Comparison of Radiological and Clinical Outcomes Between Aggressive and Limited Discectomy During Transforaminal Percutaneous Endoscopic Lumbar Discectomy: A Propensity Score-Matched Study

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AIM: To compare the clinical, functional, and radiological outcomes of two nucleus pulposus management strategies, limited discectomy and aggressive discectomy, during percutaneous endoscopic lumbar discectomy (PELD), and to investigate the association between the extent of disc removal, postoperative Modic changes, and functional recovery.

METHODS: A total of 200 patients with lumbar disc herniation who underwent transforaminal PELD between January 2023 and January 2025 were retrospectively enrolled. Patients were classified into an aggressive discectomy group (n = 88) and a limited discectomy group (n = 112) according to the intraoperative nucleus pulposus removal strategy. Propensity score matching (PSM) at a 1:1 ratio was performed to balance baseline characteristics between the two groups, resulting in 72 matched pairs for analysis. The primary outcome was the incidence of Modic changes at 1 year postoperatively. Secondary outcomes included recurrence, reoperation, complications, modified MacNab outcomes, and recovery of neurological function, pain, lumbar function, and quality of life.

RESULTS: A total of 144 patients were included after PSM. Compared with the limited discectomy group, the aggressive discectomy group exhibited a significantly higher incidence of Modic changes at 1 year postoperatively (37.50% vs. 22.22%, $p = 0.045$). No significant differences were observed between the two groups in the 1-year recurrence rate, reoperation rate, complication rate, or the proportion of patients achieving excellent or good modified MacNab outcomes (all $p > 0.05$). At 1 month postoperatively, the aggressive discectomy group had higher low-back pain visual analogue scale (VAS) and Oswestry Disability Index (ODI) scores than the limited discectomy group (Holm-adjusted $p = 0.012$ and $p < 0.001$, respectively), whereas no significant between-group differences were observed at 6 or 12 months (all Holm-adjusted $p > 0.05$). Repeated-measures analysis showed significant group-by-time interactions for low-back pain VAS and ODI scores ($p_{interaction} = 0.036$ and 0.004, respectively), whereas the trajectories of the other functional outcomes were comparable between the groups (all $p_{interaction} > 0.05$).

CONCLUSIONS: Among patients undergoing PELD for lumbar disc herniation, aggressive discectomy was associated with a higher incidence of Modic changes at 12 months, whereas no significant between-group difference in recurrence was observed. The association between aggressive discectomy and long-term recurrence requires further investigation.

Keywords: lumbar disc herniation; percutaneous endoscopic lumbar discectomy; aggressive discectomy; limited discectomy; Modic changes

Introduction

Lumbar disc herniation (LDH) is a common degenerative disorder causing low back and leg pain. For patients who fail to respond to conservative treatment or present with progressive neurological deficits, surgical decompression remains an important therapeutic intervention [1,2]. In recent years, percutaneous endoscopic lumbar discectomy (PELD) has gradually become a mainstream minimally invasive surgical technique for the treatment of LDH because it enables precise, targeted decompression under direct visualization while maximizing preservation of the integrity of the posterior ligamentous complex and osseous structures [3,4]. Contemporary concepts of minimally invasive spine surgery emphasize that, in addition to achieving adequate neural decompression, damage to normal tissues should be minimized whenever possible to maintain the long-term biomechanical stability of the spinal motion segment [5].

Despite the increasing maturity of PELD techniques, the optimal extent of nucleus pulposus removal remains a subject of considerable debate. Currently, two principal strategies are adopted in clinical practice: limited discectomy and aggressive discectomy. The former involves removal of only the herniated, extruded, or sequestrated disc material directly compressing the neural structures, without additional intradiscal intervention, thereby maximizing preservation of the residual disc architecture and annular integrity [6]. However, concerns persist regarding a potentially in-

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creased risk of postoperative recurrence. In contrast, aggressive discectomy involves further exploration of the intervertebral disc space and removal of loose or degenerated nucleus pulposus tissue following adequate neural decompression, with the aim of reducing the risk of recurrent disc herniation arising from residual disc material [7]. Nevertheless, whether excessive tissue removal is associated with adjacent segment degeneration and differences in long-term functional recovery remains inconclusive [8,9]. Therefore, determining the optimal balance between sufficient decompression and structural preservation to improve long-term clinical and radiological outcomes remains a critical issue in PELD surgery.

Previous comparisons of different discectomy strategies have mainly been conducted in conventional open or microscopic discectomy, with study endpoints largely focusing on short-term symptom relief, perioperative outcomes, and recurrence risk, whereas postoperative structural radiological changes have received relatively limited attention [10,11]. Modic changes are signal abnormalities of the vertebral endplates and adjacent bone marrow on magnetic resonance imaging (MRI) and are associated with endplate injury, abnormal mechanical loading, and local inflammatory responses. They have also been associated with disc degeneration, chronic low-back pain, and functional impairment [12,13]. Within the relatively consistent minimally invasive setting of PELD, evidence remains limited regarding whether different extents of nucleus pulposus removal are associated with postoperative Modic changes and functional recovery. Clarifying the radiological and clinical differences between limited and aggressive discectomy is therefore clinically relevant to balancing adequate neural decompression against preservation of the disc–endplate complex.

Accordingly, the present study used propensity score matching to balance measured baseline characteristics and compared the radiological and clinical outcomes of limited and aggressive discectomy during PELD. Modic changes at 12 months postoperatively were evaluated as the primary outcome, together with recurrence, reoperation, complications, and longitudinal functional recovery. Compared with previous studies that mainly focused on symptom improvement or recurrence, the present study combined postoperative radiological changes with functional outcomes assessed at multiple follow-up time points to further clarify the associations between the extent of disc removal and structural and functional outcomes.

Methods

Study Population

This was a single-center retrospective cohort study. Consecutive patients with LDH who underwent transforaminal PELD at the Lishui People's Hospital between January 2023 and January 2025 were enrolled. All patients were followed until March 2026. A total of 200 eligible patients were ultimately included in the analysis. The study was approved by the Ethics Committee of The First Affiliated Hospital of Lishui University, Lishui People's Hospital (approval No. 2026-06-08). All patient information was de-identified before data analysis, and no personally identifiable information was included in the analytical dataset; given the retrospective nature of the study, the Ethics Committee of The First Affiliated Hospital of Lishui University, Lishui People's Hospital waived the requirement for written informed consent.

The inclusion criteria were as follows: (1) age ≥18 years; (2) clinical manifestations consistent with lumbar radiculopathy and MRI-confirmed single-level lumbar disc herniation (L3/4, L4/5, or L5/S1); (3) undergoing PELD after failure of at least 6 weeks of standardized conservative treatment; (4) surgery performed using a transforaminal approach; and (5) availability of complete clinical, radiological, and follow-up data with a minimum follow-up duration of 12 months.

The exclusion criteria were as follows: (1) previous lumbar spine surgery; (2) multilevel lumbar disc herniation requiring simultaneous surgical treatment; (3) concomitant spinal disorders that could substantially affect clinical outcomes, including spinal stenosis, lumbar spondylolisthesis of Meyerding grade I or higher, scoliosis with a Cobb angle >10°, spinal infection, or spinal tumor; (4) severe systemic diseases or neurological/psychiatric disorders that could interfere with postoperative functional assessment; and (5) inability to accurately determine the extent of disc removal or missing key clinical data.

Surgical Technique

All patients underwent transforaminal PELD performed by the same experienced spine surgery team. Patients were placed in the prone position with appropriate abdominal support to reduce intra-abdominal pressure. The procedure was performed under local infiltration anesthesia combined with intravenous sedation. Intraoperatively, 0.5% lidocaine was administered layer by layer for local infiltration anesthesia, and an additional approximately 10 mL of 0.5% lidocaine was injected around the target foramen to ensure adequate analgesia.

Under fluoroscopic guidance using a C-arm system, the target level was identified. The puncture trajectory was individualized according to patient body habitus and the affected segment. The entry point was typically located approximately 8–14 cm lateral to the spinous process. An 18-gauge puncture needle was advanced through the intervertebral foramen into the target area. After satisfactory positioning was confirmed, a guidewire was inserted, followed by a skin incision of approximately 6–8 mm. Soft tissues were sequentially dilated to establish the working channel. According to foraminal anatomy and intraoperative exposure requirements, partial ventral osteoplasty of the superior articular process was performed using trephines or a high-

speed burr to enlarge the working space. Subsequently, a working cannula and endoscopic system were introduced. Under continuous saline irrigation, soft and adipose tissues were removed to fully expose the affected nerve root, dural sac, and herniated disc material. Herniated nucleus pulposus tissue compressing the nerve root was gradually removed using pituitary forceps, and decompression was assessed by probing along the nerve root. The procedure was considered complete when the affected nerve root was adequately decompressed, regained free mobility, and showed no persistent mechanical compression under endoscopic visualization. After satisfactory hemostasis was confirmed, the working cannula was removed, and the incision was closed.

Patients were classified according to the actual discectomy strategy performed, as confirmed by the operative records. The same predefined operational classification criteria were applied to all patients, with the key decision rule being whether further intradiscal exploration and proactive removal of residual non-compressive disc material were performed after adequate neural decompression. Patients in whom neither further intradiscal exploration nor proactive removal of residual non-compressive disc material was performed after adequate removal of the responsible herniated fragment and neural decompression were classified into the limited discectomy group. Patients in whom the surgeon further entered the disc space through the annular defect and actively explored and removed loose, degenerated, or mobile residual nucleus pulposus tissue were classified into the aggressive discectomy group. Patients whose actual discectomy strategy could not be clearly determined from the operative records were excluded from the analysis.

In the limited discectomy group, neural decompression was the sole surgical objective. Only the herniated, extruded, or sequestrated disc fragments directly compressing the nerve root were removed. Limited exploration through the existing annular defect was permitted; however, routine enlargement of the intradiscal working area was avoided, and neither central nucleus pulposus curettage nor proactive removal of residual non-compressive disc material was performed. The procedure was terminated once adequate decompression of the affected nerve root had been achieved, thereby maximizing preservation of disc structure and annular integrity.

In the aggressive discectomy group, after removal of the responsible herniated disc fragments and completion of neural decompression, the surgeon further entered the disc space through the annular defect. Loose, degenerated, or mobile nucleus pulposus tissue was explored and removed under direct visualization. When necessary, the extent of intradiscal debridement was moderately expanded to reduce the risk of recurrent herniation caused by residual disc material. The procedure was completed after confirming the absence of obvious mobile disc fragments within the disc space and adequate decompression of the nerve root.

Data Collection and Outcome Assessment

Data Collection

All clinical data were retrospectively collected from the hospital electronic medical record system, picture archiving and communication system (PACS), and follow-up database. The collected data included demographic characteristics, comorbidities, preoperative imaging findings, perioperative information, and postoperative follow-up data.

MRI Protocol and Radiological Assessment

All patients underwent lumbar magnetic resonance imaging (MRI) using a 1.5-T United Imaging MRI scanner (U 586, United Imaging Healthcare, Shanghai, China) with a dedicated spine coil in the supine position. The routine imaging protocol included sagittal T1-weighted imaging (T1WI; repetition time [TR]/echo time [TE], 390/8.38 ms; slice thickness, 4 mm; field of view [FOV], 300 mm), sagittal T2-weighted imaging (T2WI; TR/TE, 2849/114 ms; slice thickness, 4 mm; FOV, 300 mm), and axial T2WI (TR/TE, 2200/107 ms; slice thickness, 4 mm; FOV, 240 mm). For radiological assessment, the preoperative MRI examination performed closest to the date of surgery and the follow-up MRI examination obtained 12 months postoperatively were used. Intervertebral disc degeneration was assessed on preoperative MRI using the five-grade Pfirrmann classification system and categorized as grades I–II, III, and IV–V for analysis. Disc herniation morphology was classified on preoperative MRI as protrusion, extrusion, or sequestration according to the established lumbar disc nomenclature criteria, based on the morphology of displaced disc material and its continuity with the parent disc.

All MRI examinations were anonymized and independently reviewed by two spine surgeons experienced in spinal imaging assessment. Both assessors were blinded to the surgical strategy and clinical outcome data. Modic changes involving the vertebral endplates and adjacent bone marrow at the operated level were primarily assessed on sagittal T1WI and T2WI images. The two assessors completed their evaluations independently, and interobserver agreement was assessed using Cohen's κ coefficient. Any disagreements were resolved by consensus after completion of the reliability assessment.

Primary Outcome

The primary radiological outcome was the presence of Modic changes at the operated level at 12 months postoperatively. Preoperative Modic status at the operated level was also assessed in all patients and classified as absent, type I, type II, or type III. According to the Modic classification system, type I changes were characterized by hypointense signals on T1WI and hyperintense signals on T2WI; type II changes by hyperintense signals on both T1WI and T2WI; and type III changes by hypointense signals on both T1WI and T2WI [14].

Secondary Outcomes

Secondary outcomes included postoperative recurrence, reoperation, complications, and clinical functional recovery. (1) Postoperative recurrence was defined as the reappearance of radicular symptoms corresponding to the operated level after initial symptom relief, with recurrent disc herniation at the same level confirmed by MRI [15]. (2) Reoperation was defined as repeat surgery at the same level during follow-up due to symptom recurrence or surgery-related complications. (3) Complications included transient sensory disturbance, infection, dural injury, epidural hematoma, and other surgery-related adverse events. (4) Clinical functional outcomes included pain intensity, neurological function, lumbar function, and quality of life. (5) Pain intensity was assessed using the visual analogue scale (VAS), including low-back pain VAS and leg pain VAS, which were used to evaluate pain severity in the lower back and affected lower extremity, respectively [16]. (6) Motor function was assessed using the Medical Research Council (MRC) grading system [17]. Sensory function was evaluated through clinical examination of light-touch and pinprick sensation in the affected lower-limb dermatomes, with normal sensory function defined as the absence of detectable sensory deficits. (7) Lumbar function was evaluated using the Oswestry Disability Index (ODI) [18]. (8) Quality of life was assessed using the EuroQol 5-Dimension (EQ-5D) questionnaire [19]. These outcomes were assessed preoperatively and at 1, 6, and 12 months postoperatively.

In addition, overall clinical outcomes were evaluated at the final follow-up according to the modified MacNab criteria [20]. Outcomes were classified as excellent, good, fair, or poor. An excellent outcome was defined as complete symptom resolution with a return to normal work and daily activities; a good outcome indicated marked symptom improvement without limitation in daily activities; a fair outcome was defined as partial symptom improvement with persistent functional limitation; and a poor outcome indicated no improvement or worsening of symptoms compared with the preoperative condition. Excellent and good outcomes were collectively defined as favorable clinical outcomes, and the modified MacNab success rate was calculated accordingly.

Statistical Analysis

All statistical analyses were performed using R software (version 4.4.1; R Foundation for Statistical Computing, Vienna, Austria). Baseline continuous variables are presented as mean ± standard deviation or median (interquartile range), as appropriate. Between-group comparisons of continuous variables were performed using Welch's independent-samples *t*-test or the Mann–Whitney U test, as appropriate. Categorical variables are presented as frequencies (percentages) and were compared using Pearson's chi-square test without continuity correction or Fisher's exact test, as appropriate. Propensity score matching (PSM) was performed to reduce selection bias and confounding. Propensity scores were estimated using logistic regression incorporating age, sex, body mass index (BMI), herniation level, herniation type, degree of disc degeneration, and preoperative neurological status. One-to-one nearest-neighbor matching without replacement was performed with a caliper width of 0.1. Covariate balance was assessed using standardized mean differences (SMDs), with an SMD <0.20 indicating acceptable balance. Following PSM, outcome analyses were conducted at the group level in the matched cohort, consistent with the use of matching as a preprocessing approach for subsequent outcome analysis [21]. In the propensity score–matched cohort, univariable logistic regression was used to estimate the overall association between surgical strategy and postoperative Modic changes, with the results reported as odds ratios (ORs) and 95% confidence intervals (CIs). Exploratory subgroup analyses were then performed to assess whether patient characteristics modified this association. Logistic regression models were used to estimate ORs and 95% CIs within each subgroup, and interaction terms were used to assess effect modification. Longitudinal functional outcomes were analyzed using generalized estimating equation (GEE) models including group, time, and group-by-time interaction terms. Continuous longitudinal outcomes are presented as mean ± standard error. A binomial distribution with a logit link function was used for binary outcomes, whereas a Gaussian distribution with an identity link function was used for continuous outcomes. An exchangeable working correlation structure was specified to account for within-patient correlations across repeated measurements. Post hoc between-group comparisons were performed at each time point, with the Holm method used to adjust for multiple comparisons within each outcome. All tests were two-sided, and $p < 0.05$ was considered statistically significant.

Results

Baseline Characteristics

A total of 200 eligible patients with LDH were included in the study, comprising 88 patients in the aggressive discectomy group and 112 patients in the limited discectomy group. After 1:1 PSM, 72 matched pairs were successfully generated and included in the subsequent analyses (Table 1).

Before matching, the two groups were generally comparable with respect to demographic characteristics and most baseline clinical variables. Significant differences were observed only in the distribution of herniation levels ($p = 0.042$) and herniation types ($p = 0.028$) between the groups. After PSM, baseline characteristics were well balanced, with all covariates demonstrating SMDs <0.20. In addition, no statistically significant differences were observed in any baseline variables between the two groups (all $p > 0.05$).

Table 1. Comparison of baseline characteristics between the two groups before and after propensity score matching.

Variables	Aggressive discectomy group (n = 88)	Limited discectomy group (n = 112)	SMD	*p* value	Aggressive discectomy group (n = 72)	Limited discectomy group (n = 72)	SMD	*p* value
Age (years)	53.00 [39.75, 61.25]	51.00 [40.00, 65.25]	0.055	0.768	51.08 ± 14.59	50.15 ± 14.31	0.064	0.700
Gender, n (%)			0.112	0.431			0.168	0.319
Male	45 (51.14)	51 (45.54)			37 (51.39)	31 (43.06)		
Female	43 (48.86)	61 (54.46)			35 (48.61)	41 (56.94)		
Herniation level, n (%)			0.372	0.042			0.131	0.734
L3/4	17 (19.32)	17 (15.18)			13 (18.06)	13 (18.06)		
L4/5	63 (71.59)	70 (62.50)			52 (72.22)	49 (68.06)		
L5/S1	8 (9.09)	25 (22.32)			7 (9.72)	10 (13.89)		
Herniation type, n (%)			0.392	0.028			0.191	0.520
Protrusion	33 (37.50)	29 (25.89)			24 (33.33)	28 (38.89)		
Extrusion	44 (50.00)	53 (47.32)			38 (52.78)	38 (52.78)		
Sequestration	11 (12.50)	30 (26.79)			10 (13.89)	6 (8.33)		
Herniation side, n (%)			0.085	0.837			0.065	0.928
Left	40 (45.45)	49 (43.75)			31 (43.06)	30 (41.67)		
Right	41 (46.59)	56 (50.00)			34 (47.22)	36 (50.00)		
Central	7 (7.95)	7 (6.25)			7 (9.72)	6 (8.33)		
Disc degeneration grade, n (%)			0.036	0.969			0.059	0.940
Grade I–II	30 (34.09)	40 (35.71)			26 (36.11)	24 (33.33)		
Grade III	31 (35.23)	38 (33.93)			28 (38.89)	29 (40.28)		
Grade IV–V	27 (30.68)	34 (30.36)			18 (25.00)	19 (26.39)		
Preoperative Modic changes, n (%)			0.026	0.854			0.077	0.643
Yes	15 (17.05)	18 (16.07)			12 (16.67)	10 (13.89)		
No	73 (82.95)	94 (83.93)			60 (83.33)	62 (86.11)		
BMI (kg/m^2)	24.90 ± 2.44	24.95 ± 2.41	0.023	0.874	24.82 ± 2.41	24.85 ± 2.30	0.011	0.947
Hypertension, n (%)	27 (30.68)	40 (35.71)	0.107	0.454	21 (29.17)	23 (31.94)	0.060	0.717
Diabetes mellitus, n (%)	14 (15.91)	12 (10.71)	0.153	0.278	10 (13.89)	7 (9.72)	0.129	0.438
Smoking, n (%)	13 (14.77)	15 (13.39)	0.040	0.780	11 (15.28)	9 (12.50)	0.080	0.630
Preoperative MRC grade, n (%)			0.267	0.468			0.181	0.879
Grade 0	3 (3.41)	4 (3.57)			3 (4.17)	2 (2.78)		
Grade 1	0 (0.00)	0 (0.00)			0 (0.00)	0 (0.00)		
Grade 2	5 (5.68)	4 (3.57)			4 (5.56)	4 (5.56)		
Grade 3	13 (14.77)	11 (9.82)			11 (15.28)	9 (12.50)		
Grade 4	20 (22.73)	37 (33.04)			15 (20.83)	20 (27.78)		
Grade 5	47 (53.41)	56 (50.00)			39 (54.17)	37 (51.39)		
Preoperative low-back pain VAS	6.00 [5.00, 6.00]	6.00 [5.00, 7.00]	0.015	0.769	6.00 [5.00, 6.00]	6.00 [5.00, 6.00]	0.027	0.930
Preoperative leg pain VAS	7.00 [6.00, 7.00]	6.00 [6.00, 7.00]	0.186	0.121	6.50 [6.00, 7.00]	6.00 [6.00, 7.00]	0.116	0.365
Preoperative ODI	61.99 ± 8.50	63.19 ± 8.30	0.143	0.318	61.48 ± 8.05	63.01 ± 8.48	0.185	0.269

Abbreviations: BMI, body mass index; MRC, Medical Research Council; ODI, Oswestry Disability Index; VAS, visual analogue scale.

Comparison of Postoperative Clinical and Radiological Outcomes

Interobserver agreement in the assessment of Modic changes was high (Cohen's κ = 0.86, 95% CI: 0.78–0.94). As shown in Table 2, the incidence of Modic changes at 1 year postoperatively was significantly higher in the aggressive discectomy group than in the limited discectomy group (37.50% vs. 22.22%, $p = 0.045$). In the propensity score–matched cohort, univariable logistic regression further showed that aggressive discectomy was associated

Table 2. Comparison of postoperative clinical and radiological outcomes between the two groups.

Variables	Aggressive discectomy group (n = 72)	Limited discectomy group (n = 72)	*p* value
Modic changes at 1 year, n (%)	27 (37.50)	16 (22.22)	0.045
Reoperation within 1 year, n (%)	0 (0.00)	0 (0.00)	1.000
Recurrence within 1 year, n (%)	8 (11.11)	7 (9.72)	0.785
Favorable modified MacNab outcome, n (%)	64 (88.89)	66 (91.67)	0.574
Complications, n (%)	3 (4.17)	1 (1.39)	0.620

Table 3. Subgroup analysis of the association between surgical strategy and postoperative modic changes according to baseline characteristics.

Variables	Aggressive discectomy	Limited discectomy	OR (95% CI)	*p* value	*p* for interaction
Age					0.941
<50 years	10/30	7/35	2.00 (0.65–6.15)	0.227	
≥50 years	17/42	9/37	2.12 (0.80–5.59)	0.131	
BMI					0.777
<25 kg/m^2	14/39	8/41	2.31 (0.84–6.36)	0.105	
≥25 kg/m^2	13/33	8/31	1.87 (0.64–5.42)	0.250	
Herniation level					0.183
L3/4 or L5/S1	5/20	6/23	0.94 (0.24–3.74)	0.935	
L4/5	22/52	10/49	2.86 (1.18–6.94)	0.020	
Disc degeneration					0.487
I–III	14/54	8/53	1.97 (0.75–5.18)	0.170	
IV–V	13/18	8/19	3.58 (0.90–14.15)	0.070	
Herniation type					0.589
Extrusion/sequestration	18/48	11/44	1.80 (0.73–4.42)	0.200	
Protrusion	9/24	5/28	2.76 (0.77–9.85)	0.118	

Note: Values in the aggressive and limited discectomy columns are presented as the number of patients with postoperative Modic changes/total number of patients within the corresponding subgroup. All subgroup denominators were derived from the propensity score–matched cohort. Abbreviation: OR, odds ratio.

with higher odds of postoperative Modic changes than limited discectomy (OR = 2.10, 95% CI: 1.01–4.37; $p = 0.047$; **Supplementary Table 1**). However, no significant differences were observed between the two groups in terms of the 1-year recurrence rate, reoperation rate, or overall complication rate (all $p > 0.05$). At the final follow-up, satisfactory clinical outcomes were achieved in both groups, with no statistically significant differences in the distribution of modified MacNab grades or in the proportion of patients achieving favorable outcomes between the two groups (all $p > 0.05$; **Supplementary Table 2**).

Exploratory Subgroup Analysis

To explore whether baseline characteristics potentially modified the association between surgical strategy and postoperative Modic changes, exploratory subgroup analyses were performed according to age, BMI, herniation level, degree of disc degeneration, and herniation type (Table 3). A nominally significant association was observed only in patients with L4/5 disc herniation; however, none of the interaction tests reached statistical significance (all *p* for interaction > 0.05).

Postoperative Functional Recovery and Quality-of-Life Changes

Functional outcomes at each follow-up time point and the corresponding statistical comparisons are presented in Table 4, and their longitudinal trajectories are shown in Fig. 1. At 1 month postoperatively, the aggressive discectomy group had higher low-back pain VAS scores than the limited discectomy group (Holm-adjusted $p = 0.012$). The ODI scores were also higher in the aggressive discectomy group (Holm-adjusted $p < 0.001$). No significant between-group differences in these outcomes were observed at 6 or 12 months postoperatively. Significant group-by-time interactions were observed for low-back pain VAS and ODI scores ($p_{interaction} = 0.036$ and 0.004, respectively). No significant group-by-time interactions were observed for normal sensory function, MRC grade 5 muscle strength, leg pain VAS, or EQ-5D scores (all $p_{interaction} > 0.05$).

Discussion

The present study compared the clinical and radiological outcomes of two nucleus pulposus management strategies, limited discectomy and aggressive discectomy, in a PSM

Table 4. Longitudinal functional outcomes and holm-adjusted post hoc comparisons in the propensity score-matched cohort.

Outcome	Time point	Aggressive discectomy group (n = 72)	Limited discectomy group (n = 72)	*p* value	*p* for interaction	Holm-adjusted *p* value
Normal sensory function, n (%)	Preoperative	33 (45.83)	39 (54.17)	0.317	0.798	1.000
	1 month postoperatively	50 (69.44)	54 (75.00)	0.457		1.000
	6 months postoperatively	61 (84.72)	63 (87.50)	0.630		1.000
	12 months postoperatively	67 (93.06)	70 (97.22)	0.441		1.000
MRC grade 5 muscle strength, n (%)	Preoperative	39 (54.17)	37 (51.39)	0.738	0.965	1.000
	1 month postoperatively	52 (72.22)	52 (72.22)	1.000		1.000
	6 months postoperatively	57 (79.17)	57 (79.17)	1.000		1.000
	12 months postoperatively	63 (87.50)	62 (86.11)	0.806		1.000
Low-back pain VAS, mean ± SE	Preoperative	5.83 ± 0.13	5.81 ± 0.12	0.871	0.036	1.000
	1 month postoperatively	2.49 ± 0.11	2.00 ± 0.12	0.003		0.012
	6 months postoperatively	0.42 ± 0.08	0.50 ± 0.08	0.451		1.000
	12 months postoperatively	0.39 ± 0.07	0.46 ± 0.07	0.484		1.000
Leg pain VAS, mean ± SE	Preoperative	6.47 ± 0.13	6.35 ± 0.12	0.483	0.921	1.000
	1 month postoperatively	5.24 ± 0.13	5.11 ± 0.13	0.500		1.000
	6 months postoperatively	2.89 ± 0.11	2.88 ± 0.12	0.931		1.000
	12 months postoperatively	2.06 ± 0.10	2.04 ± 0.10	0.919		1.000
ODI, mean ± SE	Preoperative	61.48 ± 0.95	63.01 ± 1.00	0.264	0.004	0.792
	1 month postoperatively	30.23 ± 0.60	26.77 ± 0.55	<0.001		<0.001
	6 months postoperatively	23.21 ± 0.53	22.63 ± 0.57	0.454		0.909
	12 months postoperatively	11.30 ± 1.08	11.26 ± 1.44	0.983		0.983
EQ-5D, mean ± SE	Preoperative	0.53 ± 0.03	0.52 ± 0.03	0.801	0.902	1.000
	1 month postoperatively	0.82 ± 0.03	0.83 ± 0.02	0.749		1.000
	6 months postoperatively	0.91 ± 0.02	0.91 ± 0.01	0.991		1.000
	12 months postoperatively	0.95 ± 0.01	0.97 ± 0.01	0.352		1.000

Abbreviation: EQ-5D, EuroQol 5-Dimension.

cohort of patients undergoing PELD. The results demonstrated that the incidence of Modic changes at 1 year postoperatively was higher in the aggressive discectomy group than in the limited discectomy group, whereas no significant differences were observed between the two groups in terms of modified MacNab outcomes, complication rates, reoperation rates, or 1-year recurrence rates. In addition, the limited discectomy group showed better low-back pain relief and functional recovery only at 1 month postoperatively, and this advantage did not persist during subsequent follow-up. These findings suggest that different discectomy strategies may exhibit distinct characteristics with respect to

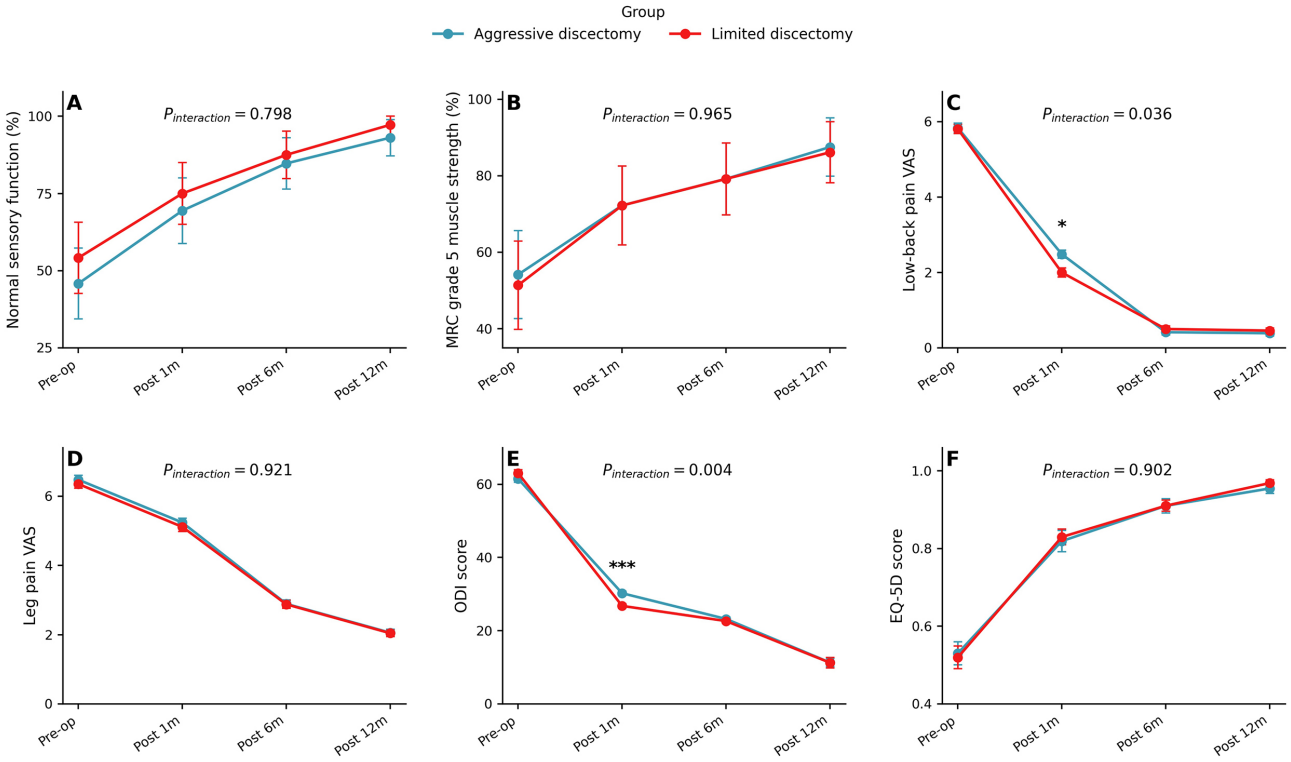


Fig. 1. Changes in neurological function, pain, and quality of life at different follow-up time points between the two groups. Note: (A) Normal sensory proportion of patients with normal sensory function; (B) proportion of patients with MRC grade 5 muscle strength; (C) visual analogue scale (VAS) score for low-back pain; (D) VAS score for leg pain; (E) Oswestry Disability Index (ODI) score; (F) EuroQol 5-Dimension (EQ-5D) score. Data in panels A and B are presented as proportions (%), whereas data in panels C, D, E, and F are presented as means ± standard errors. Error bars represent standard errors. *p* values for interaction were calculated using the generalized estimating equation (GEE) to evaluate differences in recovery trends between the two groups. Asterisks indicate Holm-adjusted between-group comparisons at specific time points: *$p < 0.05$ and *** represent $p < 0.001$. Abbreviation: MRC, Medical Research Council.

postoperative radiological changes and short-term clinical recovery, while overall clinical outcomes at 1 year remain comparable.

The most notable finding of this study was that the proportion of patients with Modic changes at 1 year postoperatively was significantly higher in the aggressive discectomy group, whereas no statistically significant difference was observed in the 1-year recurrence rate between the two groups. Although direct evidence comparing the relationship between different discectomy strategies and Modic changes remains limited, previous research has suggested that the extent of disc removal may be associated with the development of postoperative Modic changes [6]. Furthermore, previous radiological and biomechanical studies have indicated that more extensive disc tissue removal may be associated with progression of disc degeneration, reduction in disc height, and alterations in segmental biomechanical loading, thereby potentially affecting postoperative structural integrity [22,23].

This phenomenon may be closely related to alterations in the biomechanical and biological environment of the intervertebral disc and vertebral endplate. On the one hand, aggressive discectomy removes not only the herniated nucleus pulposus but also additional residual disc tissue, which may reduce intradiscal pressure and redistribute segmental loading. Consequently, the vertebral endplate may be subjected to greater mechanical stress, increasing the risk of endplate microdamage and bone marrow remodeling [24]. On the other hand, substantial loss of nucleus pulposus tissue may impair nutrient exchange between the intervertebral disc and vertebral endplate, promote extracellular matrix degradation and local inflammatory responses, and subsequently induce signal alterations in the endplate and adjacent vertebral bone marrow, ultimately manifesting as Modic changes [25]. Previous basic science and imaging evidence have likewise demonstrated that endplate injury, abnormal mechanical loading, and chronic inflammatory responses are important pathological mechanisms underlying the development of Modic changes [26].

Additionally, the present study did not demonstrate a significant reduction in the 1-year recurrence rate with aggressive discectomy. This finding is consistent with a previous meta-analysis, which similarly reported no significant difference in the risk of postoperative recurrence between

limited and aggressive discectomy strategies [8]. Taken together, these findings suggest that further expansion of the extent of nucleus pulposus removal after adequate neural decompression does not appear to provide a clear advantage in preventing recurrence, while being associated with a higher incidence of postoperative Modic changes. Therefore, for patients undergoing PELD, the choice of discectomy strategy should place greater emphasis on achieving an optimal balance between adequate neural decompression and preservation of the disc–endplate complex, rather than simply pursuing more extensive tissue removal.

The present study also observed that the aggressive discectomy group exhibited higher low-back pain VAS and ODI scores only at 1 month postoperatively, whereas pain and functional outcomes gradually converged during subsequent follow-up. In contrast to the relatively substantial reduction in low-back pain, leg pain VAS scores showed more modest improvement at 1 month postoperatively in both groups. This difference may reflect distinct recovery patterns of axial and radicular pain, as residual nerve root irritation or pre-existing neural injury may persist after adequate decompression. However, these potential explanations were not directly evaluated in the present study and should therefore be interpreted cautiously. No significant between-group difference in leg pain VAS scores was observed at this time point. These findings suggest that different discectomy strategies may influence early postoperative recovery, although such effects do not appear to persist during mid- to long-term follow-up. A previous randomized controlled trial and its 2-year follow-up comparing sequestrectomy with conventional discectomy reported limited differences in long-term pain relief and functional improvement between the two procedures [27,28]. However, as these studies involved different surgical techniques and discectomy strategies, their findings may not be directly generalizable to limited versus aggressive discectomy during transforaminal PELD. Therefore, short-term postoperative symptom changes may primarily reflect transient characteristics of the perioperative recovery process rather than the long-term clinical value of different discectomy strategies. For patients undergoing PELD, the extent of nucleus pulposus removal should be evaluated in conjunction with long-term functional and radiological outcomes.

Several limitations of this study should be acknowledged. First, this was a single-center retrospective cohort study. Although PSM was applied to balance major baseline characteristics, residual confounding could not be completely eliminated. Although propensity score matching was used to improve baseline comparability, the primary outcome analysis did not explicitly account for within-pair dependence, which may have affected variance estimation and statistical inference. Several important variables potentially associated with both surgical strategy selection and postoperative outcomes, including intraoperative annular injury, operative duration, endplate injury, and the actual extent of nucleus pulposus removal, were not objectively quantified or incorporated into the analysis and may therefore have influenced the results. Second, the follow-up duration was limited to 1 year, which may have been insufficient to fully capture long-term recurrent lumbar disc herniation. Moreover, only a small number of recurrence events occurred during the study period, limiting the statistical power to detect a potentially modest difference in recurrence risk between the two surgical strategies. Therefore, the absence of a statistically significant between-group difference in 1-year recurrence should not be interpreted as evidence of equivalent long-term recurrence risk. Third, the classification of limited and aggressive discectomy was based on the actual intraoperative discectomy strategy, as confirmed by the operative records. Although standardized operational criteria were applied, objective quantitative measures of the actual volume or weight of disc material removed were unavailable; therefore, some degree of procedural variability and classification bias may have remained. Although preoperative Modic status was recorded, the primary analysis assessed the presence of Modic changes at 1 year postoperatively rather than specifically evaluating new-onset or progressive Modic changes. Therefore, the findings should not be interpreted as evidence of an increased risk of developing new Modic changes. Finally, the present study focused primarily on clinical and conventional radiological outcomes and did not incorporate quantitative endplate imaging parameters, biomechanical assessments, or inflammatory biomarkers to explore the underlying mechanisms. Therefore, the causal relationship and biological mechanisms linking aggressive discectomy to Modic changes remain to be clarified in future basic science and prospective clinical studies.

Overall, the present findings indicate that more extensive nucleus pulposus removal was not associated with a detectable reduction in recurrence during the 1-year follow-up, whereas a higher incidence of postoperative Modic changes was observed in the aggressive discectomy group. Given the retrospective design, relatively short follow-up period, and limited number of recurrence events, these findings require further validation in larger prospective studies with longer follow-up.

Conclusions

This study demonstrated that, among patients with LDH undergoing PELD, aggressive discectomy was associated with a higher proportion of patients with Modic changes at 1 year postoperatively compared with limited discectomy. However, no significant differences were observed between the two groups in terms of the 1-year recurrence rate, reoperation rate, or overall clinical outcomes. Repeated-measures analysis showed different trajectories of low-back pain VAS and ODI scores between the groups, whereas overall functional recovery at 1 year was comparable. These findings suggest that, in the setting of ade-

quate neural decompression, the extent of nucleus pulposus removal may be associated with postoperative radiological changes and early functional recovery. Future large-scale, multicenter prospective studies are warranted to further clarify the relationship between the extent of disc removal and long-term clinical and radiological outcomes.

Availability of Data and Materials

The data analyzed are available from the corresponding author upon reasonable request.

Author Contributions

Conception and design: KZ, PQ. Administrative support: KZ, WG. Provision of study materials: PQ, WG. Collection and assembly of data: KZ. Data analysis and interpretation: KZ, PQ, WG. Manuscript writing: KZ, PQ, WG. All authors have been involved in revising the manuscript critically for important intellectual content. All authors gave final approval of the version to be published. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

Ethics Approval and Consent to Participate

This study was carried out in strict accordance with the ethical guidelines of the Declaration of Helsinki. The study was approved by the Ethics Committee of The First Affiliated Hospital of Lishui University, Lishui People's Hospital (approval No. 2026-06-08). All patient information was de-identified before data analysis, and no personally identifiable information was included in the analytical dataset; given the retrospective nature of the study, the Ethics Committee of The First Affiliated Hospital of Lishui University, Lishui People's Hospital waived the requirement for written informed consent.

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Conflict of Interest

The authors declare no conflict of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.62713/aic.4866.

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