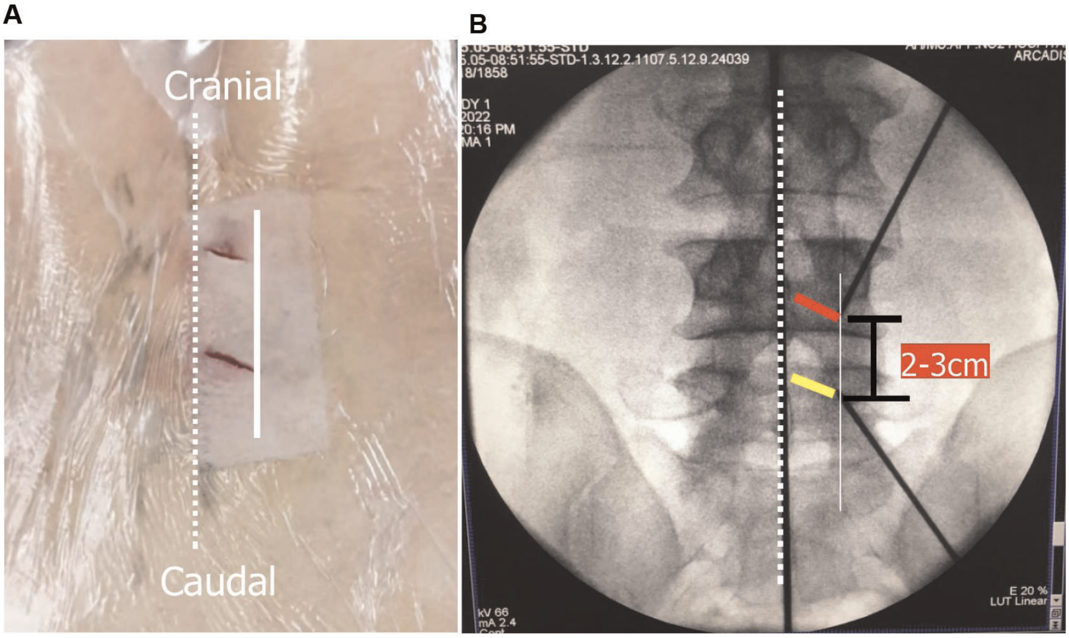

FIGURE 3
Initial placement of two portals and related anatomy. (A). Skin entry points for two portals; and (B) position of two portals on an anteroposterior view of x-ray (yellow line: the site for placement of the cranial portal; red line: the site for placement of the caudal portal; dotted line: midline; white line: medial pedicular line).

the pedicle was made to achieve lateral recess decompression until the traversing root was satisfied exposed (Figures 5C–F). In cases where the exiting root was compressed by a protruded or ruptured disc, a discectomy was required. It could be performed using pituitary forceps after adequately exposing the shoulder regions of the traversing root. Cranial foraminal decompression and adhesiolysis proceeded until the exiting root was exposed. In the case of severe foraminal stenosis, which requires wider decompression of the exiting root, the cranial tip of the superior articular process was

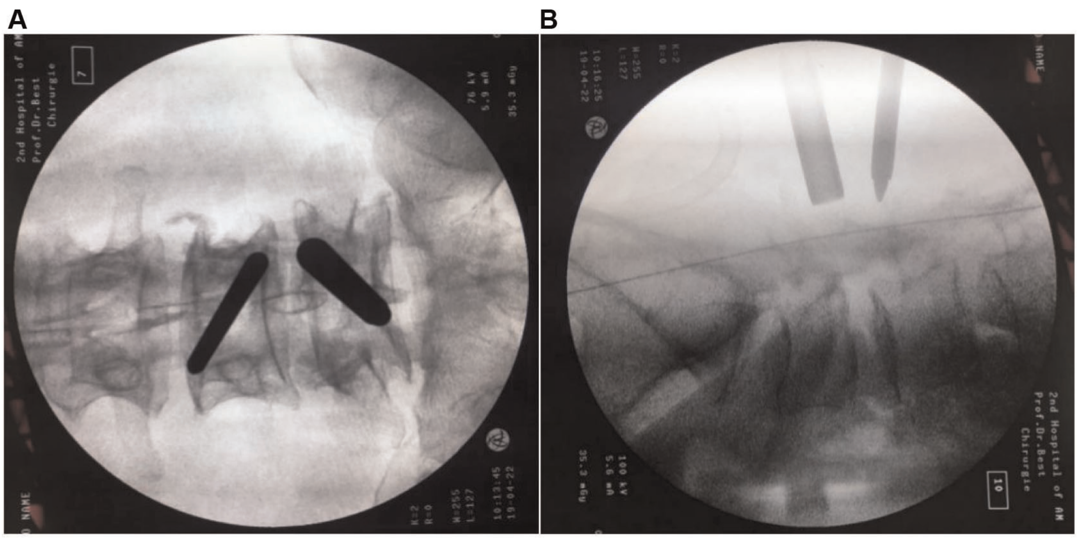

FIGURE 4
Intraoperative fluoroscopic confirmation of metal rods. Triangulation of metal rods is done at the docking point (the medial of facet joint) under the C-arm: anteroposterior (A); and lateral views (B).

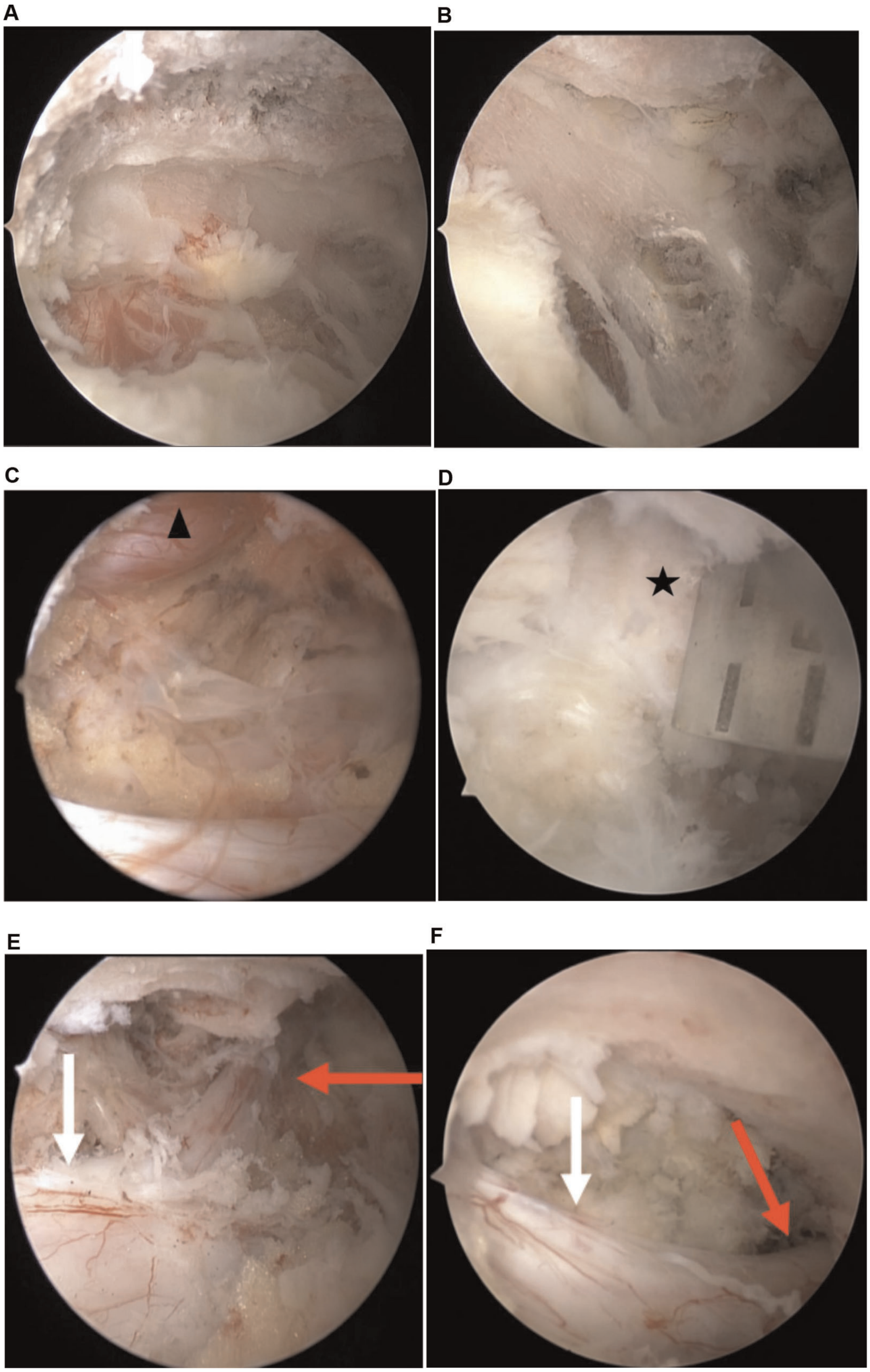

FIGURE 5
Operative illustrations in the endoscopic view. (A) Laminotomy of the crania; (B) laminotomy of the cauda; (C) cranial tip of the superior articular process is cut by an angled chisel; (D) decompressed exiting root in foraminal is observed; (E) thecal sac and shoulder margin of traversing root were revealed; (F) decompressed traversing root is demonstrated (black Asterisk: cranial tip of the superior articular process; black triangle: L5 exiting root; red arrow: L5 traversing root; black arrow: thecal sac).

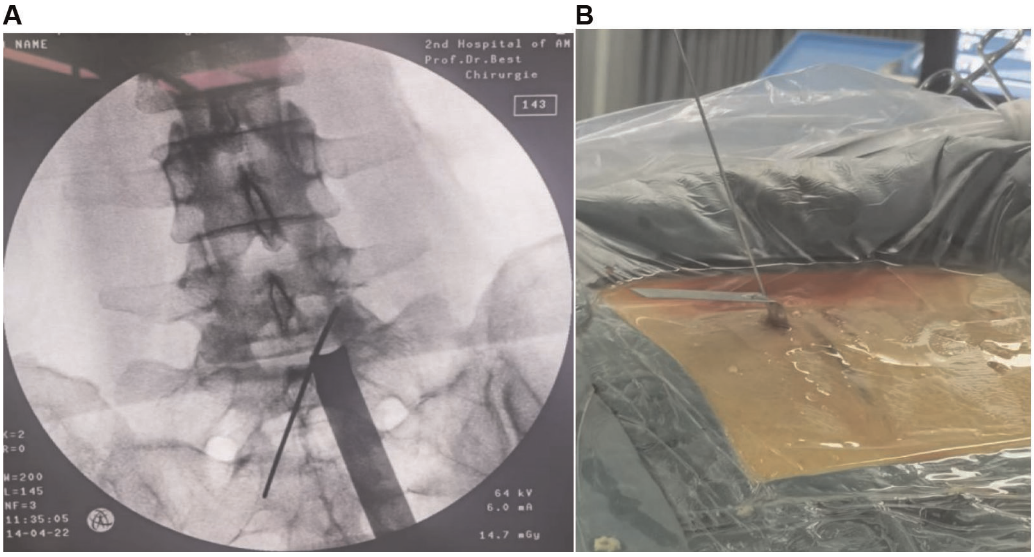

FIGURE 6
Sufficient decompression in the foraminal area is verified by passing a Kirschner wire probe through the foraminal canal.

removed by using a small up-curved chisel. After decompression, sufficient foraminal decompression was verified by passing a ball tip probe through the foraminal canal without any resistance (**Figure 6**).

Wound closure

After meticulous hemostasis was done by radiofrequency coagulation, free traversing and exiting nerve roots were confirmed by gentle retraction with nerve hooks. A drainage catheter was inserted through the working port to prevent postoperative hematoma. Then, the drainage catheter was secured in its place with a suture, and the wounds were closed using two single stitches.

Results

A total of 10 patients (three men and seven women; mean age 56.92 ± 13.26 years) were enrolled in this study. All patients had only two-level compression (one lateral recess compression and one adjacent foraminal). A total of 10 levels were operated using the aforementioned CIA-UBE in 10 patients. Of these, five patients underwent decompression at L4–L5, and five patients underwent decompression at L5–S1. There were six levels of lumbar disc herniation and four levels of pure foraminal and lateral recess stenosis. No cases were converted to open surgery in any of the patients. None of the patients had dural tears or other adverse events during surgery. The mean operation time was 85.14 ± 25.65 min, and the mean hospital stay was 4.84 ± 1.26 days. The mean follow-up period was 7.60 ± 4.47 months (**Table 1**).

Preoperative VAS and ODI scores improved significantly after the surgeries: VAS scores changed from 8.36 ± 0.65 preoperatively to 0.69 ± 0.45 at the last follow-up visit, while ODI scores changed from 79.56 ± 23.56 to 10.74 ± 5.67 ($p < 0.05$). There were no significant complications after the surgery, such as motor weakness or postoperative hematoma.

Postoperative MRI images and CT scans successfully depicted neural root decompression in the lateral recess and

TABLE 1 Patients' demographics and disease characteristics ($n = 10$).

Characteristic	Value
Sex, male:female	3:7
Age (year)	56.92 ± 13.26
Level	
L4–5	5
L5–S1	5
Side (lesions)	
Right	8
Left	2
Disc herniation	
Up-migrated	4
Intervertebral	2
None	4
Operative time (min)	85.14 ± 25.65
Hospital stay (day)	4.84 ± 1.26
Final follow-up period (month)	7.60 ± 4.47
MacNab	
Good	2
Excellent	8

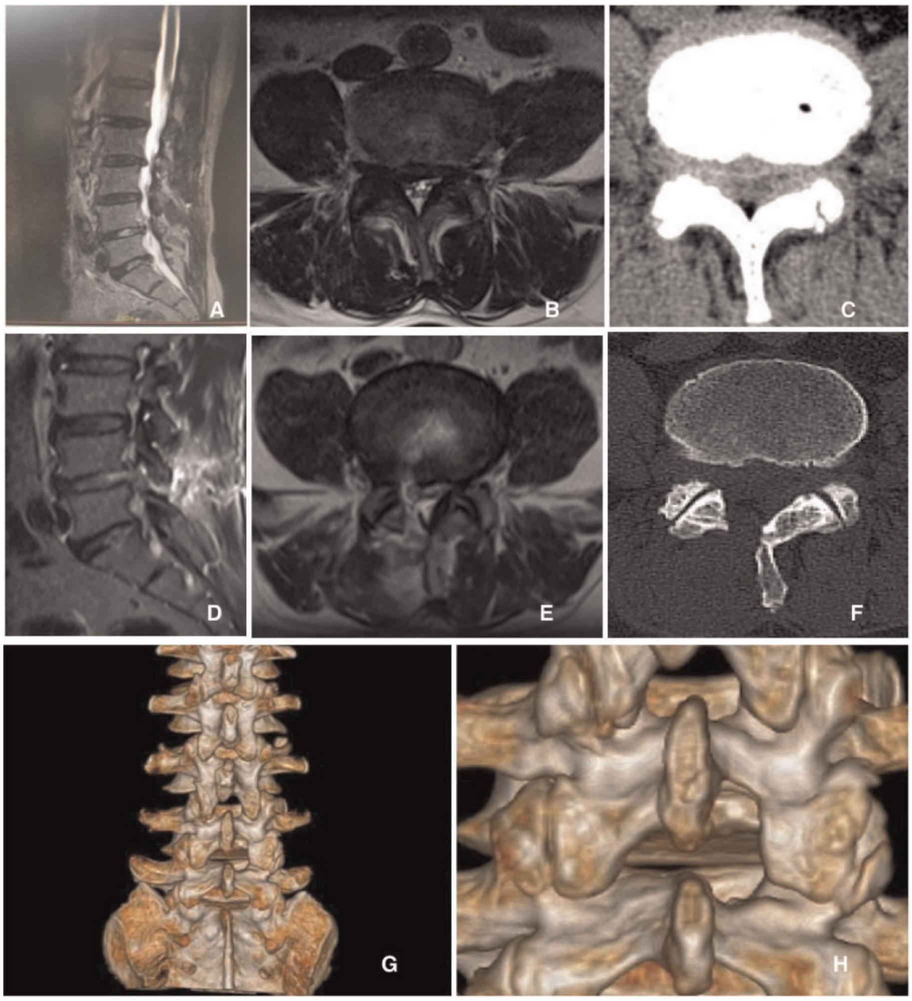

FIGURE 7
Pre-and postoperative radiologic images of the sixth case. A 58-year-old man presented with lateral recess and cranial level foraminal stenosis on the L4–L5 level. He underwent UBE-CIA on the right side of the L4–L5 level. Preoperative images showed foraminal stenosis on the right side of the L4–L5 level (A–C); ideal foraminal decompression with an obliquely undercut facet joint was shown in postoperative images (D–F); and three-dimensional computed tomography scan identified the remained facet joints and the range and adequacy of foraminotomy (G, H).

foraminal regions of the treated segments in all patients (**Figure 7**). The mean preoperative and postoperative CSA-CS values were 100.70 ± 32.12 mm^2 and 143.23 ± 35.12 mm^2, respectively. The mean preoperative and postoperative CSA-IVF values were 52.35 ± 14.23 mm^2 and 84.87 ± 19.34 mm^2, respectively. The mean preoperative and postoperative CSA-FJ values were 216.04 ± 28.23 mm^2 and 196.64 ± 21.34 mm^2, respectively (**Table 2**).

Discussion

Symptomatic lumbar lateral recess and same-level foraminal stenosis is a lesion that leads to significant disability from both traversing and exiting nerve root dysfunction (14, 15). Decompression with interbody fusion surgery is considered the standard gold treatment for these lesions. However, unfavorable postoperative complications, such as pseudoarthrosis, instrumental failure, and adjacent segment disease, have been reported (16).

Various minimally invasive nonfusion techniques have been developed to solve these problems (7). UBE surgery has significant advantages, such as a good operative view, easy surgical manipulation, reduced blood loss, and decreased postoperative back pain. It has been considered a minimally invasive technique with favorable clinical outcomes and high patient satisfaction (17). For nonfusion endoscopic spinal surgery, the preservation of facet joints on the pathological side is the most crucial consideration (18, 19). Despite UBE surgery leading to less iatrogenic injury due to its flexible

TABLE 2 Morphometric of MRI and clinical outcomes.

	Preoperative	Postoperative (last follow-up visit)	*P*
Cross-sectional area of the spinal canal (CSA-SC) (mm^2)	100.70 ± 32.12	143.23 ± 35.12	<0.05
Cross-sectional area intervertebral foramen (CSA-IVF) (mm^2)	52.35 ± 14.23	84.87 ± 19.34	<0.05
Cross-sectional area of the facet joint (CSA-FJ) (mm^2)	216.04 ± 28.23	192.64 ± 21.34	<0.05
VAS	8.36 ± 0.65	0.69 ± 0.45	<0.05
ODI	79.56 ± 23.56	10.74 ± 5.67	<0.05

manipulation and good visualization, there are still challenges to overcoming the violation of the facet joints in ipsilateral approach surgery (20). As the visualization is limited to the vertical trajectory in the ipsilateral approach, partial resection of the facet joint may be necessary to approach the lateral recess and the foramen. It has been reported that the violation of the medial facet joint is inevitable for adequate exposure to the surgical field in the ipsilateral approach, especially in conditions such as facet hypertrophy combined with foramina stenosis (21).

A contralateral inclinatory approach has been attempted by some authors to overcome the iatrogenic facet violation in the ipsilateral approach (22, 23). Chang et al. (24) reported that the contralateral inclinatory approach can be an effective alternative surgical approach in managing cervical spondylotic radiculopathy in microscopic decompression surgery using a tubular retractor. Kwan-Su Song et al. (25) first introduced contralateral inclinatory cervical foraminotomy by applying the UBE surgery technique to treat cervical radiculopathy pathologies. This approach allowed enough foraminal decompression with less facetectomy without violating the facet capsule compared with conventional ipsilateral UBE surgery, which needed more facetectomy for sufficient foraminal decompression. De Antoni et al. (26) first described the contralateral approach to biportal surgery using arthroscopy with a patient in the lateral position in 1996. However, to our knowledge, there is no description of the merits of contralateral inclinatory approach decompression *via* UBE surgery at the lumbar level with patients in the prone position. In this study, the CIA-UBE technique was applied to acquire a wider operative view of the surgical region, and its results have been reported with successful radiological and clinical outcomes.

In our series, CIA-UBE achieved good clinical and radiological outcomes. All patients had improved leg pain, VAS and ODI values were satisfied with less postoperative leg pain, operative scarring was minimal, and hospital stay was short. Radiological results in this study showed significant enlargement of the lateral recess and foraminal area in all 10 cases and successfully removed protruded discs without compromising the stability of the lumbar spine in six cases. This indicates that CIA-UBE may be a useful technology for foraminal and lateral recess stenosis with facet joint preservation at the lumbar level.

In our described CIA-UBE approach, the surgeon stands on the contralateral side of the lesion, whereas two portals are created at the lesion side over the spinous process. The inclinatory trajectory angle is usually 30–40°, which is between an ipsilateral approach and a contralateral sublaminar approach. An appropriate angle visualization of the surgical field can enable optimal decompression of the lateral recess and same-level foraminal region, which is a significant factor in such successful clinical results in the current cases. Compared to the vertical ipsilateral approach, CIA-UBE enables more incline and a longer trajectory, and the spinal inner space for surgical intervention to the lateral recess and same-level foramen will be proportionally increased. During decompression, endoscopy and the instruments can direct laterally toward the lateral recess and same-level foraminal region, and the plane between the nerve roots and the pathological regions can be visualized from an overhead direction using a 30° endoscope. Compared to the contralateral sublaminar approach, which also can treat the combined lumbar lateral recess and foraminal lesions (13), CIA-UBE provides a more direct and shorter trajectory, which can reduce bone-cutting work and intracanal manipulation.

In addition to adequacy decompression, another important purpose of adopting the CIA-UBE approach is the minimization of violations of the facet joint. During ipsilateral approach decompression, for the vertical trajectory, more of the outer superficial bone needs to be resected before the inner bone can be undercut to expose the lateral recess and foraminal. However, during CIA-UBE decompression, the facet joint could be more effectively preserved by undercutting the facet joint and saving the dorsal portion of the facet capsule in the inclinatory operative trajectory. In our radiological results, the reduction rate of the facet joint plane was calculated at about 10.83%, which was lower than that of the early reported reduction rate of the facet joint after the ipsilateral approach (18).

There are some technical points to contralateral keyhole endoscopic surgery, listed as follows:

1. There are certain limitations associated with CIA-UBE surgery. Various conditions can restrict access when approaching from the pathological side with the surgeon standing on the contralateral side, for example, spinous process deviation toward the pathological side, spinous process hypertropy, and central or extra-foraminal disc herniation. Furthermore, severe degenerative scoliosis with facet arthropathy and the narrow lamina in the upper

segments may also block the approach. Therefore, the choice depends on each patient's spinal anatomy and pathology.

2. Another demerit of CIA-UBE is a technical difficulty with a steep learning curve (27). In the process of laminotomy, the initial operative field is relatively narrow, and sometimes, a steep operative angle is needed. In addition, extensive drilling of the facet joint is more possible than the ipsilateral approach for the inclinatory operative trajectory if surgeons are unfamiliar with the anatomic landmark. Thus, surgeons should try this approach after they are familiar with the ipsilateral approach.
3. The skin incisions are suggested to be made obliquely along the multifidus muscle in the vicinity of the spinous process, being 5 mm lateral to the spinous process locking at the spinolaminar junction. If a skin incision is made other than locking at the spinolaminar junction, it is easy to drill out on the contralateral side of the laminar along the inclinatory trajectory, leading to violations of the facet joint and joint capsule.
4. Because the operative field of the primary region is relatively narrow *via* CIA-UBE, to obtain a wider vision, 30° endoscopy was recommended. In addition, angled chisel and bent drills were useful surgical tools to remove the medial part of the lateral recess and the tip of the superior articular process. Therefore, for easy handling of these angled endoscopic instruments, the laminectomy should be made wide enough at the base of the spinous process.

There are several limitations to this study. First, this study is a retrospective study of case series involving a small sample size and having a short follow-up period, which prevented the detection of complications such as the development of segmental instability and recurred disc herniation. Second, although we demonstrated better lateral recess and same-level foraminal stenosis decompression in our cases, most cases (8 of 10) involved a left-sided stand approach (lesions on the right side), which our right-handed surgeon found easier to operate. During the left-sided stand approach, the endoscope can show a more broad and detailed view of the foraminal space than the right-sided stand approach (lesions on the left side) and the instruments can access the foraminal area conveniently and efficiently. The statistics from a right-sided approach were lacking, and this is another limitation of our study. Third, measurement of the reduction rate may be inaccuracte in reflecting facet joint violation with bias. A further follow-up evaluation with a large number of patients would be necessary to prove the efficacy of CIA-UBE in the long term.

Conclusion

CIA-UBE can provide direct access to the lateral recess and same-level foramen with one window at the lumbar level, avoiding another incision. This approach may also minimize the iatrogenic damages to the facet joint by undercutting the bony structure with an inclinatory approach angle and is worthy of further application.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the ethics committee of the Second Hospital of Anhui Medical University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

DT: conceptualization, design, formal analysis, and writing—original draft; BZ: data curation, writing—original draft, software, and investigation; JL investigation; LC: resources and data analysis; HZ: software and drafting paper; YS: visualization and writing—review and editing; JJ (corresponding author): conceptualization, funding acquisition, resources, supervision, and writing—review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Endoscopic lumbar foraminotomy for foraminal stenosis in stable spondylolisthesis

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Background: Open decompression with fusion is the gold-standard surgical technique for spondylolisthesis. However, it may be too extensive for patients with foraminal stenosis with stable spondylolisthesis. The endoscopic lumbar foraminotomy (ELF) technique was developed as a minimally invasive surgical option for foraminal stenosis. Some authors have reported the outcomes of ELF for various spondylolistheses. However, few studies have demonstrated foraminal stenosis in advanced stable spondylolisthesis. This study aimed to describe the surgical technique and results of ELF for radiculopathy due to foraminal stenosis in patients with stable spondylolisthesis.

Methods: Consecutive 22 patients who suffered from radiculopathy with spondylolisthesis underwent ELF. The inclusion criterion was unilateral radicular leg pain due to foraminal stenosis in stable spondylolisthesis. After the percutaneous transforaminal approach, foraminal decompression was performed using various surgical devices under endoscopic visualization. Surgical outcomes were measured using the visual analog pain score, Oswestry disability index, and modified MacNab criteria.

Results: Pain scores and functional outcomes improved significantly during the 12-month follow-up periods. The rate of clinical improvement was 95.5% (21 of 22 patients). One patient experienced a dural tear and subsequent open surgery.

Conclusion: ELF can be effective in foraminal stenosis in stable spondylolisthesis. Technical points specializing in foraminal decompression in spondylolisthesis are required for clinical success.

KEYWORDS

endoscopic, foraminal stenosis, foraminoplasty, foraminotomy, lumbar, percutaneous, spondylolisthesis

Abbreviations
endoscopic lumbar foraminotomy, (ELF); visual analog pain score, (VAS); oswestry disability index, (ODI); superior articular process, (SAP); exiting nerve root, (ENR); ligamentum flavum, (LF)

Introduction

The gold standard surgical technique for lumbar spondylolisthesis with foraminal stenosis is decompression and fusion surgery, which may be performed using different methods. However, this surgery may result in considerable morbidity or sequelae, particularly in older patients.

In cases of foraminal stenosis with fixed or stable spondylolisthesis, adequate foraminal decompression may be a good solution while avoiding the surgical risk of extensive fusion surgery. Therefore, a minimally invasive decompression technique is required for cases with stable stenosis.

The endoscopic lumbar foraminotomy (ELF) or foraminoplasty technique was developed for effective foraminal decompression under a working channel endoscopic view (1–4). The foraminal decompression technique has evolved using different surgical tools such as microforceps, lasers, bone trephines, and endoscopic burrs. Moreover, the advanced ELF technique is as effective as open foraminotomy (4). However, this technique is unfamiliar to standard spine surgeons and challenging for endoscopic surgeons.

Some studies have been published on transforaminal endoscopic decompression for spondylolisthesis with lumbar stenosis (5–12). However, most studies have described this technique for lumbar intracanal stenosis or disc herniation in spondylolisthesis. Furthermore, few studies have demonstrated transforaminal endoscopic decompression procedures specific to severe foraminal stenosis in patients with stable and advanced spondylolisthesis. Therefore, we believe this study will help aspiring endoscopic spine surgeons understand the endoscopic foraminal decompression procedure and apply this technique in exceptional cases such as spondylolisthesis.

This study aimed to demonstrate the clinical outcomes of ELF for foraminal stenosis in stable spondylolisthesis and describe a practical and technical approach to achieving good clinical outcomes with ELF.

Materials and methods

Patients and evaluation

Twenty-two consecutive patients with foraminal stenosis in spondylolisthesis were treated with ELF between January 2019 and January 2021. Cases were prospectively registered in the database, and records were retrospectively analyzed. The institutional review board approved the study, and written informed consent was obtained from all participants.

The inclusion criteria for ELF were as follows: 1) chronic unilateral radicular leg pain despite more than 3 months of nonoperative treatment, 2) foraminal stenosis in spondylolisthesis demonstrated on magnetic resonance imaging (MRI) and computed tomography (CT) scans, 3) spondylolisthesis without definitive hypermobility on dynamic x-rays, and 4) foraminal stenosis documented as the source of radiculopathy by imaging studies, neurologic examination, and selective nerve root block.

The exclusion criteria were low back pain alone, acute lumbar disc herniation, severe central stenosis, segmental instability or hypermobility, and other pathological conditions such as inflammation, infection, trauma, or tumor.

Changes in clinical status were assessed using the visual analog pain score (VAS) and Oswestry disability index (ODI). The global outcome was evaluated using the modified MacNab criteria. Follow-up data were obtained through regular outpatient clinic visits or telephone interviews.

Surgical technique

The surgical procedure was performed according to a previously described method of ELF (4, 13). It consists of three processes: 1) the transforaminal approach under fluoroscopic view, 2) bone resection using endoscopic burrs, and 3) soft tissue removal using micropunches.

Intramuscular midazolam (0.05 mg/kg) and intravenous fentanyl (0.8 µg/kg) were administered on call. The patient was placed in a prone position on a radiolucent spine table.

Transforaminal approach (outside-in technique)

This step was performed to ensure the safe docking of the working sheath at the foraminal zone. The skin entry point and approach angle were determined according to the target point and body size on preoperative MRI, CT scan, and x-rays.

An 18-gauged needle was introduced into the foraminal zone in the posterolateral direction under fluoroscopic guidance (lateral and anteroposterior projections). The typical approach angle is approximately 45° for foraminal decompression and can be adjusted to become steeper when the pathologic point is located in the extraforaminal zone. The needle tip was deeply inserted into the foraminal disc or on the vertebral body, along the surface of the superior articular process (SAP). The needle was replaced with a guidewire, and an obturator was introduced along the guidewire until the head of the obturator was fitted into the foramen without any access pain. The beveled final working sheath was advanced along the obturator by gently tapping with a mallet and placed firmly in the foraminal zone with its sharp end away from the exiting nerve root (ENR). The surgical field was created outside the foramen, and decompression proceeded into the foramen (outside-in approach). Thus, the ENR was protected during the entire procedure (**Figures 1A, 2A**).

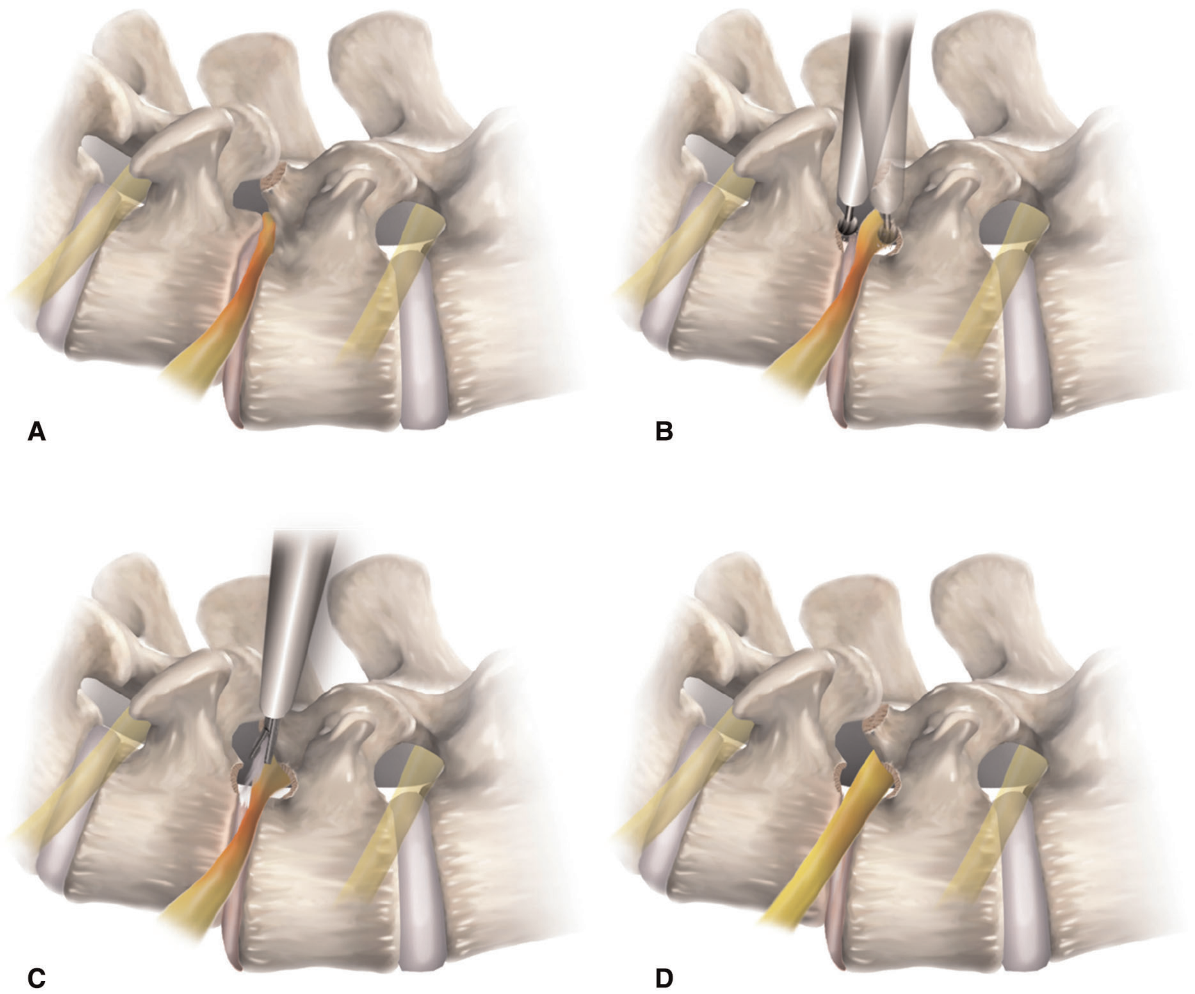

FIGURE 1
Conceptual illustrations depicting the surgical procedure of endoscopic lumbar foraminotomy for spondylolisthesis. (A) Foraminal docking of the working sheath viewing the foraminal surgical field protecting the exiting nerve root (outside-in approach). (B) Foraminal unroofing using endoscopic burrs for resecting the upper pedicle and lower vertebral endplate. (C) Soft tissue decompression with removal of the ligamentum flavum. (D) Final point of the full-scale foraminal decompression from the axillary side to the lateral exit zone.

Endoscopic bone work

Endoscopic foraminal decompression was initiated after a working channel endoscope was inserted. The initial view included the ENR with perineural fat and disc surface. These structures helped the surgeon maintain the correct orientation during the entire procedure. Next, the surface of the SAP was exposed by rotating the working sheath and the endoscope. The tip of the SAP was then drilled using various endoscopic burrs along the ENR until the ligamentum flavum (LF) and foraminal ligaments at the axillary zone were sufficiently exposed. Finally, any bone or venous bleeding was coagulated using radiofrequency tips and hemostatic agents. In cases of advanced spondylolisthesis, the ENR is usually pinched by a narrow space between the upper pedicle and lower vertebral endplates rather than by the SAP. Therefore, the ENR should be decompressed by resecting these bony structures. Bone resection is an essential and critical process of foraminal decompression specific to spondylolisthesis cases (Figures 1B, 2B).

Endoscopic soft tissue work

After sufficient bone work, delicate soft tissue removal was performed, and the ENR was released. The decompression process was directed toward the proximal side, and the nerve root course was traced to the axillary epidural zone. The hypertrophied LF and protruding disc material were removed gradually using micropunches, forceps, and radiofrequency tips (Figure 1C). Although minor, bleeding may seriously interfere in the endoscopic surgical field. Therefore, meticulous hemostasis was essential to ensure a clear vision

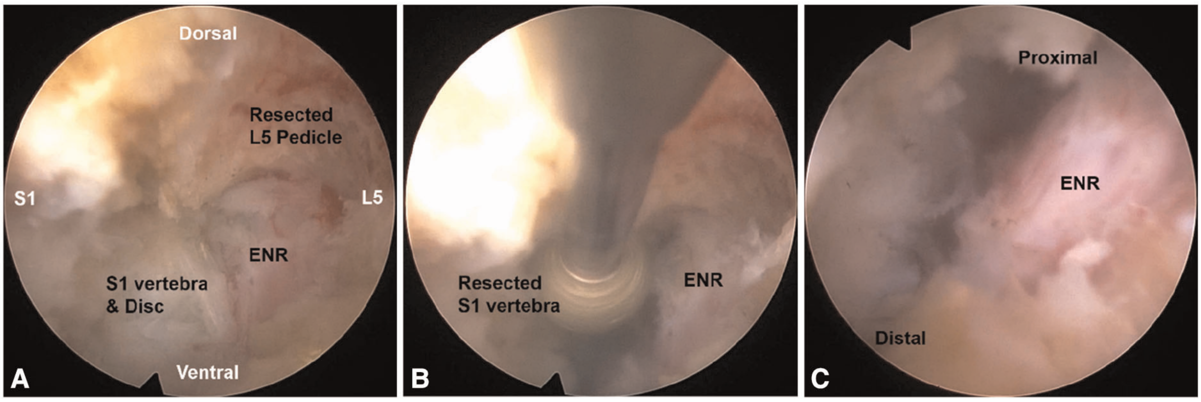

FIGURE 2
Intraoperative endoscopic views. Foraminal unroofing with the removal of the upper pedicle (A) and lower vertebral endplate (B) compressing the exiting nerve root (ENR). After the full-scale decompression, the ENR was freely released from the proximal axillary zone to the lateral exit zone (C).

during the procedure. The ENR became exposed and released as soft tissue work proceeded. Surgeons were careful not to damage the dural membrane. The tissue debris was cleared with radiofrequency, and the neural tissues were separated from the offending tissues. The axillary epidural zone is a key landmark for foraminal decompression. Exposure of the dural sac to the starting point of the ENR indicated successful foraminal decompression. Once the proximal axillary zone was released, the nerve root was examined from the proximal side to the lateral exit zone. Any remaining ligament or disc tissue was trimmed during full-scale foraminal decompression. Finally, determining the definitive finishing point is mandatory to prevent an incomplete decompression. The endpoint of ELF was determined by sufficient exposure and strong pulsation of the neural tissue (**Figures 1D**, **2C**). Postoperatively, the surgeon checked each patient's status for 3 h. The patient was discharged within 24 h in the absence of complications (**Figures 3**, **4**).

Statistical analysis

Statistical analysis was performed between the pre- and postoperative clinical results using repeated-measures analysis of variance and a paired t-test. Statistical significance was set at $P < 0.05$.

Results

The mean age of the patients (14 females and 8 males) was 69.2 years (range, 53–83). The mean BMI was 22.94 ± 2.59 kg/m^2. The degrees of spondylolisthesis were grade 1 in 20 patients (90.9%) and grade 2 in 2 (9.1%). The operating levels were L5-S1 in 12 (54.5%) patients, L4–5 in 8 (36.4%), and L3–4 in 2 (9.1%). The mean operative time was 63.6 min (range, 35–115). The mean postoperative hospital stay duration was 1.9 days (range, 1–5).

The mean preoperative VAS score for the lumbar radiculopathy was 7.91 ± 0.75, which improved to 2.73 ± 0.94, 2.05 ± 0.79, and 1.64 ± 0.95 at 6 weeks, 6 months, and 1 year postoperatively, respectively ($P < 0.001$) (**Figure 5A**). The mean preoperative ODI was 74.82 ± 8.34%, which improved to 29.24 ± 6.08%, 23.35 ± 7.24%, and 18.18 ± 7.73% at 6 weeks, 6 months, and 1 year postoperatively, respectively ($P < 0.001$) (**Figure 5B**). The global results based on the modified MacNab criteria were rated as follows: excellent in 6 patients (27. 3%), good in 14 (63.6%), fair in 1 (4.5%), and poor in 1 (4.5%). Therefore, the success rate was 90.9%, and the clinical improvement rate was 95.5% (**Figure 6**).

During the procedure, one patient experienced a dural tear in the axillary zone at the L3–4 level. The patient complained of severe pain and underwent subsequent open surgery (transforaminal lumbar interbody fusion with dural repair). Otherwise, no other significant perioperative complications were observed. No newly developed back pain or radiological signs of further instability were noted during the follow-up period.

Discussion

Surgical data and clinical outcome

The ELF technique is usually suitable for geriatric patients because of its minimal invasiveness. However, the average age of the surgical candidates in this study was higher than that of other case series of ELF. The disease entity appears to be chronic radiculopathy due to long-standing or advanced spondylolisthesis. Therefore, most patients may be older

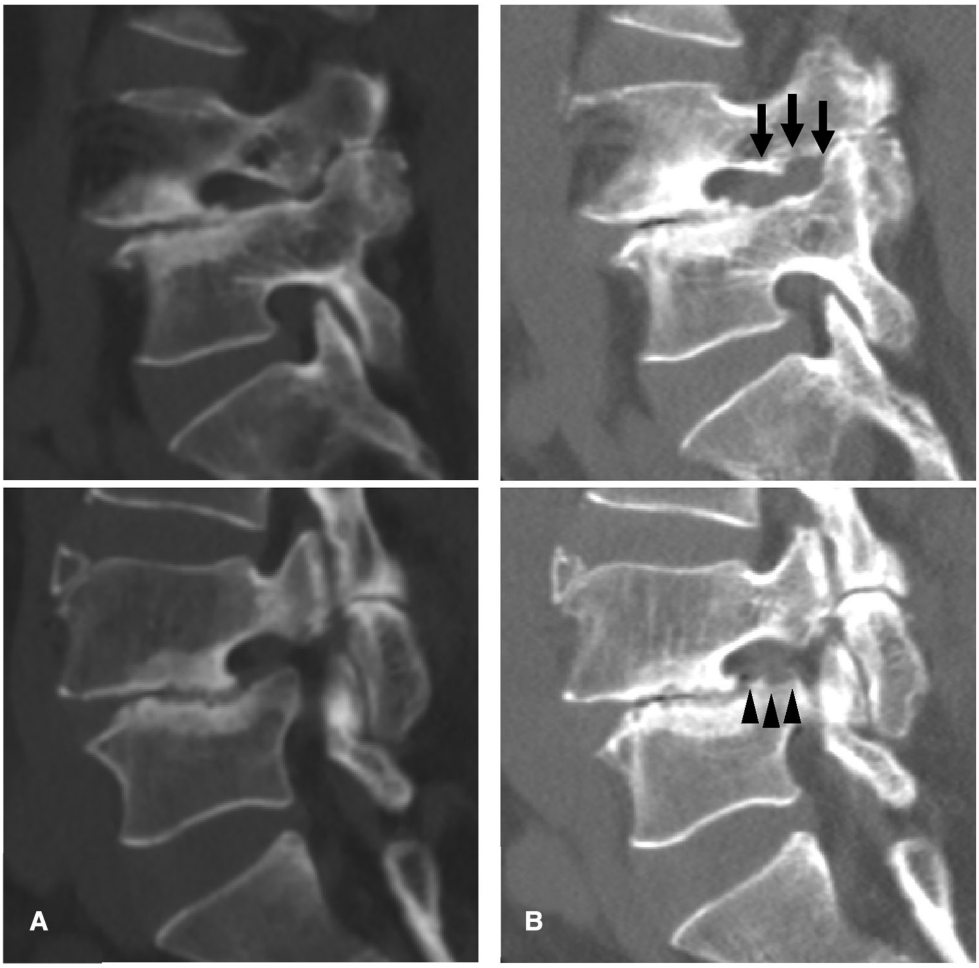

FIGURE 3
An illustrative case of a 62-year-old Male patient. **(A)** Preoperative computed tomography (CT) images showing foraminal stenosis with spondylolisthesis at the L4-5 level. **(B)** Postoperative CT images showing foraminal decompression with resection of a part of the upper pedicle (arrow) and lower vertebral endplate (arrowheads).

individuals or long-suffering. Additionally, older patients do not prefer extensive fusion surgery for perioperative morbidities.

The operative data showed the typical benefits of minimally invasive spine surgery. The mean operative time was 63.6 min, which was shorter than that of open fusion surgery (14–17). Blood loss was negligible, and postoperative hospital stays were fairly straightforward. These findings can facilitate a patient's earlier return to ordinary life.

The patient outcomes significantly improved in both the VAS and ODI scores. The mean VAS score of radiculopathy decreased by 6.327 at the final evaluation ($P < 0.001$). Conversely, the mean ODI improved by 56.64 at the final assessment ($P < 0.001$). A reduction of more than 50% in the VAS score (18) or an improvement of more than 20%–30% in the ODI is clinically relevant (19, 20). Therefore, our data indicate that the ELF technique for spondylolisthesis is efficacious in ENR decompression and results in significant functional improvement.

The success rate (excellent or good) based on the modified MacNab criteria was 90.9%, with a clinical improvement rate of 95.5%. These findings are comparable to those of published open foraminotomy procedures (21–27).

Our series had no significant complications except for one dural tear and conversion to open surgery. None of the patients experienced any further clinical or radiological segmental instability during the follow-up period. Although some bony structures were removed to decompress the nerve root, the ELF technique did not cause the development of further instability in any of the patients in our study.

Given the innate characteristics of ELF, the clinical success and complication rates may depend on the surgeon's skill. However, once technical proficiency is achieved, surgeons can

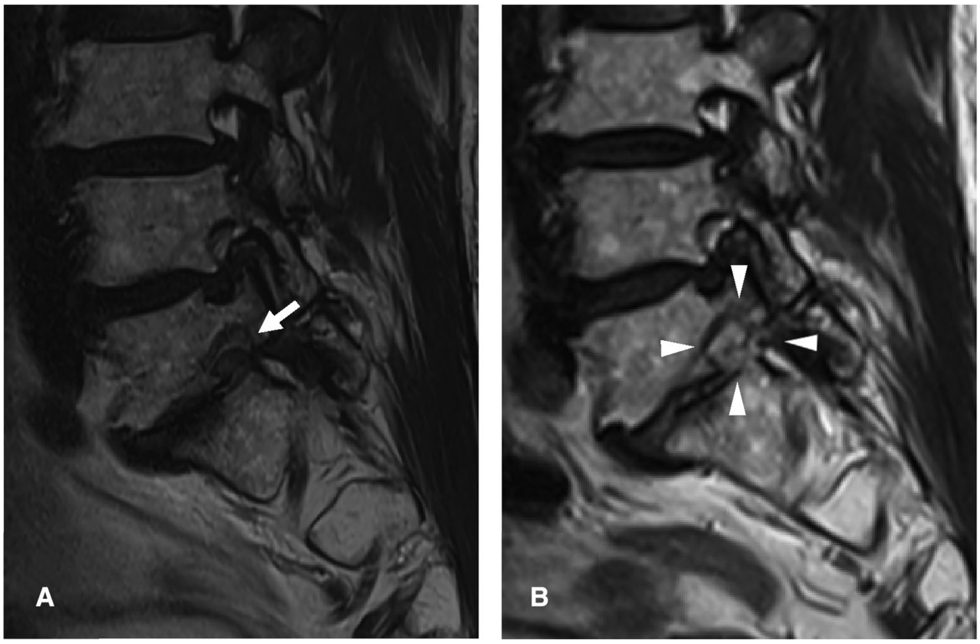

FIGURE 4
An illustrative case of a 75-year-old Male patient. **(A)** Preoperative magnetic resonance image (MRI) showing foraminal stenosis with spondylolisthesis at the L5-S1 level (arrow). **(B)** Postoperative MRI showing foraminal decompression with removal of the protruded disc and surrounding bony tissues (arrowheads).

produce relevant and reliable results. Therefore, an extensive and systematic learning process is required to implement this procedure.

History of ELF/foraminoplasty

Owing to the development of decompression devices, ELF has become a practical foraminal decompression technique. The first-generation procedure uses a laser for foraminal decompression. Knight et al. (1, 28) introduced an endoscopic laser foraminoplasty technique. The central concept of laser foraminoplasty is sculpting the foramen by ablating the hypertrophic foraminal ligaments using a side-firing laser under an endoscopic view. Although the soft tissues and fibrotic adhesion could evaporate, the hard tissue or hypertrophic bone could not be effectively removed with the laser beam. The second-generation technique uses bone trephine or reamer. Ahn et al. (2) reported an endoscopic foraminotomy technique using a bone trephine and Ho: YAG side-firing lasers. Schubert and Hoogland (29) described a foraminoplasty method using a bone trephine to remove the migrated lumbar disc herniation. Being a blind percutaneous technique under fluoroscopic view, the use of bone trephine has inherent limitations, such as possible bone bleeding and neural injury. The ELF procedure employed in this study was achieved with the third-generation technique, in which spine surgeons applied endoscopic burrs and punches. Specially designed surgical tools enable precise, full-scale foraminal decompression as effective as open foraminotomy (1, 30–32).

Current studies and theoretical benefits

Since Knight et al. published endoscopic lumbar laser foraminoplasty for isthmic spondylolisthesis (5), some authors have published transforaminal endoscopic decompression techniques for lumbar stenosis or disc herniation in spondylolisthesis (6–12). They decompressed the spinal canal or herniated disc using various surgical devices, such as lasers, trephines, forceps, and burrs. However, few studies have described precise techniques specific to foraminal stenosis in stable and advanced spondylolisthesis. Moreover, in stable spondylolisthesis, open decompression and fusion surgery under general anesthesia may be too extensive in foraminal stenosis without intracanalicular stenosis.

Without open fusion surgery, ELF can resolve chronic and intractable radiculopathy caused by spondylolisthesis. In addition, this minimally invasive technique may be efficient for patients who refuse fusion surgery or medically compromised older patients because the procedure can be

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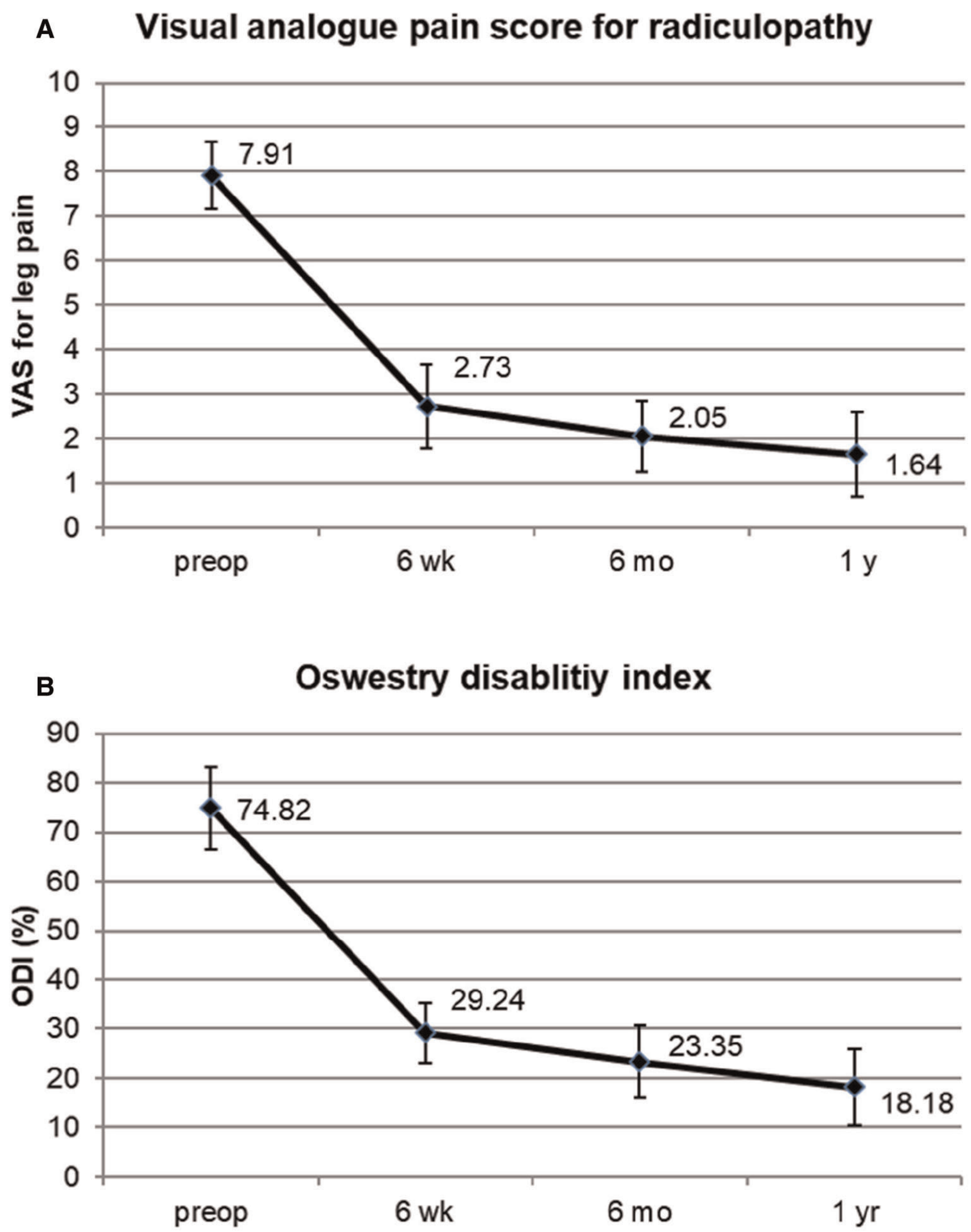

FIGURE 5
Clinical outcomes. (A) Visual analog pain score for radicular leg pain preoperatively and at 6 weeks, 6 months, and 1 year after surgery. (B) Oswestry disability index scores preoperatively and at 6 weeks, 6 months, and 1 year after surgery.

performed percutaneously under local anesthesia. Consequently, the surgical complications of extensive fusion surgery can be reduced, and the patient can return to normal life earlier.

However, this minimally invasive procedure has a steep learning curve and limited indications. Therefore, the clinical application of ELF in spondylolisthesis should be carefully considered.

Technical keys specific to foraminal stenosis with spondylolisthesis

Hypertrophic SAP and thickened LF compressing the ENR are the primary pathologies of foraminal stenosis. Therefore, the basic ELF technique consists of bone resection of the SAP and removal of the LF by endoscopic burrs and other surgical devices. The final landmark of the decompression process is

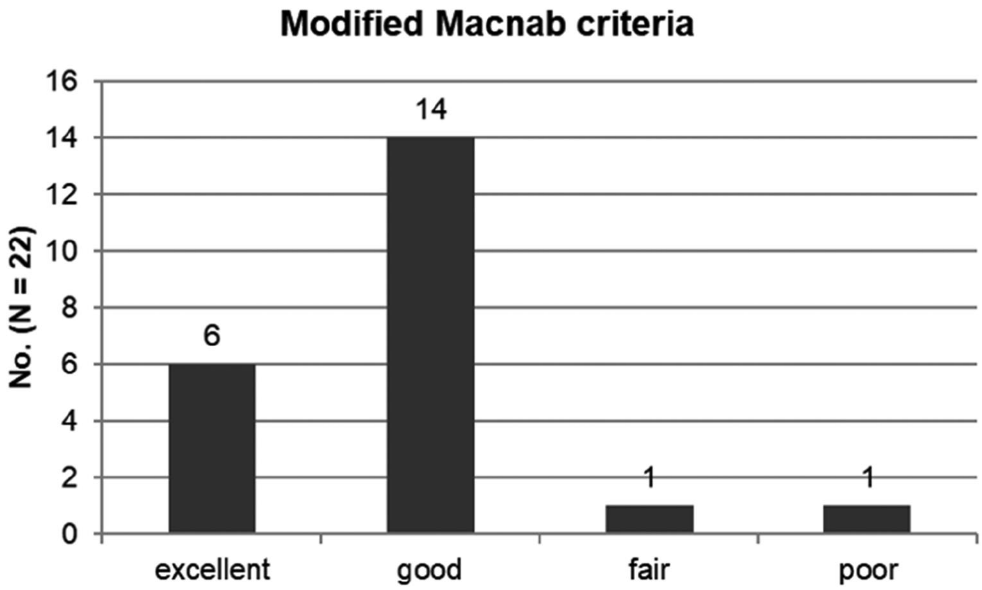

FIGURE 6
The global outcome according to the modified macNab criteria: excellent in 6 patients (27. 3%), good in 14 (63.6%), fair in 1 (4.5%), and poor in 1 (4.5%). Therefore, the success rate was 90.9%, and the clinical improvement rate was 95.5%.

the axillary epidural space, which is the starting point of the ENR.

However, the foraminal anatomy of advanced spondylolisthesis is different. Unlike the usual foraminal stenosis cases, the main offending structure may be the lower vertebral endplate rather than the SAP. In the foraminal zone of spondylolisthesis, the SAP is away from the ENR because of slippage of the upper vertebral body. Therefore, the ENR may impinge between the upper pedicle and lower vertebral body.

To achieve sufficient foraminal decompression, the surgeon should target the lower vertebral endplate rather than the SAP during the initial approach. Once the working sheath and endoscope are ensured to be in the foraminal working zone, the surgeon should confirm the route of the ENR and disc between the upper pedicle and lower vertebral endplate. Next, the upper pedicle and lower vertebral endplate should be sculptured using an endoscopic burr and punch. Finally, the ENR is released between the two resected bony walls after bone work.

Limitation of the study

This study had some limitations. First, the study was conducted retrospectively without a control group. Therefore, selection bias in the inclusion criteria may have been present. Therefore, a prospective randomized trial or comparative cohort study comparing ELF and open fusion surgery for foraminal stenosis with spondylolisthesis is warranted. Second, the one-year follow-up period may be relatively short for drawing a conclusive result because the spondylolisthesis status or segmental stability may change with time, even after successful decompression. Therefore, a long-term follow-up study with a larger number of cases is required to verify the effectiveness of ELF for foraminal stenosis in spondylolisthesis.

Conclusion

The advanced ELF technique is effective in adequately selected cases of lumbar spondylolisthesis. In addition, ELF may be suitable for intractable radiculopathy due to foraminal stenosis with fixed spondylolisthesis without segmental hypermobility—a specialized technique is required for the clinical success of foraminal decompression in spondylolisthesis. Moreover, it may provide an excellent minimally invasive alternative to extensive fusion surgery in older or medically compromised patients.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Gachon University Gil Medical Center. The patients/participants provided their written informed consent to participate in this study.

Author contributions

AY provided ideas and the design of the study and was a major contributor to the data analysis and paper writing. PHB collected the data and participated in the data analysis and paper writing. YBR also participated in the data analysis and paper writing. JTS supervised the study and revised the paper. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Full-endoscopic uniportal retropharyngeal odontoidectomy: A preliminary case report

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Summary of background data: Odontoidectomy aims to decompress the medulla oblongata and is usually performed through the classical transoral approach, which affects oropharynx and accompanied with high rate of complications comprising swallowing and respiratory tract. We have developed a minimal invasive method *via* a standard cervical anterior approach: full-endoscopic trans-cervical odontoidectomy, which provides an alternative access for the resection of odontoid process and medulla oblongata decompression without traversing potentially contaminated cavities.
Methods: From 2018 to 2020, three patients with either odontoid process lesion or basilar invagination underwent full-endoscopic uniportal trans-cervical odontoidectomy with/without combining the posterior instrumentation. With fluoroscopic guidance, a uniportal endoscope sleeve was placed inside of the odontoid process; then odontoid process was gradually resected from the inside to outside under endoscopic monitoring. Postoperative images and clinical data were collected during post-op follow-up.
Result: Patients were soon extubated after surgery when patients wake up from general anesthesia. There were no severely perioperative complications, especially dysphagia and airway obstruction, and the symptoms and neurological function was improved immediately after surgery. The final pathology of one patient with odontoid osteolytic lesion was confirmed as plasmacytoma. The postoperative CT scans proved that the range of odontoid process resection was consistent with the preoperative expectation.
Conclusion: In summary, our proposed endoscopic trans-cervical odontoidectomy provides a valid choice for non-oral approach, which would reduce postoperative approach related complications and accelerate postoperative recovery.

KEYWORDS

basilar invagination, axis, endoscopy, odontoidectomy, trans-cervical approach

Introduction

Odontoidectomy is necessary in cases of irreducible spinal cord compression induced by dislocated odontoid process or odontoid process lesion. Transoral approach odontoidectomy remains to be the "gold standard" in the literature (1, 2). Progress in surgical technique and improvement of understanding anatomic characteristics in this region has deceased the complications and mortality of odontoidectomy. However, there is still a high rate of complications related to throat dysfunction in odontoidectomy via transoral approach due to its damage to mucosal sensory receptors (1, 3, 4). Sensory receptors in the mucosa of pharynx and larynx are essential to the pharyngeal reflex. Attenuation or lack of pharyngeal reflex would increase the opportunity of postoperative aspiration due to post-op bleeding, secretions, and gastric contents. At the same time, severe pharyngeal and laryngeal edema may cause perioperative asphyxia. In addition, bacterial colonization and non-effective preoperative disinfection of the pharyngeal cavity give rise to the incidence of postoperative infection (3, 4).

To avoid the damage to pharynx and larynx mucosa in bypassing these cavities, surgeons had been attempting to apply a trans-cervical approach in odontoidectomy. A trans-cervical retropharyngeal exposure of the odontoid process was reported by Fong and DuPlessis (5). The approach was similar to the classic anterior approach for the placement of anterior axis dens screws and the Minimal Exposure Tubular Retractor (METRx) was placed to maintain the surgical field. Although their proposed procedure had the advantage of avoiding traversing the oral, the limited, deep operative field, and inconvenient extra-long working distance made big challenge to surgeons.

Advance in endoscopic technology has allowed the appliance of endoscope in the odontoidectomy. Wolinsky et al. described a full endoscopic trans-cervical approach for odontoid resection (6). A modified METRx, the neural endoscope, and high-speed burr contributed to make a clear operative view and convenient procedure. But placing a retractor more than 2-cm diameter also accompanies the high risk of stretch injury of superior laryngeal nerve, hypoglossal nerve, and marginal branch of the mandibular nerve. Meanwhile, continuous bleeding of cancellous bone added much disruption in endoscopic procedures.

Recent progress in spinal endoscopy, especially the closed tubular sleeve that enables stop bleeding with water pressure and irrigation, integrated coaxial spinal endoscope system, and high-speed tip-changeable endoscopic burr, enables spine surgeon to perform bone resection and decompression of the occipitocervical region in a 6–7 mm tubular sleeve (7). Based on the accumulated experience in anterior cervical surgeries and percutaneous endoscopic lumbar discectomy (PELD), we developed a novel full-endoscopic trans-cervical odontoidectomy and medulla oblongata ventral decompression.

Materials and methods

Patient characteristics

This retrospective case series contains two patients undergoing the full-endoscopic trans-cervical odontoidectomy from 2018 to 2020 upon obtaining their signed and informed consent.

Case 1. A 62-year-old man with a history of severe neck pain for one month. Computed tomography (CT) and magnetic resonance (MR) scans of cervical spine demonstrated an osteolytic lesion of odontoid process combining pathological fracture. Positron emission tomography (PET) showed a single, 18 g-fdg high concentrated lesion in the odontoid process. Infection and septic markers were basically normal and no abnormality in tumor markers was noted. The Gram-stained smears from bone marrow aspiration suggested the plasmacytic myeloma. We considered that patient with odontoid process lesion and pathological fracture was candidate to perform odontoid process biopsy and resection, combining posterior C1–C3 instrumentations.

Case 2. A 70-years-old man was diagnosed as basilar invagination and had foramen magnum decompression surgery history 10 years ago. In the last 3 years, the weakness of his right limbs and the numbness of both lower limbs have gradually exacerbated. X-ray and CT scans showed that the odontoid process protruded into the foramen magnum (**Figures 1A–C**). MR showed medulla oblongata compression by odontoid process, combining with cervical syringomyelia (**Figure 1D**). Electromyography suggested that neurological impairments originated from upper spinal cord lesions, due to the obvious compression of medulla oblongata, which resulted in syringomyelia and neurological deficits. Resection of the odontoid process, the medulla oblongata decompression, and posterior occipitocervical fusion was required.

Case 3. A 54-year-old female with a history of numbness in her limbs for 3 years and inability to walk in her lower limbs for half a year. X-ray and CT scans showed that the odontoid process protruded into the foramen magnum. MR showed medulla oblongata compression by odontoid process, combining with cervical syringomyelia. Thus, resection of the odontoid process and medulla oblongata decompression was required.

Surgical technique

After general anesthesia with tracheal intubation, the patient was positioned prone on the Jackson table, with somatosensory

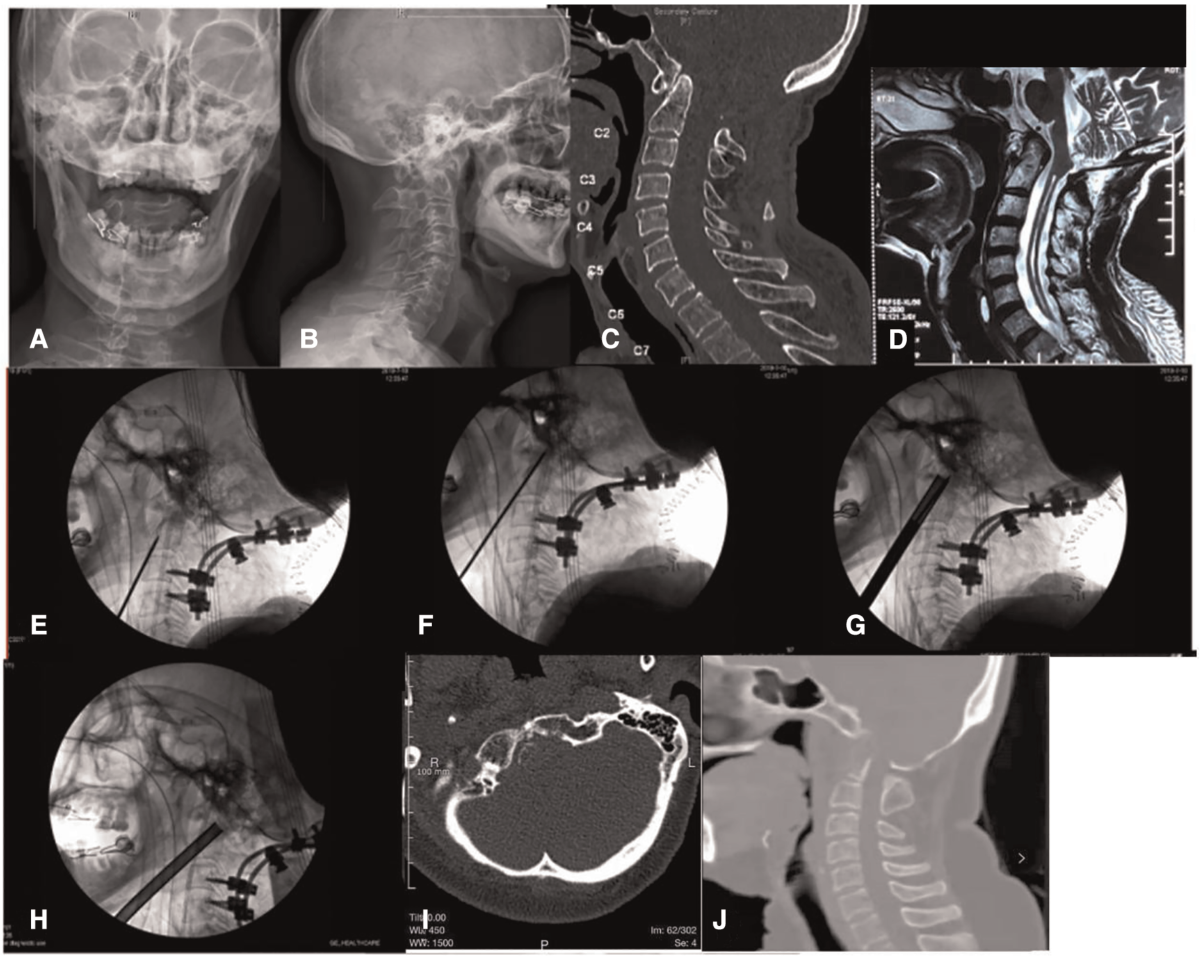

FIGURE 1
(A) AP x-ray of cervical spine of Case 2 before operation. (B) Lateral x-ray of cervical spine of Case 2 before operation. (C) Sagittal section of CT scan of Case 2 before operation. (D) Sagittal section of MR scan of Case 2 before operation. (E) The C-arm image when a Kirschner wire was drilled into the middle of the odontoid process of the axis in operation. (F) The C-arm image showed the depth of Kirschner wire reach the front of the odontoid process rear cortex and do not penetrate the rear cortex of the odontoid process. (G) The C-arm image showed a 7.2-mm hollow ring saw remove an annular bone block around the Kirschner wire. (H) The C-arm image showed lifting the end of the ring saw (the supine position) to make the angle between the ring saw and the axis of the spine larger, and removing more cancellous bone of the dentate bottom with the ring saw. (I) Cross section of CT scan after surgery. (J) Sagittal section of CT scan after surgery.

and motor evoked potential monitoring throughout the operation. Additional posterior instrumentations and fusion was performed to stabilize the spine before the odontoidectomy.

Subsequently the patient was placed in a recumbent position with a shoulder roll placed behind the neck to achieve gentle cervical extension. The head was fixed by a Mayfield head-holder. The operative area was prepped and draped in a standardized fashion for anterior cervical operations.

The standard Smith–Robinson approach was chosen for the access to cervical spine (8). A transverse incision was made at approximately C-4 level on the right side of the patient, starting from the central line, horizontally extending to right side about 3-cm length (Figure 2A). Dissect the subcutaneous tissue and platysma muscle. The esophagus and trachea were swept medially; the sternocleidomastoid muscle, carotid sheath, and the areolar tissue were swept laterally by blunt dissection. The spine was exposed rostrally to the anterior tubercle of atlas. Under fluoroscopy guidance, a Kirschner wire was drilled from the base of the dens, then cranially track to the tip of odontoid process. The position of the Kirschner wire was recommended to be located in the center of the dens, verified by fluoroscopic images on two orthogonal planes (Figures 1E, 2B). The rostral tip of Kirschner wire should keep close but in front of dorsal cortex of odontoid process. Penetration of the dorsal cortex must to be avoided (Figure 1F). Then a 7.2-mm hollow ring saw (Figures 1G, 2C) was applied to remove an annular bone block around the Kirschner wire and the resection of bone

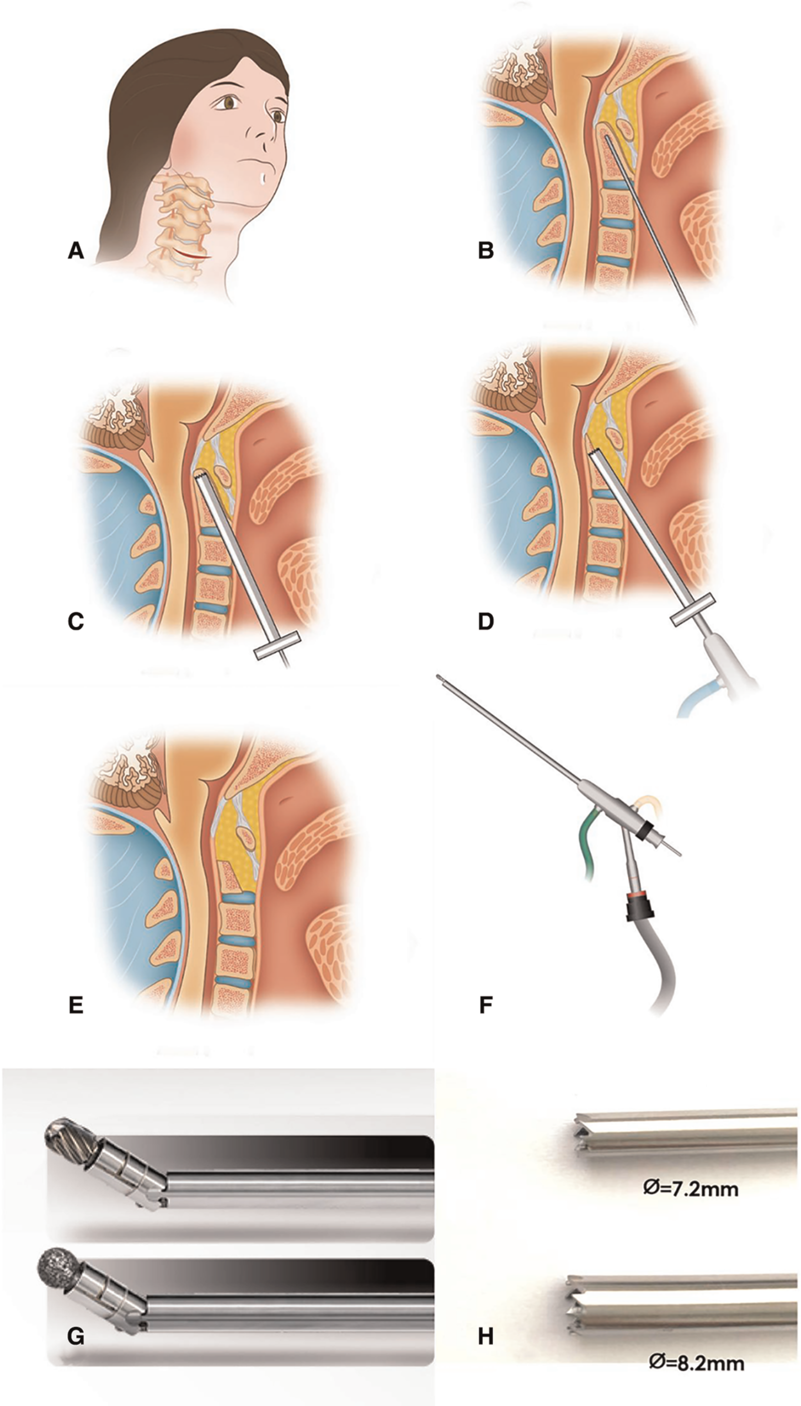

FIGURE 2
(A) A transverse incision was made at approximately the C-4 level on the right hand side of the patient, starting from the center line, extending to 3 cm in horizontal. (B) A Kirschner wire was drilled into the middle of the odontoid process of the axis. The position of the Kirschner wire was recommended to be located in center of the odontoid process in both AP and lateral x-ray. (C) A hollow ring saw was used to remove an annular bone block with the direction of the Kirschner wire. The hollow ring saw should also stop before odontoid process posterior cortex. (D) After removing the tip of the odontoid, simply lift the end of the ring saw (patient in the supine position) to make the angle between the ring saw and the axis of the spine larger and continue to remove more cancellous bone of the dentate bottom with the ring saw. (E) The odontoid process is removed and decompression of spinal cord is completed. (F) The 6.5-mm diameter coaxial spine endoscope. (G) The electric high-speed grinding drill, which is designed for endoscopy specifically and the direction of tip is changeable. (H) Feature of the tip of 7.2/8.2-mm hollow ring saw.

block should progress carefully without breaching to the dorsal cortex. Slightly rotation of the hollow ring saw in situ can separate the front part of the annular bone block, which will be taken out as the ring saw pulled out. A 7.2-mm, circular osseous space was built in the central part of odontoid process, then a 7.2-mm endoscopic working sleeve was inserted into the circular osseous space. A 6.5-mm coaxial spine endoscope was placed in the working sleeve. Continuous water irrigation was needed to stop bleeding of cancellous bone and maintain the clarity of the endoscopic vision during the procedure. The tip of the odontoid process was gradually resected from the inside to outside by an electric high-speed burr, which was especially designed for endoscopy, and the angle of the burr's tip was adjustable from 0° to 45° (**Figure 2G**). After removing the cranial part of the dens, backed off the endoscopic sleeve but no exit completely from the bone tunnel. Then re-inserted the ring saw and tilted the end of the ring saw (the supine position) to increase the angle between the ring saw and the odontoid process, and removed more cancellous bone of the odontoid process's bottom (**Figures 1H**, **2D**). Because the bottom portion of the odontoid process was little wider, a larger diameter sleeve and ring saw can be chosen in this procedure (**Figure 2H**), which can improve the efficiency of bone resection and decompression. The decompression of the medulla oblongata was completed until all the ventral bone was removed and the alar ligaments was exposed; however, the dura need not to be exposed (**Figure 2E**).

Because it is difficult to determine the range of the odontoid resection and medulla oblongata decompression under endoscope, the O-arm scan was necessary to judge whether the range of odontoid resection and decompression was enough.

Results

Patients were extubated soon after surgery. Continuous monitoring of pulse oxygen saturation at fingertip showed 100%. They were able to normally vocalize and communicate without complaining of discomfort such as dyspnea and dysphagia. Without the need for nasogastric tube placement, oral feeding can be resumed at 6 h postoperatively, no coughing caused by feeding or dysphagia reported.

In Case 1, the VAS score was two points at third days postoperative and improved significantly compared with nine points preoperative. Immunohistochemical staining of the extracted sample confirmed the diagnosis of plasmacytoma. The patient received local radiotherapy 3 weeks after operation and still under follow-up.

In Case 2, the patient claimed that the numbness of lower limbs and the weakness of right limbs significantly release at a week postoperatively. At 6-month's follow-up, Japanese Orthopedic Association (JOA) score increased from 7 preoperatively to 18 postoperatively, with no progression of myelopathy symptoms.

In Case 3, the patient claimed that the numbness of her limbs and the weakness of lower limbs significantly release at two week postoperatively. At 6-month's follow-up, Japanese Orthopedic Association (JOA) score increased from 6 preoperatively to 15 postoperatively, with no progression of myelopathy symptoms.

The postoperative CT scans displayed the extent of odontoid process resection consistent with the pre-operative expectation (**Figures 1I,J**).

Discussion

Nowadays, the trans-oral approach has been the benchmark for odontoidectomy (1, 2). With the advent of its various surgical modifications (e.g., an extended trans-maxillary, maxillary split, trans-palatal, or trans-mandibular approach), these practices are noted to be complicated by phonation dysfunction and velopharyngeal insufficiency as well as cosmetic deformity (9). In addition to the limited operative view, the deep location and complex surrounding structures that hinder the operated structures, the trans-oral approach is highly complicated by bacterial contamination from flora in the oropharynx, prolonged intubation or tracheostomy due to swelling of soft tissue, and pharyngeal wound dehiscence that requires nasogastric tube feeding (10). Patients with severe oral cavity deformities like micrognathia are not suitable candidates for this procedure.

Alternative approaches were implemented to decrease the complications related to approach in conventional transoral procedure. Among alternative approaches, studies on retropharyngeal technique were sporadically reported. Fong and DuPlessis have developed a retropharyngeal exposure to the odontoid process in the cadaver (5). They used the METRx as retractor and working channel. Wolinsky et al. reported a similar surgical approach with endoscopic assisted to perform the retropharyngeal odontoidectomy and brainstem decompression without traversing the oral cavity (6). In their practice, endoscopic odontoidectomy was mainly performed through modified METRx, which was more than 2 cm in diameter. Compared with Wolinsky's method, our endoscopic trans-cervical odontoidectomy has some advantages. First, the diameter of hollow ring saw and endoscopic retractor was no more than 8.2 mm and the exposure was similar to placing the axial odontoid screw, which has been proved to be safe and feasible. The choice of 7.2-mm or 8.2-mm ring saw was made upon personalized size of the odontoid process. In Wolinsky's method, the operation was performed through a retractor which diameter is more than 2 cm. It needs a much larger exposure than us, and the superior laryngeal nerve, hypoglossal nerve along with marginal branch of the mandibular nerve were at higher risk of a stretch injury. Second, the technique reported by Wolinsky was susceptible to possible tubular retractor displacement resulting in range deviation of the surgical resection and accidentally injuring the surrounding structure. In our method, the 7.2-mm endoscopic sleeve was embedded into axial vertebrae and fixed by the circular bone. It has very few opportunity of sleeve displacement. Therefore, there is no need for external fixtures to restrain the displacement of the retractor. Third, Wolinsky's endoscope is more similar to MED (micro endoscopic discectomy), occasionally bleeding due to the paravertebral veins and cancellous bone marrow would blur the surgical vision. We performed this operation with a 6.5-mm coaxial spine endoscope, which is frequently applied in percutaneous lumbar transforaminal endoscopic discectomy. Continuous water irrigation and water pressure guaranteed a clear vision during endoscopic operation.

Ruetten et al. performed the similar procedure as us to treat infections of the anterior craniocervical junction (11–13). In their report, sufficient decompression and debridement resulted rapid regression of the clinical and neurological symptoms, as well as healing of the infection. In the report, they claimed that the sign of free floating of dura mater in the irrigation fluid indicated effective decompression. Our method had some similarities with Ruetten's method. The two methods both had the trans-cervical approach, both performed the operation with coaxial spine endoscope and have continuous water irrigation guarantees to stop bleeding. Additionally, because this is a typical full-endoscopic uniportal approach, other common technology for bleeding control also be used in our approach including controlled hypotension and radiofrequency ablation. But we also had some improvement compared with Ruetten's. First, in Ruetten's method, the working sleeve is placed in front of the odontoid process and outside of the bone, and the odontoid process was totally resected from the ventral to dorsal. In our method, a uniportal working sleeve was placed inside of the odontoid process with fluoroscopic guidance, then odontoid process was gradually resected from the inside to outside with the help of electric high-speed burr, which was newest designed for endoscopy and the tip is adjustable from 0° to 45° (**Figure 2G**). It should be safer that the resection of odontoid process from the inside to outside. Second, in Ruetten's method, the endoscopic sleeve was removable to achieve extent the range of resection and decompression. In our method, endoscopic working sleeve was embedded into axial vertebrae and fixed by the circular osseous space. With the help of special burr to extend the range of resection and decompression, the uniportal spinal endoscope has a very high magnification and accompanies a very limited version, so it is difficult to identify anatomical structure and locate the operation site *via* the view gotten from the monitor. If the sleeve was lack of effective fixation, deviation of the operative site from the target area may not to be realized in time. With fluoroscopic guidance, endoscopic sleeve is embedded into axial vertebrae and fixed by the circular osseous space could avoid deviation from the target area and repeatedly fluoroscopic position. Third, we had the hollow ring saw to remove the majority of the odontoid process, and it is more efficient than burr. The tip changeable burr enlarges the range of osteotomy and decompression on the basis of circular saw.

Additionally, Yukoh Ohara et al. also performed the similar procedure as us for odontoidectomy (14). Both of us used an "inside to outside" approach for odontoidectomy. However, there are still some differences between our approaches. In our approach, we first used a 7.2-mm hollow ring saw to remove most of the odontoid process whereas Yukoh Ohara et al. conducted the whole odontoidectomy throughout the drill. Thus, we believe our approach should be more efficient. Moreover, similar to Ruetten's approach, they need constant fluoroscopy to identify anatomical structures and avoid displacement of the working sleeve, while in our approach, the endoscopic sleeve is embedded into axial vertebrae and fixed by the circular osseous space which can avoid deviation from the target area and repeatedly fluoroscopic position. In summary, we believe Yukoh Ohara's approach is more like Ruetten's than ours.

However, there are some notable disadvantages associated with the full-endoscopic trans-cervical odontoidectomy we proposed. First, the bone resection and decompression was mainly limited to odontoid process, so only odontoid process biopsy and resection could be performed in case. Other procedures such as loosening and integration the lateral joint of axis and atlas seem to be difficult to perform with our method. Second, due to current equipment limitations, it is impossible to implement ventral supportive bone grafting and anterior instrumentation for axis and atlas. In addition, it is difficult to judge the actual extent of resection visually in the view of the endoscope, which in turn necessitates the use of the O-arm or C-arm for confirmation. The obese and the patients with severe cervical spine deformity also need to be excluded. Additionally, more patients treated with this technique with longer follow-up is warranted to confirm the feasibility and validity.

Conclusion

When performing simple odontoid resection, the proposed endoscopic trans-cervical odontoidectomy provides a valid choice for non-oral approach, which would reduce postoperative approach-related complications and accelerate postoperative recovery. But it needs a surgeon to be highly experienced in endoscopic procedures, and the range of surgery is mainly restricted to odontoid processes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

YT performed the surgery. JY, BL, and JH participated in the surgery as assistants. JL and GZ wrote the initial draft of the manuscript. KD collected preoperative and postoperative imaging data from patients. LG and JY helped YT to design the surgical procedures. CZ acted as the surgical nurse during the operations. YT and JY edited the final version of the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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