Analysis of Clinical Efficacy of Percutaneous Endoscopic Posterior Transforaminal Lumbar Interbody Fusion with Height-Adjustable Titanium Cage for Lumbar Spondylolisthesis with Lumbar Spinal Stenosis: Postprint

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Abstract

Background With advancing medical technology, the indications for spinal endoscopic techniques have become increasingly widespread. Percutaneous endoscopic posterior transforaminal lumbar interbody fusion (Endo-P/TLIF) has been rapidly and extensively applied in lumbar spondylolisthesis combined with lumbar spinal stenosis, achieving certain clinical efficacy. Compared with conventional cages, height-adjustable titanium cages offer better distraction effects and can effectively restore intervertebral space height. When used in Endo-P/TLIF procedures, the clinical outcomes are remarkable. This approach warrants further investigation and represents a further refinement of minimally invasive techniques in spinal disorders.

Objective To investigate the application and clinical efficacy of Endo-P/TLIF combined with height-adjustable titanium cages in the treatment of lumbar spondylolisthesis with lumbar spinal stenosis.

Methods A retrospective analysis was conducted on the clinical data of 171 patients with lumbar spondylolisthesis combined with lumbar spinal stenosis who were treated at the First Affiliated Hospital of Guangxi University of Chinese Medicine from January 2019 to June 2021. According to the surgical approach, patients were divided into four groups: Endo-P/TLIF + adjustable cage group (35 cases), Endo-P/TLIF + conventional cage group (57 cases), percutaneous endoscopic transforaminal lumbar interbody fusion (Endo-TLIF) + conventional cage group (47 cases), and unilateral biportal endoscopy (UBE) + conventional cage group (32 cases). The following parameters were compared among the four groups: sex, age, operative time, intraoperative blood loss, hospital stay, preoperative and postoperative (immediate, 6-month, and 12-month) Oswestry

Disability Index (ODI) scores, Visual Analogue Scale (VAS) scores, Japanese Orthopaedic Association (JOA) scores, degree of lumbar spondylolisthesis, lumbar lordosis angle, and dural sac cross-sectional area.

Results There were no statistically significant differences in sex, age, operative time, intraoperative blood loss, or hospital stay among the four groups (P>0.05). No interaction effects between group and time were observed for ODI scores, VAS scores, JOA scores, lumbar lordosis angle, or dural sac cross-sectional area (P>0.05); however, a significant interaction effect between group and time was found for the degree of lumbar spondylolisthesis (P<0.05). Significant main effects of group were observed for ODI scores, JOA scores, lumbar lordosis angle, and dural sac cross-sectional area (P<0.05). Significant main effects of time were observed for ODI scores, VAS scores, JOA scores, degree of lumbar spondylolisthesis, lumbar lordosis angle, and dural sac cross-sectional area (P<0.05). At the immediate postoperative period, the dural sac cross-sectional area in both the Endo-P/TLIF + adjustable cage group and the Endo-P/TLIF + conventional cage group was significantly higher than that in the Endo-TLIF + conventional cage group and the UBE + conventional cage group (P<0.05). At 6 months postoperatively, the ODI scores in both the Endo-P/TLIF + adjustable cage group and the Endo-P/TLIF + conventional cage group were significantly lower than those in the Endo-TLIF + conventional cage group and the UBE + conventional cage group, while their dural sac cross-sectional areas were significantly higher (P<0.05). At 12 months postoperatively, the Endo-P/TLIF + adjustable cage group demonstrated lower ODI and VAS scores compared with the other three groups, and higher JOA scores, degree of lumbar spondylolisthesis, and dural sac cross-sectional area compared with the Endo-TLIF + conventional cage group and the UBE + conventional cage group (P<0.05).

Conclusion Endo-P/TLIF is a modified spinal endoscopic interbody fusion technique that offers advantages including minimal trauma, reduced intraoperative blood loss, shorter hospital stay, and thorough decompression. Combined with height-adjustable titanium cages, it can effectively restore intervertebral space height and demonstrates favorable short-term efficacy, warranting widespread clinical application.

Full Text

Clinical Efficacy of Percutaneous Endoscopic Posterior Transforaminal Lumbar Interbody Fusion Combined with Height-Adjustable Titanium Fusion Cage in the Treatment of Lumbar Spondylolisthesis with Lumbar Spinal Stenosis

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Abstract

Background: With advances in medical technology, the indications for spinal endoscopic techniques have become increasingly broad. Percutaneous endoscopic posterior transforaminal lumbar interbody fusion (Endo-P/TLIF) has been rapidly and widely applied in lumbar spondylolisthesis combined with lumbar spinal stenosis, achieving certain clinical efficacy. Compared with traditional fusion cages, height-adjustable titanium fusion cages offer superior distraction effects and can effectively restore intervertebral space height, demonstrating notable efficacy when used in Endo-P/TLIF procedures. This approach warrants further investigation to advance minimally invasive techniques for spinal disorders.

Objective: To investigate the application and clinical efficacy of Endo-P/TLIF combined with height-adjustable titanium fusion cages in treating lumbar spondylolisthesis with lumbar spinal stenosis.

Methods: We retrospectively analyzed clinical data from 171 patients with lumbar spondylolisthesis and lumbar spinal stenosis treated at the First Affiliated Hospital of Guangxi University of Traditional Chinese Medicine between January 2019 and June 2021. Patients were divided into four groups based on surgical approach: Endo-P/TLIF with adjustable cage (35 cases), Endo-P/TLIF with conventional cage (57 cases), endoscopic transforaminal lumbar interbody fusion (Endo-TLIF) with conventional cage (47 cases), and unilateral biportal endoscopy (UBE) with conventional cage (32 cases). We compared gender, age, operative time, intraoperative blood loss, hospital stay, and preoperative, immediate postoperative, 6-month postoperative, and 12-month postoperative Oswestry Disability Index (ODI) scores, Visual Analogue Scale (VAS) scores, Japanese Orthopaedic Association (JOA) scores, degree of lumbar spondylolisthesis, lumbar lordosis angle, and dural cross-sectional area among the four groups.

Results: No statistically significant differences were found among the four groups in gender, age, operative time, intraoperative blood loss, or hospital stay ($P>0.05$). No interaction effects between group and time were observed for ODI score, VAS score, JOA score, lumbar lordosis angle, or dural cross-sectional area ($P>0.05$), though a significant interaction was found for degree of lumbar spondylolisthesis ($P<0.05$). Group showed significant main effects on ODI score, JOA score, lumbar lordosis angle, and dural cross-sectional area ($P<0.05$), while time showed significant main effects on all outcome measures ($P<0.05$). At the immediate postoperative period, the Endo-P/TLIF with adjustable cage

and Endo-P/TLIF with conventional cage groups demonstrated greater dural cross-sectional area compared to the Endo-TLIF and UBE groups (P<0.05). At 6 months postoperatively, the two Endo-P/TLIF groups showed lower ODI scores and greater dural cross-sectional area compared to the Endo-TLIF and UBE groups (P<0.05). At 12 months postoperatively, the Endo-P/TLIF with adjustable cage group exhibited lower ODI and VAS scores, and higher JOA scores, degree of lumbar spondylolisthesis reduction, and dural cross-sectional area compared to the other three groups (P<0.05).

Conclusion: As a modified spinal endoscopic interbody fusion technique, Endo-P/TLIF offers advantages including minimal trauma, reduced intraoperative blood loss, shorter hospitalization, and thorough decompression. Combined with height-adjustable titanium fusion cages, this approach effectively restores intervertebral space height and demonstrates favorable short-term outcomes, warranting broader clinical application.

Keywords: Spinal stenosis; Spinal fusion; Lumbar spondylolisthesis; Percutaneous endoscopic posterior transforaminal lumbar interbody fusion; Clinical effectiveness

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Introduction

Lumbar spondylolisthesis combined with lumbar spinal stenosis represents a major cause of low back and leg pain among degenerative spinal diseases. Conservative treatment generally yields unsatisfactory results, often necessitating surgical intervention. Traditional open surgical approaches primarily include classic posterior lumbar interbody fusion (PLIF) and transforaminal lumbar interbody fusion (TLIF). However, open surgery carries disadvantages such as extensive paraspinal muscle stripping, significant soft tissue damage, and prolonged intraoperative nerve root retraction, which can lead to chronic low back and leg pain and reduced quality of life. As medical standards advance, patients increasingly demand less invasive treatments with faster recovery.

In recent years, minimally invasive techniques have developed rapidly, with endoscopic lumbar interbody fusion gaining widespread application. These approaches significantly reduce trauma and intraoperative bleeding while offering faster recovery and shorter postoperative hospital stays. Common techniques such as endoscopic transforaminal lumbar interbody fusion (Endo-TLIF) and unilateral biportal endoscopy (UBE) each have distinct advantages. However, clinical studies have revealed that both methods suffer from incomplete decompression and suboptimal restoration of intervertebral height. To address these limitations, our research team modified the existing Endo-TLIF technique by incorporating characteristics of both TLIF and PLIF approaches, developing a more thoroughly decompressive procedure called percutaneous endoscopic posterior transforaminal lumbar interbody fusion (Endo-P/TLIF) combined with height-adjustable titanium cages. This approach not only achieves complete

decompression but also restores intervertebral space height, improving clinical outcomes and providing new insights for treating lumbar spondylolisthesis with spinal stenosis.

Methods

1.1 Study Subjects We retrospectively selected 171 patients with lumbar spondylolisthesis and lumbar spinal stenosis treated at the First Affiliated Hospital of Guangxi University of Traditional Chinese Medicine between January 2019 and June 2021. The cohort comprised 94 males and 77 females, aged 33-67 years with a mean age of (54.0$±$6.7) years. Patients were divided into four groups based on surgical approach: Endo-P/TLIF with adjustable cage (35 cases), Endo-P/TLIF with conventional cage (57 cases), Endo-TLIF with conventional cage (47 cases), and UBE with conventional cage (32 cases). This study was approved by the Ethics Committee of the First Affiliated Hospital of Guangxi University of Traditional Chinese Medicine (KY2019-115), and all patients provided informed consent.

1.1.1 Inclusion Criteria: (1) Clinical presentation of low back pain with unilateral or bilateral neurological symptoms, possibly including intermittent claudication; (2) Complete imaging data; (3) Imaging evidence of single-level lumbar spondylolisthesis with lumbar spinal stenosis; (4) Failure of systematic conservative treatment for 3 months; (5) All surgeries performed by the same medical team; (6) Minimum 12-month follow-up period.

1.1.2 Exclusion Criteria: (1) Significant scoliosis deformity with Cobb angle >20°; (2) Unilateral or bilateral isthmic spondylolysis with grade II or higher slippage; (3) Previous lumbar surgery; (4) Severe osteoporosis; (5) Pregnancy or comorbid cardiocerebral conditions precluding surgery tolerance.

1.2 Endo-P/TLIF Surgical Technique Following general anesthesia, patients were positioned prone with hips and knees flexed and the abdomen suspended. C-arm fluoroscopy was used to identify the target segment, and the spinous process midline, upper and lower vertebral pedicles, and intervertebral space were marked. After standard sterile preparation and draping, a Mammut needle was used to locate pedicle screw entry points. A transverse incision approximately 0.5 cm was made along the positioning needle, and an opening was created at the pedicle using a cannulated awl. A guide pin was inserted under fluoroscopic guidance to confirm appropriate angle, position, and depth. Pedicle screws of appropriate size and length were placed on the non-decompression side, while guide pins were retained on the decompression side to avoid interference with the endoscopic system.

An extracorporeal trephine and sleeve were inserted through the inferior pedicle incision. Fluoroscopic anteroposterior views confirmed the trephine position at the inferior articular process of the superior vertebra or at the junction between

the inferior articular process and lamina, with lateral views showing alignment with the posterior laminar edge and orientation parallel to the disc space. The endoscopic system was connected, and the inferior articular process was resected using the extracorporeal trephine under endoscopic visualization. The superior attachment point of the ligamentum flavum was exposed by identifying the inferior edge of the superior vertebral lamina. The endoscopic view clearly revealed the superior edge of the inferior vertebral lamina and the articular surface of the superior articular process. A rongeur or extracorporeal trephine was used to remove the superior edge of the inferior lamina and the medial border of the articular process, exposing the superior, inferior, and lateral margins of the ligamentum flavum. The ligamentum flavum was removed en bloc to expose the dura and traversing nerve root, with exploration of the exiting root along the lateral margin of the ligamentum flavum when necessary.

The working cannula was replaced to protect the nerve root and expose the intervertebral disc. The disc material was removed under direct visualization, and the intervertebral space was thoroughly prepared with the cartilaginous endplates scraped clean. For patients with bilateral preoperative symptoms, the working cannula could be advanced to the contralateral side for complete decompression.

After disc space preparation, the endoscopic channel was removed and replaced with a fusion working cannula with a snakehead design to protect the nerve root. For height-adjustable titanium cage placement: after ensuring no neural or vascular structures remained in the disc space, a distractor trial was used to determine the appropriate height, which was recorded. Autologous and allogeneic bone grafts were placed, followed by insertion of the expandable cage, which was then distracted to the trial height. For conventional cage placement: a nerve probe was used for dual protection of the nerve root (a specialized nerve probe was placed under endoscopic visualization before removing the standard channel, then a conventional cage delivery channel was inserted with the nerve probe positioned medially within the channel). After confirming the absence of neural or vascular structures, sequential trials were used to determine the maximum cage size, which was recorded. Bone grafting was performed, followed by insertion of a conventional cage matching the trial size. Final endoscopic inspection confirmed no nerve root damage or compression, verified cage position, and ensured hemostasis. The endoscopic system was removed, and pedicle screws of appropriate size and length were placed on the decompression side using the reserved guide pins. Rods were inserted and secured with compression and distraction. The incision was closed in layers, and patients were returned to the ward in stable condition. Postoperative management included routine anti-inflammatory, analgesic, and neurotrophic supportive therapy, with monitoring of bilateral lower extremity motor and sensory function.

1.3 Outcome Measures We compared gender, age, operative time, intraoperative blood loss, hospital stay, and preoperative, immediate postoperative,

6-month postoperative, and 12-month postoperative ODI scores, VAS scores, JOA scores, degree of lumbar spondylolisthesis, lumbar lordosis angle, and dural cross-sectional area.

1.3.1 ODI Score: Developed by FAIRBANK et al. in 1976 and first published in 1980 (version 1.0) after large-sample validation, the ODI is a self-administered questionnaire assessing chronic low back pain disability. It comprises 10 items covering pain intensity, self-care, lifting, walking, sitting, standing, sleep disturbance, sexual life, social life, and travel. Each item contains one question with six options scored 0-5. If all 10 questions are answered, the scoring method is: (actual score/45 [maximum possible score]) × 100%. Higher scores indicate more severe disability.

1.3.2 VAS Score: Introduced by HUSKISSON in 1974, the VAS uses a 10 cm horizontal line with "0" representing "no pain" and "10" representing "severe pain." Patients mark their pain level on the line, and the distance from the "no pain" endpoint to the mark constitutes the VAS score. The VAS demonstrates good sensitivity, reliability, and validity.

1.3.3 JOA Score: Developed by the Japanese Orthopaedic Association in 1997 for evaluating lumbar function, the JOA score includes four domains: subjective symptoms, clinical signs, daily activities, and bladder function. The total score is 29 points, with lower scores indicating more severe dysfunction.

1.4 Follow-up All patients were instructed to attend outpatient follow-up visits every 2 months unless otherwise indicated, with follow-up continuing through June 2022.

1.5 Statistical Analysis Data were analyzed using SPSS 22.0 software. Normally distributed continuous variables are expressed as ($\bar{x}\pm s$) and compared between two groups using independent samples t-tests, among multiple groups using one-way ANOVA, and across time points using repeated measures ANOVA. Non-normally distributed continuous variables are expressed as M(P25, P75) and compared using rank-sum tests. Categorical data are expressed as frequencies and compared using ^{2} tests. Statistical significance was set at $P<0.05$.

Results

2.1 Comparison of General Data All 171 patients completed surgery successfully with follow-up exceeding 1 year and no cases lost to follow-up. No statistically significant differences were found among the four groups in gender, age, operative time, intraoperative blood loss, or hospital stay ($P>0.05$) .

2.2 Comparison of ODI Scores No interaction effect between group and time was observed for ODI scores (F_{interaction}=0.969,

P_{interaction}=0.465). Group showed a significant main effect on ODI scores (F_{group}=4.406, P_{group}=0.005), and time showed a significant main effect (F_{time}=4,433.689, P_{time}<0.001). At 6 months postoperatively, the Endo-P/TLIF with adjustable cage and Endo-P/TLIF with conventional cage groups demonstrated lower ODI scores compared to the Endo-TLIF and UBE groups (P<0.05). At 12 months postoperatively, the Endo-P/TLIF with adjustable cage group showed lower ODI scores than all other groups, while the Endo-P/TLIF with conventional cage group showed lower ODI scores than the Endo-TLIF and UBE groups (P<0.05) .

2.3 Comparison of VAS Scores No interaction effect between group and time was observed for VAS scores (F_{interaction}=1.072, P_{interaction}=0.382). Group showed no significant main effect on VAS scores (F_{group}=0.960, P_{group}=0.441), while time showed a significant main effect (F_{time}=697.803, P_{time}<0.001). At 12 months postoperatively, the Endo-P/TLIF with adjustable cage group demonstrated lower VAS scores than all other groups (P<0.05) .

2.4 Comparison of JOA Scores No interaction effect between group and time was observed for JOA scores (F_{interaction}=1.423, P_{interaction}=0.175). Group showed a significant main effect on JOA scores (F_{group}=3.417, P_{group}=0.019), and time showed a significant main effect (F_{time}=1,927.491, P_{time}<0.001). At 12 months postoperatively, the Endo-P/TLIF with adjustable cage group showed higher JOA scores than the Endo-TLIF and UBE groups (P<0.05) .

2.5 Comparison of Lumbar Spondylolisthesis Degree A significant interaction effect between group and time was observed for degree of lumbar spondylolisthesis (F_{interaction}=4.051, P_{interaction}<0.001). Group showed no significant main effect (F_{group}=1.368, P_{group}=0.255), while time showed a significant main effect (F_{time}=2,042.74, P_{time}<0.001). At 12 months postoperatively, the Endo-P/TLIF with adjustable cage group demonstrated greater reduction in spondylolisthesis degree compared to the Endo-TLIF and UBE groups (P<0.05) .

2.6 Comparison of Lumbar Lordosis Angle No interaction effect between group and time was observed for lumbar lordosis angle (F_{interaction}=1.311, P_{interaction}=0.919). Group showed a significant main effect (F_{group}=3.691, P_{group}=0.013), and time showed a significant main effect (F_{time}=798.519, P_{time}<0.001) .

2.7 Comparison of Dural Cross-Sectional Area No interaction effect between group and time was observed for dural cross-sectional area (F_{interaction}=1.408, P_{interaction}=0.181). Group showed a significant main effect (F_{group}=4.336, P_{group}=0.006), and time showed a

significant main effect (F_{time}=906.684, P_{time}<0.001). At immediate postoperative, 6-month, and 12-month time points, the Endo-P/TLIF with adjustable cage and Endo-P/TLIF with conventional cage groups demonstrated greater dural cross-sectional area compared to the Endo-TLIF and UBE groups (P<0.05) .

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3. Typical Case Analysis

A 52-year-old male patient, diagnosed with grade I lumbar spondylolisthesis combined with lumbar spinal stenosis, underwent Endo-P/TLIF under general anesthesia. Imaging findings are presented in [Figure 1: see original paper].

Discussion

Lumbar spondylolisthesis combined with lumbar spinal stenosis is a major degenerative spinal disease characterized by low back pain and bilateral lower extremity radicular pain, often with intermittent claudication that severely impacts quality of life. As early as the 1940s, Cloward proposed the open surgical approach PLIF for this condition, which remains in use today. However, PLIF carries risks of excessive dural sac and nerve root retraction. In the 1980s, Blume modified PLIF and introduced TLIF technology, which became widely used in open lumbar surgery. Nevertheless, this approach partially destroys the ipsilateral facet joint, potentially affecting postoperative spinal biomechanics and structural stability.

As patient expectations for quality of life have increased, demands for minimally invasive treatments have grown. In recent years, minimally invasive techniques for lumbar degenerative diseases have continuously evolved with expanding indications. Endoscopic lumbar interbody fusion has developed rapidly, offering clear advantages including reduced intraoperative bleeding, minimal trauma, shorter operative times, faster discharge, and rapid postoperative rehabilitation. The emergence of minimally invasive TLIF (MIS-TLIF) made the transition from traditional open to minimally invasive surgery possible, requiring only a 7 mm incision while avoiding facet joint destruction and maximizing preservation of native spinal stability. However, clinical practice revealed that MIS-TLIF/PLIF cannot avoid lengthy fluoroscopy times and extensive dissection, while also being unable to correct lumbar lordosis and coronal balance, potentially causing long-term postoperative back pain, stiffness, and discomfort that affect treatment outcomes.

To better address these issues, Endo-TLIF was developed through continuous clinical exploration, replicating TLIF procedures within an endoscopic system to enable nerve decompression under direct visualization. This approach combines traditional decompression concepts with minimally invasive innovation,

achieving effective decompression while reducing trauma. However, Endo-TLIF removes portions of the facet joint and lamina, preserving posterior column structures but providing insufficient decompression of posterior spinal compression. Most lumbar spinal stenosis patients experience dural compression from hypertrophic, folded ligamentum flavum, representing a limitation of Endo-TLIF. This incomplete decompression reduces its applicability for central lumbar spinal stenosis and lumbar spondylolisthesis with stenosis.

UBE technology employs unilateral biportal decompression with separate working and endoscopic channels, providing an expanded field of view and operating space that broadens indications for minimally invasive endoscopic treatment of lumbar degenerative diseases. Compared with other minimally invasive techniques, the dual-channel approach expands surgical visualization and decompression range while allowing use of traditional open surgical instruments, enabling more precise and thorough endplate preparation to increase fusion rates and prevent cage subsidence. However, UBE has a steep learning curve, demands high technical skill, and requires more extensive subcutaneous soft tissue dissection than single-channel approaches, resulting in greater blood loss and tissue damage. Additionally, large-volume irrigation, while ensuring clear visualization, may cause intramedullary hypertension and muscle edema while washing away bone nutrients, potentially compromising intervertebral fusion.

Our research team, through long-term clinical exploration, reasonably expanded the indications for minimally invasive spinal treatment by modifying Endo-TLIF. Combining traditional PLIF surgical approaches, we developed a procedure with markedly expanded surgical indications that we term Endo-P/TLIF, also referred to as modified full-endoscopic transforaminal lumbar interbody fusion. Compared with Endo-TLIF, Endo-P/TLIF preserves the superior articular process to a much greater extent, reducing injury to the superior exiting nerve root. This modified approach enables decompression of the ipsilateral lateral recess and nerve root canal, while cannula movement allows sufficient interlaminar decompression, expanding indications for central lumbar spinal stenosis. Compared with Endo-PLIF, the surgical approach is shifted laterally, substantially expanding the operating space without destroying midline structures, thereby reducing excessive retraction of nerve roots and dural sac and minimizing damage to the dura and traversing nerves.

Unilateral approach for bilateral decompression is a characteristic feature of Endo-P/TLIF, enabling bilateral decompression of facet joints, lateral recesses, spinal canal, intervertebral discs, and ligamentum flavum with minimal invasion of posterior spinal structures, pursuing maximal therapeutic effect through minimal trauma while maintaining the advantages of traditional minimally invasive surgery. Our team uses Endo-P/TLIF to treat lumbar spondylolisthesis with stenosis, achieving decompression through posterolateral removal of the inferior articular process and partial lamina, followed by bone grafting and cage insertion. The cannula provides excellent nerve protection during surgery, substantially reducing nerve injury risk.

Expandable cages were first introduced by Gepstein et al. in 2005, effectively addressing the challenges of limited visualization and space for cage placement in minimally invasive surgery. Domestic expert Ding Yi and colleagues identified clear advantages of expandable cages in clinical application: (1) minimal working channel requirements (only 8 mm); (2) strong mechanical tolerance maintaining cage integrity under high pressure; (3) satisfactory distraction height (generally reaching 13 mm) that effectively restores intervertebral space height and fully tensions the ligamentum flavum and posterior longitudinal ligament; (4) anatomic design with specific angles that meets physiological lordosis requirements and maintains close contact with endplates for long-term stability; and (5) serrated surface design enhancing cage grip and reducing migration risk.

Our results show that at 12 months postoperatively, the Endo-P/TLIF with adjustable cage group demonstrated lower ODI and VAS scores and higher JOA scores compared to other groups, likely related to the extent of intraoperative decompression. Endo-P/TLIF utilizes a posterior transforaminal approach, providing greater decompression than Endo-TLIF and UBE. Combined with expandable cages, satisfactory restoration of intervertebral height reduces ligamentum flavum and posterior longitudinal ligament folding, decreasing postoperative back pain and stiffness and improving outcomes. Repeated measures ANOVA of ODI, VAS, and JOA scores showed no significant interaction effects but significant time main effects, indicating that differences between groups became more pronounced over time, warranting observation of long-term outcomes.

At 12 months postoperatively, the Endo-P/TLIF with adjustable cage group showed greater reduction in spondylolisthesis degree compared to the Endo-TLIF and UBE groups, indicating higher postoperative stability likely related to the expandable cage design, supporting its broader application. No significant differences in lumbar lordosis angle were found among groups at any time point, suggesting that lordosis restoration is primarily related to reduction via the pedicle screw-rod system, which provides stable fixation resistant to recurrent displacement.

At immediate postoperative, 6-month, and 12-month time points, the Endo-P/TLIF groups demonstrated greater dural cross-sectional area compared to the Endo-TLIF and UBE groups, indicating superior decompression through the Endo-P/TLIF approach that is less prone to recurrent stenosis, supporting its clinical utility.

In summary, minimally invasive treatment of lumbar degenerative disease demonstrates excellent efficacy. The Endo-P/TLIF approach offers advantages including minimal bleeding, reduced trauma, short hospitalization, and thorough decompression. Combined with height-adjustable titanium expandable cages, this technique effectively restores intervertebral space height and alleviates postoperative back pain and stiffness, warranting broader clinical application. This study has limitations including short follow-up duration, small sample size, and incomplete observation indicators. Further prospective,

multicenter, large-sample studies with comprehensive long-term outcome assessment are needed.

Author Contributions

ZHANG Yisheng conceived the research question, developed the study protocol, and drafted the manuscript. TANG Fubo collected patient information and conducted follow-up assessments. SUN Yaru collected cases, organized data, and performed statistical analysis. ZHONG Yuanming provided surgical technical guidance and research supervision. LI Zhifei performed surgical procedures and revised the manuscript.

This article has no conflicts of interest.

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