Clinical Efficacy of OLIF, TLIF, and UBE-TLIF in the Treatment of Lumbar Disc Herniation—A Comprehensive Evaluation Based on Imaging and Inflammatory Indicators

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AIM: Oblique Lateral Interbody Fusion (OLIF), Transforaminal Lumbar Interbody Fusion (TLIF), and Unilateral Biportal Endoscopy (UBE)-TLIF are widely used surgical approaches in the clinical treatment of Lumbar Disc Herniation (LDH). However, comparative studies on their efficacy remain insufficient. Therefore, this study aims to compare the clinical effectiveness of the three surgical approaches for treating LDH across multiple dimensions, providing evidence-based surgical decision-making tailored to individual patient requirements.

METHODS: This retrospective study included 210 patients with LDH who underwent surgical treatment in our hospital between May 2021 and May 2024. They were divided into the OLIF group (n = 68), TLIF group (n = 72), and UBE group (n = 70) according to the surgical method, and all patients completed a follow-up of at least 3 months. Baseline characteristics of all three groups were collected, and perioperative indicators were compared and analyzed. The Visual Analogue Scale (VAS) and the Oswestry Disability Index (ODI) were used to assess pain intensity and functional recovery in patients. Serum levels of C-reactive protein (CRP), D-dimer, and hemoglobin were used to assess inflammatory response and blood loss-related indicators. Differences in imaging indicators were also compared among the three groups. The types and incidence of postoperative complications were also assessed among these groups.

RESULTS: No statistically significant differences were observed in the baseline data among the three groups ($p > 0.05$). The OLIF group had a significantly shorter operation time than the TLIF and UBE groups ($p < 0.001$) and a shorter hospital stay than the TLIF group ($p < 0.05$). The UBE group had significantly less intraoperative blood loss than the OLIF and TLIF groups ($p < 0.05$). At 3 months postoperatively, VAS and ODI scores were substantially lower for all three groups than the baseline values ($p < 0.001$), with no statistically significant differences among the three groups ($p > 0.05$). At postoperative day 3, serum CRP and D-dimer levels in all three groups were higher than the preoperative levels, whereas hemoglobin levels were lower ($p < 0.001$). However, the UBE group had lower CRP and D-dimer levels than the TLIF group ($p < 0.05$), and a smaller decrease in hemoglobin level than the TLIF group ($p < 0.05$). Imaging evaluation showed that the intervertebral space height was significantly restored in all three groups at 3 months postoperatively compared with preoperative values ($p < 0.001$), and there was no significant difference in the rate of good spinal canal decompression ($p > 0.05$). There was no significant difference in the total incidence among the three groups ($p > 0.05$).

CONCLUSIONS: OLIF, TLIF, and UBE-TLIF are all effective in alleviating pain and improving lumbar function and have comparable safety profiles. OLIF is associated with shorter operative time and hospital stays, and UBE offers less surgical trauma as well as a milder early postoperative inflammatory response.

Keywords: Lumbar Disc Herniation; Oblique Lateral Interbody Fusion; Transforaminal Lumbar Interbody Fusion; Unilateral Biportal Endoscopy

Introduction

Lumbar Disc Herniation (LDH) is a common degenerative spinal disease in clinical orthopedics. The central pathogenic mechanism involves progressive degeneration of the intervertebral disc, rupture of the annulus fibrosus, and herniation of the nucleus pulposus, resulting in the compression of the nerve roots or cauda equina. This compression leads to multiple symptoms, including lumbodorsal pain, radiating pain in the lower extremities, numbness, and neurological dysfunction, significantly compromising patients' functional capability and quality of life [1,2]. With advancing population aging and changes in lifestyle, the incidence of LDH is progressively increasing annually, and the affected population is gradually becoming younger, posing higher requirements for clinical treatment [3].

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In the therapeutic framework for LDH, conservative treatment is a widely preferred and first-line approach. However, in specific cases, when this approach fails for more than 3 months, symptoms persistently worsen, or neurological impairments progress, surgical intervention becomes a necessary option [4]. In recent years, spinal surgical approaches have developed rapidly, with a strong focus on reducing surgical trauma and accelerating postoperative recovery. Among these techniques, Oblique Lateral Interbody Fusion (OLIF), Transforaminal Lumbar Interbody Fusion (TLIF), and Unilateral Biportal Endoscopy (UBE)-TLIF have been widely adopted in clinical practice due to their distinct technical advantages [5–7].

OLIF uses a lateral approach that bypasses the psoas major muscle and dense neural structures, enabling direct removal of herniated nucleus pulposus tissue and implantation of an interbody fusion cage. This process restores intervertebral disc height and intervertebral fusion, while significantly reducing injury to posterior soft tissues [8]. TLIF is performed via a transforaminal approach, which enables precise nerve root decompression and bone graft fusion under direct visualization, providing a broad fusion interface and favorable maintenance of lumbar stability [9]. UBE-TLIF relies on a biportal endoscopic system consisting of a dedicated "observation and working channel", which combines minimal invasiveness with operational flexibility. It allows complex decompression and fusion procedures in a confined operative field, with reduced intraoperative blood loss and milder postoperative pain responses [10].

The inflammatory response induced by surgical trauma is a key determinant of postoperative recovery. Serum C-reactive protein (CRP) can directly reflect acute inflammation [11], D-dimer is associated with postoperative coagulation function and thrombus risk [12], and hemoglobin level directly indicates intraoperative blood loss [13]. Collectively, these indicators constitute key biological markers for evaluating surgical safety. In parallel, imaging indices serve as the primary basis for determining the anatomical efficacy of surgery and lumbar stability [14]. Although OLIF, TLIF, and UBE-TLIF are all widely adopted minimally invasive treatment options for LDH, most existing clinical studies have either assessed a single surgical approach or performed a simple comparison between two methods. A systematic and comprehensive comparison of all three approaches across perioperative indicators, imaging fusion outcomes, and modulation of the inflammatory response remains limited.

Given the above considerations, this study retrospectively analyzed the clinical data of 210 LDH patients treated with three different surgical methods and compared their therapeutic efficacy and outcomes across multiple dimensions. The ultimate aim of this study was to provide more comprehensive evidence-based references to guide individualized selection of surgical methods in clinical practice.

Methods

Recruitment of Study Participants

This study recruited 210 LDH patients who underwent surgical treatment in the Department of Orthopedics in The First Affiliated Hospital of Anhui University of Chinese Medicine between May 2021 and May 2024 and divided them into the OLIF group (n = 68), TLIF group (n = 72), and UBE group (n = 70) according to the surgical method.

Inclusion criteria for patient selection were as follows: (1) clinical confirmed LDH, with typical manifestations of lumbodorsal pain and radiating pain and/or numbness in the lower extremities; magnetic resonance imaging (MRI) confirming nerve root compression by herniated nucleus pulposus, with the lesioned segment consistent with the localization of clinical symptoms (Fig. 1); (2) persistent symptoms without relief after more than 3 months of conservative treatment (including bed rest, oral non-steroidal anti-inflammatory drugs, and physical therapy), or progressive manifestations such as aggravated pain, decreased lower limb muscle strength, and urinary and fecal dysfunction; (3) undergone OLIF, TLIF, or UBE-TLIF surgery; and (4) postoperative follow-up duration of at least 3 months.

Exclusion criteria included: (1) coexisting spinal tumors or infectious spinal diseases; (2) history of previous lumbar surgery or congenital abnormalities of the lumbosacral region; (3) presence of contraindications to surgical procedure, such as coagulation disorders, severe cardiopulmonary insufficiency, or hepatic/renal failure; (4) mental illness or cognitive impairment preventing reliable pain scoring and functional assessment; (5) loss to follow-up for personal reasons or lack of key data required to assess therapeutic efficacy. All procedures were performed by the same experienced surgical team. This study received ethical approval from the Ethics Committee of The First Affiliated Hospital of Anhui University of Chinese Medicine (No. 2024MCZQ28).

Surgical Procedures

All three surgical procedures were performed under general anesthesia. Each surgical procedure is described below:

OLIF Group

Patients were placed in the right lateral decubitus position with a soft pad under the waist to maintain mild lumbar convexity and facilitate exposure of the lateral surgical field. The target intervertebral level was localized using C-arm fluoroscopy, and a 5 cm skin incision was marked on the lateral abdomen, approximately 8–10 cm from the midline. The skin and subcutaneous tissue were incised sequentially, followed by dissecting the external oblique, internal oblique, and transversus abdominis muscles. Blunt dissection was then performed through the retroperitoneal space, with careful retraction of the peritoneum, intra-abdominal organs, and vascular structures to prevent neurovascular injury. After exposing the lateral aspect of the target disc

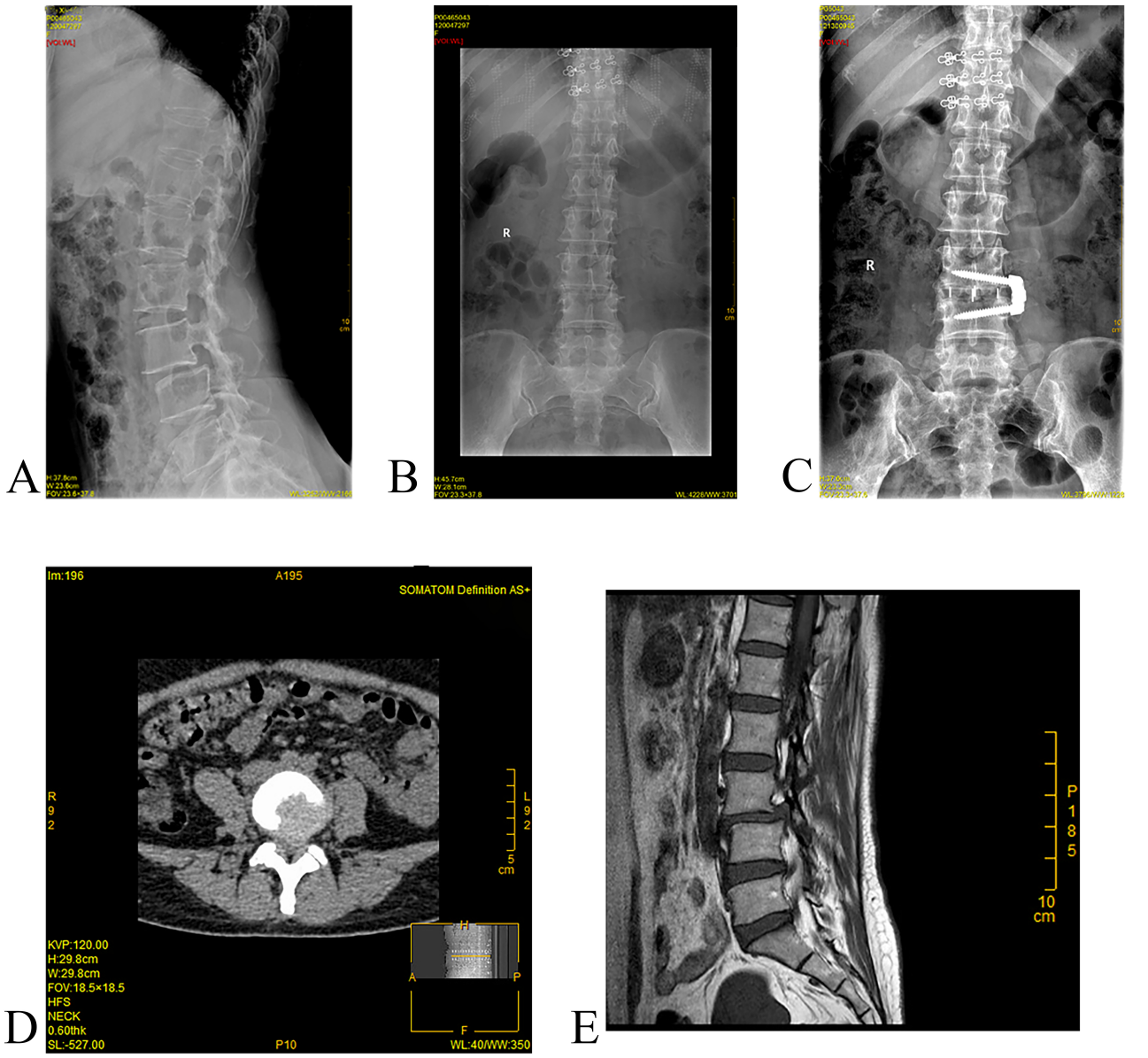

Fig. 1. Imaging findings of a 54-year-old female patient presenting with low back pain and leg numbness. (A,B) Anteroposterior and lateral lumbar radiographs show disc herniation at L4-L5 and grade I spondylolisthesis at L3. (C) Postoperative radiograph demonstrates fusion status. (D,E) CT and MRI images confirm a herniated nucleus pulposus compressing the nerve root. Note: R, right; CT, computed tomography; MRI, magnetic resonance imaging; L, lumbar vertebrae; A, anterior; F, foot; H, head; P, posterior.

space, a percutaneous endoscope was used to remove degenerated nucleus pulposus and cartilaginous endplates until fresh bleeding from the bony endplates was observed. An appropriately sized interbody fusion cage was selected based on the disc space dimensions and gradually inserted. Fluoroscopy was applied to verify that the cage was centrally positioned and stable, after which the incision was closed in layers.

TLIF Group

Patients were placed in the prone position with high-density foam pads under the chest and pelvis to maintain lumbar lordosis and prevent abdominal compression, thereby preserving respiratory mechanics and venous return. The target level was confirmed using C-arm fluoroscopy. A midline posterior incision of appropriate length was made, and the soft tissues were dissected layer by layer through the skin, subcutaneous tissue, and lumbodorsal fascia. The paraspinal muscles were subperiosteally dissected from the laminae using a periosteal elevator to expose the laminae and facet joints at the target level.

The unilateral inferior articular process and a portion of the lamina were removed with a high-speed burr to create a transforaminal window. The nerve root was identified and gently, minimally retracted with a nerve retractor to prevent traction injury. Herniated disc material was removed, neu-

ral adhesions were carefully released, and the superior and inferior endplates were prepared with a curette until fresh bleeding bone was observed. An appropriately sized interbody fusion cage was inserted, and segmental fixation was performed with a pedicle screw. Implant position and restoration of disc height were confirmed fluoroscopically. The surgical field was irrigated, a closed suction drain was placed, and the incision was closed in layers.

UBE Group

Patients were placed in the prone position, and the target segment was identified under C-arm fluoroscopy. Two parallel skin incisions were made to establish the viewing and working portals. An endoscope was inserted through the viewing portal and connected to an imaging system to get a clear view of the lamina, facet joint, and nerve root. Through the working portal, surgical instruments, such as grasping forceps and a high-speed burr, were introduced to dissect the paraspinal muscles and expose the surgical field.

Partial laminectomy and facetectomy were then performed using a high-speed burr to expand the spinal canal. The nerve root was carefully protected while the herniated nucleus pulposus was removed and the endplates were prepared. An interbody fusion cage was implanted, and its position and the adequacy of neural decompression were confirmed under fluoroscopy. The surgical field was irrigated, a drainage tube was placed, and the incisions were sutured in layers.

Data Collection

General Information

Baseline demographic and clinical information for the three groups was obtained from the hospital electronic medical record system, including gender, age, and surgery-related characteristics such as fusion segment position (lumbar vertebrae [L]3-L4, L4-L5, L5-sacral vertebrae[S]1) and the number of fused segments (single vs. double). Perioperative indicators, including operation time, intraoperative blood loss, and length of hospital stay, were collected from surgical and nursing records. Pain and functional status were assessed preoperatively and at 3-month postoperatively using the Visual Analogue Scale (VAS) and the Oswestry Disability Index (ODI), respectively.

The VAS for pain uses a 0–10 scale, where 0 indicates no pain and 10 denotes the most severe pain [15]. The ODI covers 10 dimensions, including pain intensity, daily living activities, and walking ability, with each dimension scored 0–5; the total score is the sum of all dimensions multiplied by 2, yielding a maximum of 100, and higher scores indicate more severe lumbar dysfunction [16]. Postoperative complications occurring within 3 months, including incision infection, nerve root injury, cerebrospinal fluid leakage, retroperitoneal hematoma, and thromboembolism, were recorded , and the incidence of complications was calculated for each group.

Inflammatory Indicators and Hemoglobin Assessment

Fasting venous blood samples (5 mL) were collected from all patients preoperatively and on postoperative day 3. Serum CRP, D-dimer, and hemoglobin levels were assessed using an automated biochemical analyzer (AU5800, Beckman Coulter, Inc, Pasadena, CA, USA). The normal reference ranges were as follows: CRP, 0–10 mg/L; D-dimer, 0–0.55 mg/L; hemoglobin, 120–160 g/L in males and 110–150 g/L in females.

Radiographic Evaluation

Preoperative and 3-month postoperative radiographic examinations were performed and independently evaluated by 2 experienced radiologists in a double-blind method. Imaging assessments were conducted using X-ray, computed tomography (CT) scan, and MRI.

Anteroposterior and lateral lumbar radiographs were obtained through the X-ray method. The height of the target intervertebral space (vertical distance from the midpoint of the upper endplate to the midpoint of the lower endplate of the vertebral body, in mm) was measured using RadiAnt DICOM Viewer software (Version 2020.1, Medixant, Poznan, Poland). The postoperative change in the disc height (recovery range) compared with the preoperative baseline value was then calculated.

During CT scan (Revolution Evo model, General Electric, Milwaukee, WI, USA), thin-slice lumbar CT scanning (slice thickness: 1 mm) was conducted to assess early fusion trends. Fusion was defined as the presence of trabecular bone transversing the fusion cage, without an obvious radiolucent area at the interface between the fusion cage and the upper/lower endplates. The early fusion trend rate was assessed as = the number of patients meeting the fusion criteria/the total number of patients.

MRI (SIGNA Voyager model, General Electric Medical Systems, Milwaukee, WI, USA) of the lumbar spine, including T1- and T2-weighted scans, was performed to evaluate the effect of spinal canal decompression. The criteria for "good" decompression outcomes were defined as complete relief of nerve root compression on MRI, restoration of a normal dural sac shape, and absence of evident cerebrospinal fluid leakage or nerve root edema. A poor outcome was defined as persistent or partially residual nerve root compression with continued dural sac compression. The spinal decompression rate was calculated as the number of patients with good decompression outcomes divided by the total number of patients.

Statistical Analysis

Statistical analyses were performed using SPSS 26.0 (IBM Corp., Armonk, NY, USA). Normally distributed continuous variables, assessed by the Shapiro-Wilk test, were presented as mean ± standard deviation ($\bar{x} \pm s$). Intergroup comparisons were performed using one-way analysis of variance (ANOVA), followed by least significant difference (LSD) post-hoc tests for pairwise comparisons. Paired

Table 1. Comparison of general information among the three groups.

Indicator	OLIF group (n = 68)	TLIF group (n = 72)	UBE group (n = 70)	χ^2/F	*p*-value
Gender (Male/Female)	30/38	42/30	27/43	5.932	0.052
Age (years, $\bar{x} \pm s$)	52.3 ± 4.5	53.7 ± 4.2	51.8 ± 6.9	2.423	0.091
Fusion segment position (n, %)				3.671	0.452
L3-L4 and above	2 (2.94)	7 (9.72)	5 (7.14)		
L4-L5	46 (67.65)	40 (55.56)	44 (62.86)		
L5-S1	20 (29.41)	25 (34.72)	21 (30.00)		
Number of fusion segments (n, %)				2.559	0.278
Single segment	59 (86.76)	63 (87.50)	66 (94.29)		
Double segment	9 (13.24)	9 (12.50)	4 (5.71)		

Note: OLIF, Oblique Lateral Interbody Fusion; TLIF, Transforaminal Lumbar Interbody Fusion; UBE, Unilateral Biportal Endoscopy; L, lumbar vertebrae; S, sacral vertebrae.

Table 2. Comparison of perioperative outcomes among the three groups.

Indicator	OLIF group (n = 68)	TLIF group (n = 72)	UBE group (n = 70)	F value	*p*-value
Operation time (min)	142.5 ± 15.3	165.2 ± 20.6*	198.7 ± 18.4*#	165.4	<0.001
Intraoperative blood loss (mL)	138.4 ± 25.7	255.3 ± 32.8*	92.6 ± 18.5*#	718.5	<0.001
Hospital stays (d)	5.2 ± 1.3	7.8 ± 1.9*	5.8 ± 1.5#	51.63	<0.001

Note: * indicates that compared with the OLIF group, $p < 0.05$; # indicates that compared with the TLIF group, $p < 0.05$.

t-tests were used to compare differences in each clinical outcome between preoperative and follow-up time points. Categorical variables were expressed as counts and percentages [n (%)], and between-group comparisons were performed using the χ^2 test or Fisher's exact test, as appropriate. Bonferroni correction was used to adjust *p*-values. A *p*-value < 0.05 was considered statistically significant.

Results

Comparison of Baseline Characteristics Among the Three Groups

No statistically significant differences were observed among the three groups for sex distribution, age, fused segment position, or number of fused segments (all $p > 0.05$), indicating well-balanced baseline characteristics and good comparability among groups (Table 1).

Comparison of Perioperative Indicators Among the Three Groups

Statistically significant differences in perioperative outcomes were found among the three groups (all $p < 0.05$). Specifically, the OLIF group had significantly shorter operation time than the TLIF and UBE groups (both $p < 0.05$). Intraoperative blood loss was significantly lower in the UBE group than in the OLIF and TLIF groups (both $p < 0.05$). Length of hospital stay was shorter in the OLIF group than in the TLIF group ($p < 0.05$), whereas no significant difference was observed between the OLIF and UBE groups ($p > 0.05$, Table 2).

Comparison of Pain Scores and Lumbar Function Indices Among the Three Groups

Preoperatively, no statistically significant differences were observed in VAS scores or ODI indices among the three groups ($p > 0.05$). At 3 months postoperatively, both VAS scores and ODI indices decreased significantly from the baseline values in all three groups ($p < 0.001$), with no significant intergroup differences observed ($p > 0.05$, Table 3).

Inflammatory Indicators and Hemoglobin Levels Across the Three Groups

Preoperatively, CRP, D-dimer, or hemoglobin levels showed no significant differences among the three groups ($p > 0.05$). At postoperative day 3, CRP and D-dimer levels increased, and hemoglobin levels decreased compared to baseline in all groups ($p < 0.001$). At this time, the CRP levels in the UBE group were lower than those in the TLIF and OLIF groups ($p < 0.05$), and D-dimer levels were also lower than in the TLIF group, with a smaller decrease in hemoglobin ($p < 0.05$). There were no significant differences in D-dimer and hemoglobin levels between the OLIF and UBE groups ($p > 0.05$, Table 4).

Comparison of Imaging Indicators Among the Three Groups

Preoperatively, intervertebral space height did not differ significantly among the three groups ($p > 0.05$). At 3 months postoperatively, intervertebral space height was restored considerably in all groups compared with preoperative values ($p < 0.001$), and both the rate of successful decompression and the incidence rate of early fusion trends were high. However, no significant differences were observed among the groups in these imaging outcomes ($p > 0.05$, Table 5).

Table 3. Comparison of VAS scores and ODI indices among the three groups.

Indicator	Time point	OLIF group (n = 68)	TLIF group (n = 72)	UBE group (n = 70)	F value	*p*-value
VAS	Preoperative	7.5 ± 0.8	7.4 ± 1.3	7.7 ± 1.1	1.366	0.252
	3 months postoperative	2.1 ± 0.8	2.3 ± 0.9	2.0 ± 0.7	2.560	0.079
t value		39.359	27.369	25.940		
p-value		<0.001	<0.001	<0.001		
ODI	Preoperative	66.5 ± 10.2	67.8 ± 9.8	69.2 ± 10.5	1.217	0.298
	3 months postoperative	22.3 ± 6.5	24.1 ± 7.1	21.8 ± 6.2	2.377	0.095
t value		30.135	30.641	32.523		
p-value		<0.001	<0.001	<0.001		

VAS, Visual Analogue Scale; ODI, Oswestry Disability Index.

Table 4. Comparison of inflammatory indicators and hemoglobin levels among the three groups.

Indicator	Time point	OLIF group (n = 68)	TLIF group (n = 72)	UBE group (n = 70)	F value	*p*-value
CRP (mg/L)	Preoperative	5.6 ± 2.1	4.9 ± 1.9	5.3 ± 2.0	2.164	0.117
	3 days postoperative	32.6 ± 9.5	42.3 ± 10.5*	28.5 ± 8.2*#	39.94	<0.001
t value		22.884	29.741	22.997		
p-value		<0.001	<0.001	<0.001		
D-dimer (mg/L)	Preoperative	0.27 ± 0.04	0.27 ± 0.03	0.26 ± 0.04	1.716	0.182
	3 days postoperative	1.31 ± 0.19	1.53 ± 0.21*	1.26 ± 0.13#	45.23	<0.001
t value		44.169	50.040	61.512		
p-value		<0.001	<0.001	<0.001		
Hemoglobin (g/L)	Preoperative	135.2 ± 12.5	136.8 ± 13.2	134.5 ± 12.8	0.599	0.550
	3 days postoperative	124.8 ± 10.7	118.3 ± 9.6*	124.3 ± 10.1#	9.032	<0.001
t value		5.212	9.618	5.234		
p-value		<0.001	<0.001	<0.001		

Note: * indicates that compared with the OLIF group, $p < 0.05$; # indicates that compared with the TLIF group, $p < 0.05$. CRP, C-reactive protein.

Table 5. Comparison of radiological outcomes among the three groups.

Indicator	Time point	OLIF group (n = 68)	TLIF group (n = 72)	UBE group (n = 70)	χ^2/F value	*p*-value
Intervertebral space height (mm, $\bar{x} \pm s$)	Preoperative	6.8 ± 1.5	6.4 ± 1.3	6.7 ± 1.8	1.281	0.280
	3 months postoperative	11.2 ± 2.1	11.5 ± 2.0	11.0 ± 2.3	0.987	0.374
t value		14.060	18.142	12.493		
p-value		<0.001	<0.001	<0.001		
Spinal decompression rate (n, %)	3 months postoperative	65 (95.59)	68 (94.44)	66 (94.29)	0.140	0.932
Early fusion trend (n, %)	3 months postoperative	63 (92.65)	67 (93.06)	64 (91.43)	0.144	0.931

Table 6. Comparison of postoperative complications among the three groups.

Complication type	OLIF group (n = 68)	TLIF group (n = 72)	UBE group (n = 70)	*p*-value
Retroperitoneal hematoma	1 (1.47)	0 (0.00)	1 (1.43)	-
Cerebrospinal fluid leakage	0 (0.00)	2 (2.78)	0 (0.00)	-
Nerve root injury	0 (0.00)	1 (1.39)	0 (0.00)	-
Superficial incision infection	0 (0.00)	1 (1.39)	0 (0.00)	-
Thromboembolism	1 (1.47)	0 (0.00)	0 (0.00)	-
Total complications	2 (2.94)	4 (5.56)	1 (1.43)	0.457

Note: "-" Indicates that no *p*-value is available.

Comparison of Postoperative Complications

Within the 3-month postoperative period, no severe complications occurred in any of the three groups, and the overall complication rate did not differ considerably among the groups ($p > 0.05$). All recorded complications were successfully managed with symptomatic treatment and did not adversely affect postoperative recovery (Table 6).

Discussion

This study compared the clinical efficacy of three widely applied surgical methods for the treatment of LDH, demonstrating that each method effectively reduces pain, improves lumbar function, and promotes intervertebral fusion. However, significant differences were observed in perioperative indicators and inflammatory markers across these three groups. These results highlight the significance of individualizing surgical approaches based on patients' unique characteristics and expected recovery outcomes, thereby providing promising evidence for optimizing tailored surgical decision-making in LDH management.

In this study, all three groups showed a substantial decline in VAS and ODI scores at 3 months after surgery compared to baseline values, indicating that each method effectively relieves pain and restores lumbar function in patients with LDH. These results are consistent with previous studies [17–19] and suggest that their therapeutic advantages are linked to two core mechanisms: precise decompression of compressed nerve roots and the restoration of lumbar stability through intervertebral fusion. Collectively, these surgical interventions improve both pathological and anatomical aspects of the disease, thereby contributing to significant clinical improvement.

The results of imaging further verified the anatomical efficacy of the three surgical methods. Postoperative intervertebral space height was considerably improved across all three groups, and the good rate of spinal canal decompression exceeded 94%. These observations reveal that OLIF, TLIF, or UBE-TLIF all can effectively restore the intervertebral space height and achieve sufficient spinal canal decompression. It is worth noting that the restoration of intervertebral space height can not only improve the physiological curvature of the lumbar spine but also indirectly increase the volume of the nerve root canal, thereby further reducing nerve root compression. This is also an important anatomical basis for the significant functional improvement observed with all three surgical methods [20].

From a safety perspective, all three methods showed a lower overall complication rate, with no serious adverse events observed. The incidence of cerebrospinal fluid leakage was slightly higher in the TLIF group, likely due to the posterior approach requiring lamina removal and dural sac exposure, underscoring the need for careful dural protection during the procedure. These results reveal that when conducted under standardized protocols, all three surgical methods offer a high safety profile. This is consistent with the complication rates previously reported by Shu *et al*. [21] for UBE-TLIF and Phan *et al*. [22] for OLIF, supporting the clinical reliability of these surgical methods.

Although the three surgical methods show comparable core efficacy in alleviating symptoms and restoring function, they differ substantially in perioperative efficiency, inflammatory response, and fusion stability—factors that guide their applicability for specific patient populations. The OLIF group had the shortest operation time and hospital stays, largely due to the anatomical characteristics of the lateral approach. This approach eliminates the need for extensive dissection of the paraspinal muscle, avoiding damage to the lumbodorsal muscles associated with posterior approaches. Furthermore, this method also eliminates the need for complex endoscopic navigation, thereby improving surgical efficiency and reducing surgical trauma. However, OLIF has certain limitations: the lateral approach requires passing through the retroperitoneal space, which may increase the risk of injury to the iliohypogastric and genitofemoral nerves [23]. Moreover, for patients with severe lumbar instability, a lateral fusion cage alone may not provide sufficient support, often necessitating combined posterior pedicle screw fixation, which adds to surgical trauma and duration [8]. Therefore, OLIF is best suited for patients with single-segment LDH and stable spinal alignment, particularly in younger and middle-aged patients seeking rapid postoperative recovery.

The UBE group had the lowest intraoperative blood loss, the lowest levels of CRP and D-dimer, and the smallest decrease in hemoglobin levels, demonstrating its minimally invasive nature. Through the "biportal + endoscopic magnified field of view", UBE technology enables decompression and interbody fusion through a small incision, causing substantially less damage to paraspinal muscles and bony structures than TLIF. This reduced tissue trauma results in lower intraoperative blood loss and a milder postoperative inflammatory response [24].

The postoperative inflammatory response is a crucial determinant of pain and recovery. Elevated CRP levels are positively correlated with the degree of tissue damage, while elevated D-dimer levels indicate activation of the coagulation pathway. The relatively lower inflammatory markers observed in the UBE group indicate not only milder postoperative pain but also a lower risk of complications, such as postoperative thrombosis and infection. Supporting this, Arifin *et al*. [25] revealed that patients undergoing microscopic surgery experienced lower postoperative CRP levels and shorter hospital stays. Furthermore, the clear endoscopic field allows for more accurate identification of nerve roots and the dural sac, thereby reducing the risk of nerve injury [26]. However, UBE requires advanced surgical expertise, particularly in coordinating endoscopic instruments, and it also involves a slightly longer operation time than OLIF. Thus, UBE is more suited for patients seeking minimal invasiveness, better postoperative pain control, and those with medical comorbidities that need reduced surgical trauma.

Although the difference in fusion rate among the three groups was not statistically significant, the TLIF group demonstrated higher fusion stability scores, indicating potentially more reliable long-term fusion outcomes. TLIF uses a posterior method that directly exposes the intervertebral space and facilitates a large bone grafting interface. This approach is often combined with a pedicle screw fixation, achieving "three-point fixation" and maintaining lum-

bar sagittal balance. Previous studies have suggested that TLIF outperforms lateral approach techniques in postoperative fusion rate and stability [27]. Nevertheless, the posterior approach involves greater disruption of intraspinal structures, increasing the risk of cerebrospinal fluid leakage and nerve root injury [28]. Therefore, TLIF is more suitable for patients with double-segment or multi-segment LDH, those with spinal stenosis requiring extensive decompression, or those for whom optimal fusion stability is a primary concern.

Despite promising results, this study has the following limitations: First, as a retrospective study with a relatively small sample size, there is an inherent risk of selection bias. Although baseline data across the three groups were comparable, unrecorded confounding factors, such as the duration of preoperative pain or compliance with postoperative rehabilitation, may have affected the results. Second, the short follow-up period limits the ability to assess long-term efficacy, including 5-year fusion rates, the incidence of adjacent segment degeneration, and the recurrence rates. Thus, extended follow-up is required to validate these findings. Additionally, inflammatory indicators may be influenced by various clinical factors, such as undetected infection, differences in intraoperative blood loss assessment, and individual differences in coagulation function. These factors could introduce bias and should be interpreted in combination with a variety of clinical indicators. Lastly, this study did not include patient-reported outcomes (PROs), such as quality of life scores or postoperative return-to-work time, which are crucial for understanding functional recovery and overall satisfaction. Future studies should integrate these domains to offer a more robust assessment of surgical success.

Conclusions

OLIF, TLIF, and UBE-TLIF are all effective and comparably safe surgical interventions for treating LDH, offering significant pain relief and improved lumbar function. OLIF offers shorter operative time and hospital stays, while UBE provides minimal invasiveness and reduced early postoperative inflammatory response. Clinically, the surgical approach should be individualized based on the patients' unique characteristics, considering factors such as disease complexity, comorbidities, and the need for minimally invasive requirements, to achieve optimal therapeutic outcomes.

Availability of Data and Materials

The data used to support the findings of this study are available from the corresponding author upon request.

Author Contributions

HDW, YZ, YHZ, HL and YaW designed the research study, analyzed the data and drafted the manuscript. LS, XYW and QSC performed the research. YiW participated in the data collection. All authors contributed to the critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This study received approval from the Ethics Committee of The First Affiliated Hospital of Anhui University of Chinese Medicine (No. 2024MCZQ28), and all patients signed informed consent forms. The study conformed to the provisions of the Declaration of Helsinki.

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Conflict of Interest

The authors declare no conflict of interest.

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