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Comparative analysis of short-term outcomes between minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) and traditional midline open transforaminal lumbar interbody fusion for single-level lumbar spinal stenosis

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Abstract

Background To compare the clinical efficacy of Minimally Invasive Transforaminal Lumbar Interbody Fusion (MIS-TLIF) versus Traditional Midline Open Transforaminal Lumbar Interbody Fusion (Open-TLIF) for Single-Level Lumbar Spinal Stenosis (LSS).

Methods From January 2020 to December 2023, 83 patients with single-level LSS were enrolled at our institution. Among them, 40 underwent MIS-TLIF (MIS-TLIF Group) and 43 received Open-TLIF (Open-TLIF Group). Surgical parameters including operative time, estimated blood loss, time to first ambulation, postoperative hospital stay, and intervertebral height were recorded. Clinical outcomes assessed preoperatively, at 1 month postoperatively, 3 months postoperatively, and final follow-up included: Visual Analog Scale (VAS) scores for low back pain and leg pain, and Oswestry Disability Index (ODI). Modified MacNab criteria were used to evaluate clinical efficacy at final follow-up.

Result All procedures were successfully completed. No statistically significant differences were observed in operative time or early complication rates between groups ($P > 0.05$). However, the MIS-TLIF group demonstrated significantly longer operative durations compared to Open-TLIF ($P < 0.05$), while the Open-TLIF group exhibited greater estimated blood loss, delayed time to first ambulation, and prolonged postoperative hospitalization versus MIS-TLIF (all $P < 0.05$). Both groups showed significant reductions in low back pain VAS, leg pain VAS, and ODI scores postoperatively versus preoperative baselines (all $P < 0.05$). Notably, the MIS-TLIF group achieved lower pain VAS and ODI scores at 1-month, 3-month, and final follow-up timepoints compared to Open-TLIF (all $P < 0.05$). According to modified MacNab criteria at final follow-up, both groups demonstrated excellent/good clinical outcomes without intergroup statistical significance ($P > 0.05$).

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Conclusion Both MIS-TLIF and Open-TLIF yield favorable clinical outcomes for single-level lumbar spinal stenosis (LSS). MIS-TLIF offers distinct advantages including reduced surgical trauma and accelerated postoperative recovery, demonstrating benefits in terms of reduced EBL, shorter time to first ambulation, and shorter hospitalization.

Keywords Lumbar spinal stenosis, Unilateral Biptoral Endoscopic Transforaminal Lumbar Interbody Fusion, Open Posterior Lumbar Interbody Fusion, Endoscopic Spinal Surgery, Transforaminal Lumbar Interbody Fusion, Minimally Invasive Surgery

Introduction

Lumbar spinal stenosis (LSS) is a prevalent degenerative spinal disorder particularly within the elderly population, characterized by classic symptoms such as neurogenic intermittent claudication, radicular lower-extremity pain, and sensory abnormalities. These symptoms significantly impair patients' mobility and overall quality of life [1–2]. For patients with moderate-to-severe LSS who do not respond adequately to conservative treatment, surgical decompression with interbody fusion has become a standard therapeutic approach [3].

The traditional midline open transforaminal lumbar interbody fusion (Open-TLIF) remains a widely performed procedure that effectively relieves neural compression. However, its requirement for extensive paraspinal muscle stripping and bony dissection often leads to considerable intraoperative blood loss, prolonged operative time, and extended postoperative recovery [4–5]. In response to these limitations, minimally invasive surgical techniques have been developed. Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF), in particular, has gained prominence by utilizing tubular retractor systems and microsurgical instrumentation to achieve bilateral neural decompression through a unilateral transforaminal approach. This method significantly reduces soft-tissue trauma, resulting in less blood loss, reduced postoperative pain, and faster rehabilitation [6–8].

Despite these advantages, the comparative efficacy of MIS-TLIF versus Open-TLIF continues to be a topic of discussion, especially regarding operative duration, complication profiles, and long-term functional outcomes. Existing studies have provided evidence supporting the benefits of MIS-TLIF in reducing perioperative morbidity, but nuances in patient selection, surgeon expertise, and anatomical constraints warrant further investigation [9–10]. Therefore, this study aims to compare the clinical outcomes of MIS-TLIF and Open-TLIF in treating single-level lumbar spinal stenosis, focusing on perioperative parameters and medium-term functional results. We hope to contribute more evidence to support surgical decision-making for this common spinal condition.

Subjects and methods

Inclusion criteria

(1) Radiographically confirmed single-level LSS with refractory radicular/low back pain; (2) Failure of ≥ 3 months of structured conservative management; (3) Absence of absolute surgical contraindications, including but not limited to: severe coagulopathy, active systemic or local infection, severe cardiopulmonary dysfunction (ASA class $\geq$ III), uncontrolled diabetes mellitus (HbA1c $> 7.5\%$), severe osteoporosis (T-score ≤ -3.0), or malignant tumors with life expectancy < 1 year.

Exclusion criteria

(1) Patients with conditions such as lumbar infections, spinal tuberculosis (lumbar), or lumbar tumors; (2) Patients with ossification of the posterior longitudinal ligament (OPLL); (3) Patients suffering from severe underlying diseases with impairments in heart, liver, kidney, or lung function; (4) Patients with a history of prior lumbar surgery;

Surgical methods

Surgical team

All procedures were performed by a consistent team of senior spinal surgeons specializing in degenerative disorders. The surgeons possessed extensive experience and formal specialized training in both open and minimally invasive spinal techniques. For the MIS-TLIF procedures, all surgeons had surpassed the initial learning curve associated with the technique, ensuring a high level of proficiency and procedural standardization across both patient groups throughout the study period.

MIS-TLIF group

All MIS-TLIF procedures were performed under general anesthesia with the patient prone on a radiolucent table. The target level was confirmed using fluoroscopy. A paramedian skin incision (~ 3 cm) was made on the symptomatic side approximately 4–5 cm lateral to the midline. The thoracolumbar fascia was incised, and the paraspinal muscles were bluntly dissected through the Wiltse plane (between the multifidus and longissimus muscles). Sequential tubular dilators were inserted over a guidewire to establish a working channel, and a tubular retractor (16–22 mm diameter) was positioned to expose the ipsilateral facet joint and lamina. Under

microscopic magnification, a complete ipsilateral facetectomy was performed using osteotomes and high-speed burrs, exposing the ligamentum flavum and the lateral aspect of the spinal canal. The ligamentum flavum was resected, and the traversing nerve root was identified and protected. Discectomy was performed, and the endplates were prepared. Contralateral decompression was achieved by angling the tubular retractor medially and undercutting the base of the spinous process and the ventral aspect of the contralateral lamina, allowing visualization and decompression of the contralateral lateral recess and foraminal area without disrupting the contralateral paraspinal muscles. Bone graft (local autograft mixed with allograft) was packed into the disc space, followed by insertion of a single interbody cage (size determined by trialing). Percutaneous pedicle screws were placed ipsilaterally through the same incision under fluoroscopic guidance; contralateral screws were inserted percutaneously via a separate small stab incision. A rod was passed subfascially and secured. A drain was placed, and the wound was closed in layers.

Open-TLIF group

Made an ~8 cm midline incision over the affected segment; performed bilateral subperiosteal dissection to fully expose spinous processes; determined screw entry points using anatomical landmarks; inserted bilateral pedicle screws under fluoroscopic guidance; installed connecting rods after confirmation; performed inferior facetectomy osteotomy and partial superior facetectomy; resected the ligamentum flavum to expose the disc and nerve root with hemostasis; removed the nucleus pulposus and decompressed the disc space; trialed the interbody cage followed by irrigation; packed bone fragments into the anterior disc space; implanted the cage posteriorly; performed contralateral laminectomy decompression; placed drains bilaterally before layered closure. All patients underwent unilateral TLIF decompression/fusion with ipsilateral instrumentation, combined with contralateral laminotomy decompression.

Postoperative treatment

Postoperatively, all patients followed a standardized enhanced recovery protocol. For pain control, patient-controlled analgesia (PCA) with opioids was administered for the first 24–48 h, followed by oral nonsteroidal anti-inflammatory drugs (NSAIDs) and muscle relaxants as needed; neuropathic pain agents (e.g., pregabalin) were prescribed specifically for radicular symptoms. The surgical drain was removed when output fell below 50 mL per 24 h, typically on postoperative day 1 or 2. Patients were encouraged to ambulate with a lumbosacral orthosis (LSO) as soon as tolerated, usually within 24–48 h after drain removal. The incision was kept dry for 5–7

days, with sutures or staples removed at 10–14 days postoperatively. Regarding activity, patients were advised to avoid bending, lifting (>5 kg), and twisting for 3 months, with sitting limited to 30 min at a time. Isometric lumbar muscle strengthening exercises (e.g., pelvic tilts, bridging) were initiated at 4 weeks, progressing to core stability training at 8–12 weeks under physiotherapist guidance. Finally, clinical and radiographic assessments were scheduled at 1, 3, 6, and 12 months, and annually thereafter.

Observation indicators and efficacy evaluation

The following parameters were recorded for both surgical groups: operative time, estimated blood loss (EBL), time to ambulation, postoperative hospital stay, disc space height and success fusion rate. Additionally, low back pain visual analog scale (VAS) scores, leg pain VAS scores, and Oswestry Disability Index (ODI) scores were documented preoperatively, at 1 month postoperatively, at 3 months postoperatively, and during the final follow-up. Clinical efficacy was evaluated using the Modified MacNab Criteria at the final follow-up.

VAS score for low back pain:

VAS score was performed on the day of admission, the 5th day after surgery, and the last follow-up of all patients, and the results were compared. The patient's analgesic regimen during hospitalization is oral aminophen dihydrocodeine tablets. The low back pain VAS score was used to assess the degree of pain in focal back pain (0 = no pain, 10 = worst pain).

Low back pain ODI score:

composed of 10 questions, including pain intensity, self-care, lifting, walking, sitting, standing, interfering with sleep, sex life, social life, travel and other 10 aspects of the situation, each question 6 options, the maximum score of each question is 5 points, the first option is selected for 0 points, and the last option is selected in turn for 5 points, if there are 10 questions are answered and answered. The scoring method is $100\% \times \text{of the actual score} / 50$ (maximum possible score), and if a question is not answered, the scoring method is: $\text{actual score} / 45$ (maximum possible score) $\times 100\%$, if higher indicates more severe dysfunction.

MacNab criteria

The Macnab excellent/good rate was evaluated at 3 months postoperatively, defined as follows: Excellent indicates complete resolution of symptoms with full return to pre-injury occupational and daily activities; Good represents mild residual symptoms causing minor activity limitations but no interference with work or daily living; Fair denotes partial symptom improvement

accompanied by functional restrictions that compromise normal work and daily activities; Poor reflects no improvement from baseline status or symptom exacerbation - with the combined Excellent/Good categories constituting the Macnab excellent/good rate.

Statistical methods

Statistical analyses were performed using SPSS 26.0 (IBM Corp., Armonk, NY). Continuous variables were assessed for normality via the Shapiro-Wilk test and for homogeneity of variances via Levene's test. For between-group comparisons of continuous, normally distributed variables where the estimand is a mean difference (e.g., perioperative metrics), Welch's independent samples *t*-test was employed to account for potential unequal variances and unbalanced group sizes. For continuous variables that violated normality or equal variance assumptions and where the target of estimation was a mean difference, the non-parametric Mann-Whitney U test was replaced by a permutation test (10,000 iterations) based on the Welch *t*-statistic. The Mann-Whitney U test was reserved exclusively for testing the hypothesis of stochastic superiority [$P(X > Y)$]. For these analyses, the common language effect size (Cliff's delta, *d*) with its 95% CI is reported. For longitudinal data measured at multiple timepoints (e.g., VAS, ODI), a repeated-measures analysis of variance (ANOVA) was applied. The omnibus F-test was corrected for potential violations of sphericity using the Greenhouse-Geisser epsilon (ϵ) adjustment. All planned post-hoc pairwise comparisons within the predefined family of hypotheses (e.g., between-group comparisons at each time point, or within-group changes from baseline at each follow-up) were adjusted for multiple testing using the Holm method to control the family-wise error rate (FWER). Adjusted P-values and adjusted 95% CIs for mean differences are reported. The specific family of hypotheses tested for each set of post-hoc contrasts is explicitly stated in the results. Categorical variables are described as frequencies and percentages (*n*, %), with between-group differences evaluated by χ^2 tests or Fisher's exact test, as appropriate. Statistical significance was defined as a two-sided $P < 0.05$.

Case selection

A retrospective comparative trial was conducted, which enrolled a total of 83 patients with single-level lumbar spinal stenosis (LSS) surgically treated at the Seventh Affiliated Hospital of Xinjiang Medical University between January 2020 and December 2023. The choice of surgical approach (MIS-TLIF vs. Open-TLIF) was determined by the attending surgeon based on comprehensive preoperative assessment, including the severity of spinal stenosis, the presence of bilateral symptoms, and the complexity of spinal deformity. This reflects the

real-world clinical decision-making process. Based on the surgical approach, patients were divided into two groups: 40 underwent MIS-TLIF group and 43 received Open-TLIF group.

Results

Analysis of the number of participants

From January 2020–December 2023, a total of 83 patients met the above criteria and were included in this study. They were divided into two groups according to the different surgical methods used, in which 40 cases were included in the MIS-TLIF group and 43 cases were included as the Open-TLIF group, and the flow charts of the two subgroups are shown in Fig. 1.

Comparison of preoperative data between the two groups

Preoperative comparison of demographic characteristics, radiographic severity, and surgical levels between the two groups was performed. As shown in Table 1, there were no statistically significant differences in age, gender distribution, BMI, disease course, Operative level, ASA Score, Smoking Status, Charlson Comorbidity Index, Hypertension, Diabetes, COPD, or radiographic stenosis severity (Schizas grade) between the two groups (all $P > 0.05$). This indicates that the two groups were well-balanced at baseline, see Table 1.

Comparison of perioperative indicators

All procedures were completed successfully. The operative time was significantly longer in the MIS-TLIF group compared to the Open-TLIF group. Conversely, estimated blood loss, time to postoperative ambulation, and postoperative hospital stay were significantly greater in the Open-TLIF group than in the MIS-TLIF group. All these differences were statistically significant ($P < 0.05$; Table 2). Early postoperative complications occurred in 4 patients in the MIS-TLIF group: intraoperative dural tear with cerebrospinal fluid (CSF) leakage ($n = 2$) and postoperative low back pain ($n = 2$). In the Open-TLIF group, 5 patients experienced early postoperative complications: intraoperative dural tear with CSF leakage ($n = 3$), postoperative low back pain ($n = 1$), and superficial surgical site infection (SSI) requiring non-operative management ($n = 1$). All complications resolved with appropriate management.

Comparison of clinical efficacy analysis between the two groups

All patients completed follow-up. Both groups exhibited statistically significant reductions in postoperative low back pain VAS, leg pain VAS, and ODI scores compared to preoperative values (all $P < 0.05$; Table 3). The MIS-TLIF group demonstrated significantly lower low back pain VAS, leg pain VAS, and ODI scores

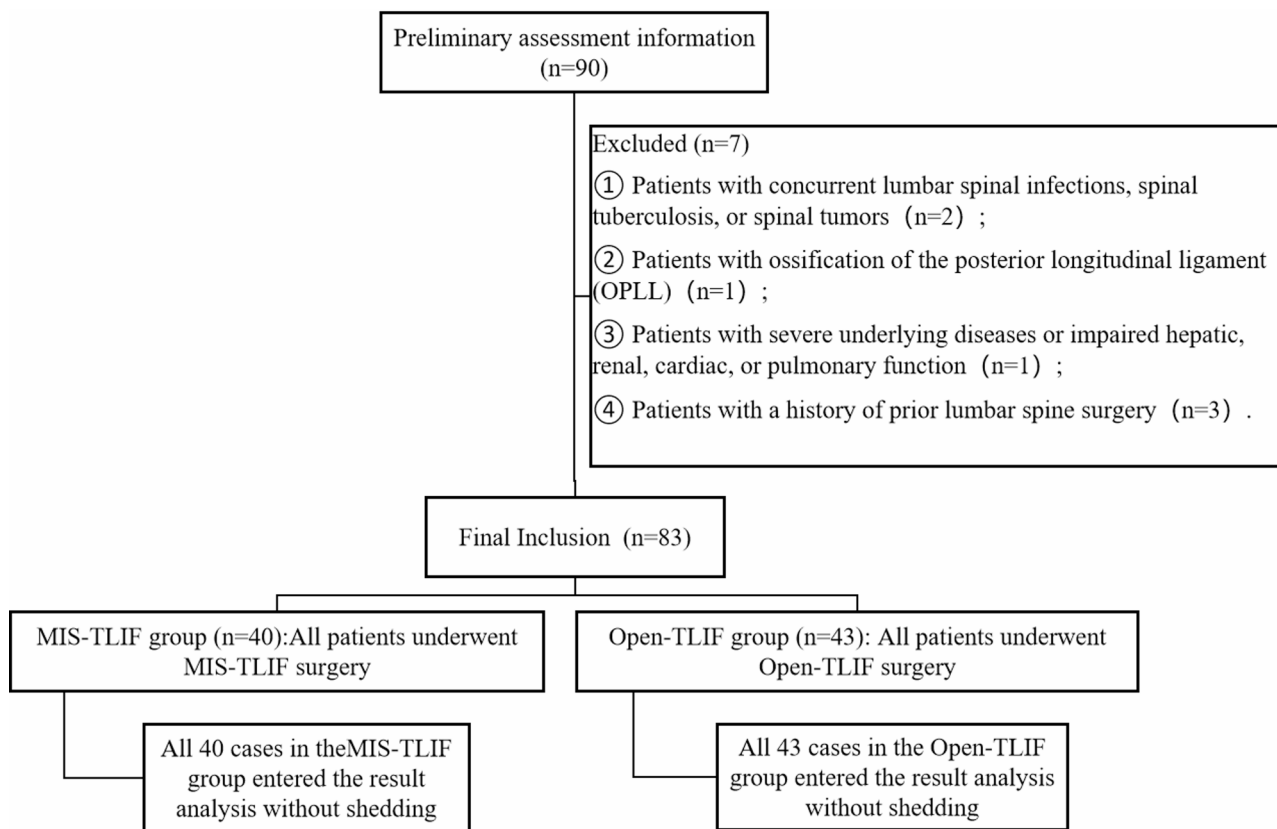


Fig. 1 Flow chart of test grouping

than the Open-TLIF group at 1 month, 3 months, and final follow-up (all $P < 0.05$; Table 3). According to the Modified MacNab criteria, all patients in both groups achieved “excellent” or “good” outcomes postoperatively, with no statistically significant intergroup differences ($P > 0.05$); All patients completed radiographic follow-up at 12 months postoperatively. According to the Bridwell grading system, the success fusion rates (Grade I+II) were 92.5% (37/40) in the MIS-TLIF group and 90.7% (39/43) in the Open-TLIF group, with no statistically significant difference between the two groups ($P = 0.749$). Table 3; Fig. 2).

Typical cases

(1) Patient 1: Female, 48 years old, presented with low back pain accompanied by bilateral lower limb numbness for 6 months. Preoperative lumbar spine anteroposterior/lateral radiographs and MRI confirmed single-level lumbar spinal stenosis at L_{4/5} (Fig. 3A-C). She underwent MIS-TLIF at L_{4/5}. One-year postoperative radiographs and MRI demonstrated satisfactory position of the internal fixation and adequate neural decompression (Fig. 3D-F).
 (2) Patient 2: Male, 53 years old, presented with low back pain accompanied by right lower limb pain for 2 years. Preoperative lumbar spine anteroposterior/lateral radiographs and MRI confirmed single-level

lumbar spinal stenosis at L_{4/5} (Fig. 3G-I). He underwent Open-TLIF at L_{4/5}. One-year postoperative radiographs and MRI demonstrated satisfactory position of the internal fixation and adequate neural decompression (Fig. 3J-L).

Discussion

This study employed a minimally invasive approach assisted by tubular or quadrant-specific retractors. This technique offers limited surgical exposure, concentrating the operative field within specific anatomical quadrants. Consequently, it demands advanced three-dimensional anatomical understanding of the lumbar spine and refined surgical skills from the operator. Only surgeons with extensive experience in transforaminal lumbar interbody fusion can reliably perform this procedure [11]. Study data revealed that the MIS-TLIF group had a significantly longer operative time (195.50 ± 18.20 min) compared to the open surgery group (144.80 ± 20.15 min) ($P < 0.001$). This difference primarily stems from the steep learning curve associated with the minimally invasive unilateral approach bilateral decompression technique as a novel procedure, requiring an extended technical familiarization phase during initial clinical practice [12]. However, MIS-TLIF combined with unilateral laminotomy for bilateral decompression demonstrated

Table 1 Comparison of the preoperative data between the two groups

Factor	MIS-TLIF group(n = 40)	Open-TLIF group(n = 43)	t/x ²	P
Gender, n(%)			0.019	0.891
Male	22 (55.0%)	23 (53.5%)		
Female	18 (45.0%)	20 (46.5%)		
Age/year	54.62 ± 5.24	55.32 ± 4.97	-0.625	0.534
BMI(kg/m ²)	23.89 ± 4.09	24.11 ± 4.74	-0.226	0.822
Duration of symptoms (months)	11.80 ± 1.69	12.14 ± 1.45	-0.986	0.327
Operative level, n(%)			0.099	0.951
L ₃ /L ₄	4 (10.0%)	5 (11.6%)		
L ₄ /L ₅	20 (50.0%)	22 (51.2%)		
L ₅ /S ₁	16 (40.0%)	16 (37.2%)		
Radiographic Severity (Schizas Grade), n (%)			2.630	0.105
A/B (Mild/Moderate)	30 (75.0)	25 (58.1)		
C/D (Severe)	10 (25.0)	18 (41.9)		
ASA Score, n (%)			0.452	0.798
I	12 (30.0%)	14 (32.6%)		
II	26 (65.0%)	26 (60.5%)		
III	2 (5.0%)	3 (7.0%)		
Smoking Status, n (%)			0.218	0.641
Smoker	9 (22.5%)	11 (25.6%)		
Non-smoker	31 (77.5%)	32 (74.4%)		
Hypertension, n (%)	12 (30.0%)	14 (32.6%)	0.065	0.799
Diabetes, n (%)	8 (20.0%)	10 (23.3%)	0.130	0.718
COPD, n (%)	3 (7.5%)	4 (9.3%)	0.086	1.000

Continuous variables are presented as mean ± standard deviation

Categorical variables are presented as n (%)

χ²: Chi-square test; t: Student's t-test

Schizas grade was assessed on preoperative MRI. Grade A/B indicates mild to moderate stenosis, while Grade C/D indicates severe stenosis

ASA: American Society of Anesthesiologists physical status classification

COPD: Chronic Obstructive Pulmonary Diseases

Table 2 Clinical efficacy indexes of 2 groups

Factor	MIS-TLIF group(n = 40)	Open-TLIF group(n = 43)	t	P
Operative Time/min	195.50 ± 18.20	144.80 ± 20.15	12.000	< 0.001
EBL/ml	220.45 ± 24.30	251.90 ± 32.50	-4.964	< 0.001
Time to Ambulation/day	2.95 ± 1.50	4.80 ± 1.75	-5.154	< 0.001
Postoperative Hospital Stay /day	6.50 ± 3.20	14.90 ± 3.80	-10.853	< 0.001
Disc Space Height/mm	10.15 ± 2.30	9.86 ± 2.70	0.526	0.601

The continuous value was given as the mean and the standard deviation

t:Student's t; EBL:Estimated blood loss

significant advantages in several perioperative metrics, including estimated blood loss (220.45 ± 24.30 ml vs. 251.90 ± 32.50 ml) and time to ambulation postoperatively (2.95 ± 1.50 days vs. 4.80 ± 1.75 days) (both $P < 0.01$). Regarding surgical strategy selection for lumbar spinal stenosis patients, an ongoing debate persists within

Table 3 Clinical efficacy indexes of 2 groups

Factor	MIS-TLIF group(n = 40)	Open-TLIF group(n = 43)	t/x ²	P
Low back pain VAS score				
Preoperatively	7.40 ± 1.30	7.20 ± 1.40	0.023	0.981
1 month	4.20 ± 1.20* Δ	5.30 ± 1.50 Δ	-3.701	< 0.001
3 month	2.00 ± 0.65* Δ	2.90 ± 1.45 Δ	-3.690	< 0.001
Last follow-up	1.05 ± 0.38* Δ	1.65 ± 0.60 Δ	-5.479	< 0.001
Leg pain VAS score				
Preoperatively	6.90 ± 1.55	7.30 ± 1.35	-1.662	0.099
1 month	4.50 ± 1.40* Δ	5.80 ± 1.30 Δ	-4.375	< 0.001
3 month	2.80 ± 1.60* Δ	3.75 ± 1.10 Δ	-3.130	0.002
Last follow-up	0.90 ± 0.70* Δ	1.75 ± 0.90 Δ	-4.820	< 0.001
ODI(%)				
Preoperatively	67.00 ± 8.90	68.50 ± 9.85	-1.051	0.293
1 month	38.50 ± 7.20* Δ	45.30 ± 8.40 Δ	-3.970	< 0.001
3 month	24.00 ± 6.50* Δ	29.10 ± 8.70 Δ	-3.039	< 0.001
Last follow-up	11.20 ± 2.25* Δ	14.15 ± 3.05 Δ	-5.038	< 0.001
MacNab			0.084	0.772
Criteria, n				
Excellent	37	39		
Good	3	4		
Follow-up time/month	18.33 ± 1.42	18.75 ± 1.61	-1.262	0.211
Success Fusion Rate (I + II)	37 (92.5%)	39 (90.7%)	0.102	0.749

The continuous value was given as the mean and the standard deviation

χ²:Chi-square test; t:Student's t;*P < 0.05 compared with the Open-TLIF group; Δ P < 0.05 compared with preoperative values

the academic community concerning whether bilateral complete decompression is necessary for cases presenting with severe unilateral stenosis combined with mild contralateral stenosis [13–14]. The current modified technique achieves bilateral neural foramen decompression via a posterior unilateral laminectomy approach while completing interbody fusion and internal fixation. Its indications should be strictly limited to radiologically confirmed cases of severe unilateral stenosis combined with mild-to-moderate contralateral stenosis (Modic changes Grade II or below). Patients with bilateral severe stenosis (Modic Grade III) are recommended for the traditional open bilateral decompression technique [15].

The traditional midline open transforaminal lumbar interbody fusion (Open-TLIF), as a well-established spinal surgical technique, utilizes a unilateral transforaminal approach to access the disc space. This involves facetectomy and laminotomy to enable discectomy and neural decompression, followed by the implantation of an interbody cage combined with posterior pedicle screw instrumentation to reconstruct segmental stability [16]. Historically recognized as a standard treatment for degenerative lumbar conditions due to its effectiveness in achieving neural decompression and providing immediate mechanical stabilization [17], the traditional

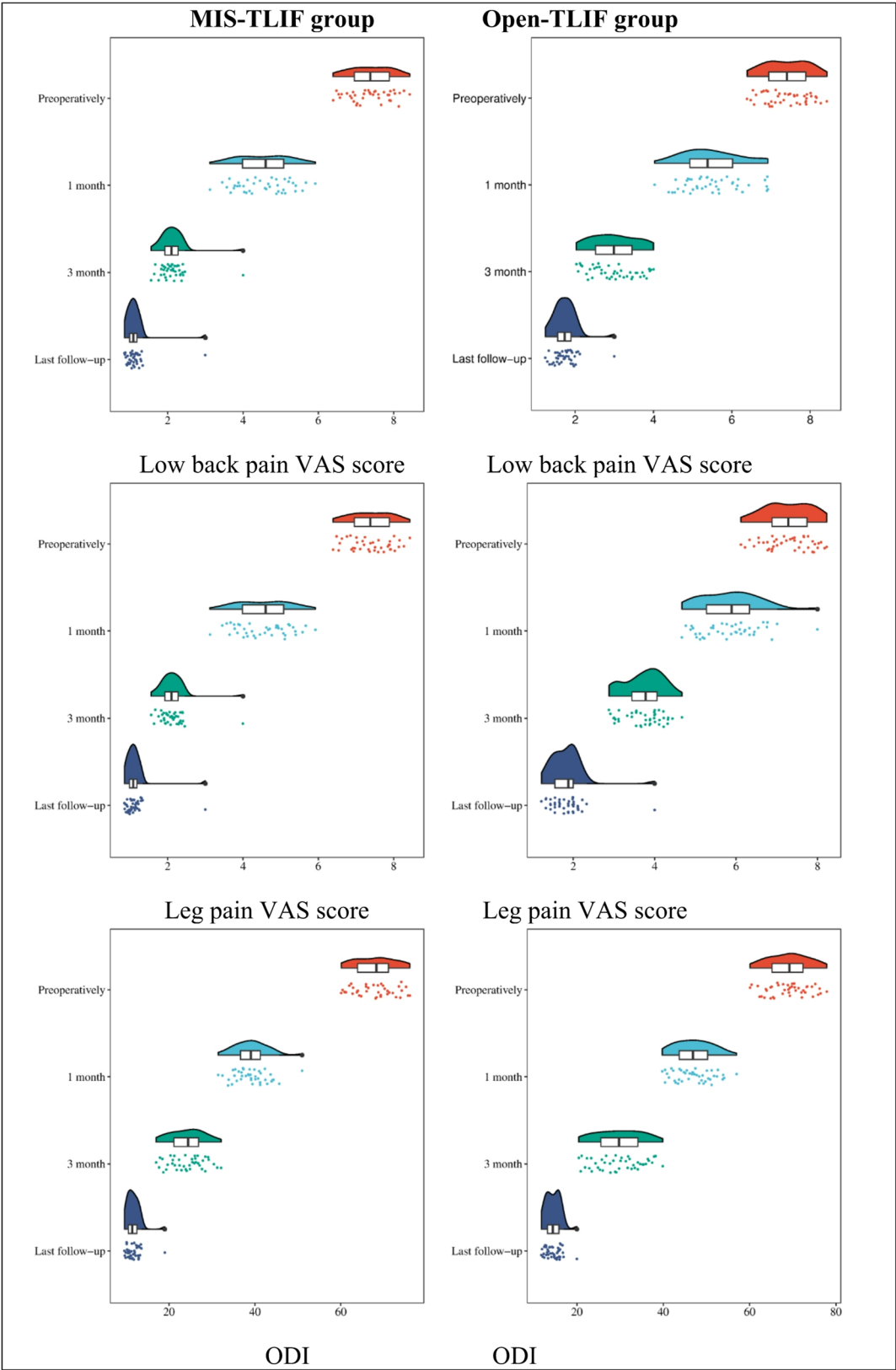


Fig. 2 Comparison chart of two groups of clinical efficacy indicators

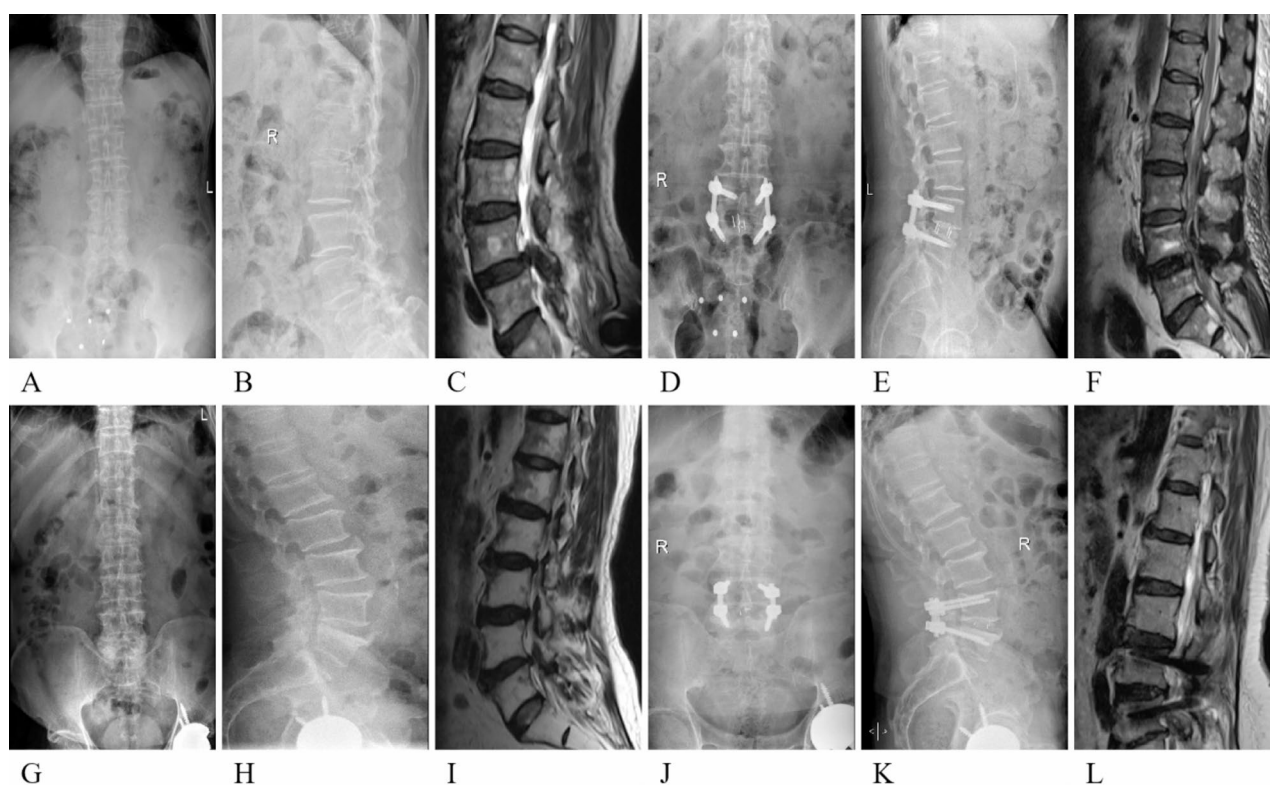


Fig. 3 Imaging data of a typical case in MIS-TLIF group

Open-TLIF approach nevertheless carries inherent drawbacks. It requires extensive paraspinal muscle dissection and retraction, which can lead to intraoperative muscle injury and compromised postoperative dynamic stability of the lumbar spine. This often contributes to complications such as chronic postoperative back pain, muscle atrophy, and in some cases, symptom recurrence [18]. Against this backdrop, MIS-TLIF has emerged. By refining surgical access and utilizing specialized instrumentation, MIS-TLIF achieves clinical outcomes comparable to traditional TLIF while significantly reducing perioperative tissue trauma and associated healthcare costs. Consequently, it has become an increasingly recognized option with enhanced clinical value [19].

During the evolution of spinal techniques, the unilateral laminotomy for bilateral decompression (ULBD) introduced by Sihvonen et al. in 1993 pioneered a novel concept of preserving contralateral spinal stabilizing structures. By achieving bilateral neural decompression through unilateral muscle dissection, it effectively reduced the incidence of postoperative lumbar instability [20]. With advancements in microsurgical techniques, Lim et al. further validated the safety and efficacy of microscope-assisted ULBD, laying the groundwork for subsequent minimally invasive approaches [21]. In 2010, Lee's team systematically described the MIS-TLIF technique, achieving minimally invasive modification

of interbody fusion through the application of tubular retractor systems and specialized dilating instruments [22].

Building upon this foundation, our research team integrated the ULBD concept, innovatively combining MIS-TLIF with precise decompression techniques. Clinical observations indicate that this combined approach offers significant advantages over traditional open surgery in terms of minimized incisions, hemorrhage control, and postoperative recovery [23]. It is crucial to emphasize, however, that this procedure presents technical challenges when performed under tubular or Quadrant retractor assistance. These include restricted surgical field exposure and fixed operative angles. Consequently, it demands surgeons possess a robust three-dimensional anatomical cognition, substantial TLIF experience, and necessitates navigating a steep learning curve to achieve proficiency [24, 25].

This study has several limitations that should be acknowledged. First, its retrospective, non-randomized design introduces inherent selection bias. Although baseline characteristics were well balanced, the choice of surgical approach was determined by the attending surgeon based on preoperative assessment, which may have been influenced by factors not fully captured in our analysis, such as the severity of facet joint arthropathy or specific anatomical variations. Second, surgeon experience and

learning curve represent a potential confounding factor. While all surgeons had surpassed the initial learning curve for MIS-TLIF, individual variations in proficiency and the cumulative effect of experience over the four-year study period could have influenced outcomes. Third, the sample size, while adequate for detecting differences in perioperative parameters, may be insufficient to identify rare complications or long-term implant-related failures. Fourth, the follow-up period (mean 18 months) is relatively short for assessing long-term fusion durability or adjacent segment degeneration. Future multicenter, prospective randomized controlled trials with larger sample sizes and longer follow-up are warranted to validate our findings and further refine patient selection criteria.

Compared to the conventional TLIF technique, this method significantly reduces estimated blood loss, the extent of muscle and soft tissue damage, and postoperative recovery time, aligning with the core principles of minimally invasive surgery (MIS) and the Enhanced Recovery After Surgery (ERAS) pathway. Future validation of its efficacy necessitates multicenter, large-sample, longitudinal prospective studies with long-term follow-up.

Abbreviations

MIS-TLIF	Minimally Invasive Transforaminal Lumbar Interbody Fusion
Open-TLIF	Open Transforaminal Lumbar Interbody Fusion
LSS	Lumbar Spinal Stenosis
ULBD	Unilateral laminotomy for bilateral decompression
ERAS	Enhanced Recovery After Surgery

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Not applicable.

Authors' contributions

Study design, conception, and critical revision: Bin Yan and Yanqing Tan. Analysis and interpretation of data: MaiWulan Mansuerjiang and Bin Yan. Literature search and drafting of manuscript: Bin Yan, Yanqing Tan, MaiWulan Mansuerjiang. Adiyati Abulati and Bin Yan contributed to critical revision of the manuscript for important intellectual content and approved the final version of the manuscript. All authors read and approved the final version of the manuscript.

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Data availability

The clinical efficacy of MIS-TLIF and posterior midline Open-TLIF for single-segment LSS was investigated, so the dataset analyzed in this study is not publicly available but is available to the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

We confirm that all experiments were performed in accordance with the Declaration of Helsinki. The study was approved by the Ethical Committee of The Seventh Affiliated Hospital of Xinjiang Medical University. Each patient provided written informed consent before participating in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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