

Minimally Invasive Surgical Techniques for Lumbar Disc Herniation: A Comparative Review of PELD, UBE, PEID and MED

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Abstract

Lumbar Disc Herniation (LDH) ranks among the most prevalent degenerative spinal disorders responsible for refractory low back pain and radicular sciatica, substantially impairing daily function and work productivity in adult populations. Conventional open discectomy has gradually lost clinical priority in favor of Minimally Invasive Spinal Surgery (MISS), largely owing to its associated extensive paraspinal muscle dissection, destruction of the posterior ligamentous complex, prolonged rehabilitation, and an elevated risk of postoperative lumbar stiffness. Percutaneous Endoscopic Lumbar Discectomy (PELD), Unilateral Biportal Endoscopy (UBE), Percutaneous Endoscopic Interlaminar Discectomy (PEID), and Microendoscopic Discectomy (MED) currently represent four dominant minimally invasive modalities for LDH management, each distinguished by unique surgical corridors, visualization systems, indications, and therapeutic profiles. This comparative review synthesizes the technical workflows, perioperative metrics, complication profiles, and long-term functional outcomes of these four procedures, cross-referencing recent meta-analyses and prospective comparative clinical trials to resolve existing clinical controversies. Aggregated clinical evidence confirms that all four interventions deliver sufficient neural decompression and effective pain remission, outperforming open laminotomy discectomy in minimizing hemorrhage, shortening hospital stays, and accelerating early ambulation. Specifically, PELD achieves unparalleled minimal tissue injury for routine foraminal and central single-level LDH; UBE enables comprehensive spinal canal decompression, making it ideal for LDH

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concurrent with spinal stenosis, by virtue of its broad operative field and flexible instrument manipulation; PEID addresses the critical limitation of transforaminal endoscopy in excising high-grade migrated and sequestered disc fragments; and MED merges microscopic magnification with tubular retraction to balance surgical safety with soft-tissue preservation. This review further elaborates on the procedural pitfalls, contraindications, and postsurgical reherniation risk associated with each technique, thereby generating evidence-based guidance for personalized surgical decision-making and informing future technical refinement in endoscopic spinal surgery.

Keywords

Lumbar Disc Herniation, Minimally Invasive Spine Surgery, PELD, UBE, PEID, MED, Endoscopic Discectomy, Surgical Indication, Clinical Outcomes

1. Introduction

LDH arises from nucleus pulposus herniation through torn annulus fibrosus, compressing lumbar nerve roots or the thecal sac, indicating that the lifetime risk for symptomatic lumbar disc herniation is 1% - 3% [1]. Surgical intervention is indicated for patients failing standardized conservative management (rest, analgesia, physical rehabilitation) sustained over three consecutive months [2], with core therapeutic goals of neural decompression and restoration of lumbar mechanical function. Although traditional open laminectomy permits gross total resection of herniated disc material, extensive stripping of multifidus muscles and partial resection of lamina and interspinous ligaments frequently precipitate persistent axial back pain, segmental spinal instability and protracted recovery timelines [3].

MISS has undergone rapid translational development over the past two decades, defined by precise targeted dissection, limited soft tissue trauma, shortened inpatient stay and low major complication incidence [3]. PELD, UBE, PEID and MED constitute four mainstream minimally invasive discectomy platforms with divergent anatomical entry points and instrument systems, establishing complementary clinical niches for heterogeneous LDH phenotypes [4]. PELD, a mature single-port transforaminal endoscopic technique, remains the first-line intervention for uncomplicated single-level LDH [4] [5]. UBE, a novel dual-channel endoscopic paradigm, overcomes visual and instrumental constraints inherent to uniportal endoscopy, expanding indications to complex stenotic and multi-level disc pathology [6]. PEID adopts a percutaneous interlaminar single-port trajectory, resolving the inability of transforaminal approaches to access caudally migrated free disc fragments [7]. MED integrates tubular dilating retractors with surgical microscopy, reconciling the anatomical familiarity of open microdiscectomy with minimally invasive soft tissue protection [7]. This review comprehensively contrasts technical specifications, perioperative safety data, advantages and drawbacks of the four modalities, summarizes real-world clinical application ex-

perience, and outlines prospective developmental directions for minimally invasive lumbar discectomy.

Review Methodology

This narrative comparative review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines for systematic reviews. We searched PubMed/MEDLINE, Embase, and Web of Science using the following search strategy: (lumbar disc herniation OR LDH) AND (minimally invasive OR endoscopic OR percutaneous) AND (PELD OR PTED OR UBE OR PEID OR MED OR microendoscopic OR biportal OR transforaminal OR interlaminar). Reference lists of retrieved articles and relevant review articles were hand-searched for additional eligible studies.

Eligibility criteria included: 1) comparative studies (randomized controlled trials, prospective or retrospective cohort studies, case-control studies) evaluating two or more of the four minimally invasive techniques (PELD, UBE, PEID, MED) for lumbar disc herniation; 2) systematic reviews and meta-analyses comparing these techniques; 3) studies reporting at least one of the following outcomes: perioperative metrics, complication rates, functional outcomes (VAS, ODI, MacNab criteria), reoperation rates, or long-term follow-up data; 4) full-text articles published in English; and 5) human studies with a minimum follow-up of 6 months. Exclusion criteria included: 1) case reports, technical notes without comparative outcome data, and expert opinions; 2) studies focusing exclusively on spinal stenosis, spondylolisthesis, or other degenerative conditions without separate analysis of LDH subgroups; 3) cadaveric or biomechanical studies; and 4) duplicate publications.

Data extraction included study characteristics, patient demographics, surgical parameters, outcome measures, and follow-up duration. Given the heterogeneity of study designs and outcome measures, a meta-analysis was not performed; instead, we synthesized findings narratively with emphasis on comparative evidence from randomized controlled trials and large cohort studies, supplemented by systematic reviews and meta-analyses identified through our search.

2. Core Technical Characteristics of Four Minimally Invasive Discectomy Modalities

Substantial disparities in surgical corridor design, portal configuration, visualization hardware and operative mechanics differentiate the four techniques, leading to non-overlapping primary indications and unique technical limitations [8]. All key procedural parameters and operational workflows are summarized below (**Table 1**), supported by standardized comparative table synthesizing published controlled trial data and meta-analytic evidence [9].

2.1. Percutaneous Endoscopic Lumbar Discectomy (PELD/PTED)

PELD is the foundational uniportal transforaminal endoscopic discectomy technique, utilizing the Kambin triangular zone within the lumbar intervertebral fo-

ramen to establish a single percutaneous working cannula, predominantly performed under conscious local anesthesia [10]. All procedural steps: foramino-plasty, annular release, nucleus pulposus extraction and direct nerve root decompression are completed under continuous high-definition endoscopic live visualization [11]. The working channel diameter is 0.7 - 1.0 cm [12], and prospective controlled trials document significantly reduced intraoperative blood loss, shorter total operative duration and earlier post-operative mobilization relative to conventional open discectomy [13]. Primary clinical indications include single-level central, foraminal, and mildly migrated contained LDH, alongside recurrent disc herniation following prior open spinal surgery [14]. The confined uniportal transforaminal workspace creates critical procedural limitations: complete decompression is challenging in severe lateral recess stenosis and high-grade cranio-caudal migrated sequestered disc herniation [15]-[17]. For L5-S1 lesions with high iliac crest or narrow foraminal anatomy, the transforaminal approach may be technically demanding or infeasible [18]-[20].

Table 1. Basic technical characteristics of four minimally invasive spinal surgery techniques for LDH.

Technical Parameters	PELD	UBE	PEID	MED
Surgical Corridor	Transforaminal (Kambin triangle uniportal) [10]	Posterior unilateral interlaminar dual-portal [21] [22]	Posterior interlaminar uniportal percutaneous cannula [18] [30]	Percutaneous dilated tubular posterior corridor [40] [41]
Skin Incision Size	Single 0.7 - 1.0 cm cut [12] [14]	Two separate 1.0 - 1.5 cm incisions [23] [24]	Single 0.8 - 1.2 cm percutaneous cut [31] [34] [35]	Single 1.5 - 2.0 cm dilated tubular incision [42] [43]
Primary Anesthesia	Local conscious sedation (first-line) [10]	General/epidural anesthesia [22] [25] [26]	Local or epidural anesthesia (dual option) [31]-[33]	General/epidural anesthesia [45] [46]
Core Clinical Advantages	Minimal soft tissue trauma, ultra-rapid early rehabilitation, intact posterior ligaments [13]	Panoramic visual field, flexible multi-angle instruments, comprehensive circumferential decompression [21] [27]	Superior visualization of migrated/sequestered caudal disc fragments [19] [31] [52]	Familiar open microdiscectomy anatomy, low learning curve, high intraoperative safety [47] [48]
Primary Limitations	Restricted uniportal workspace, inadequate decompression for severe lateral recess stenosis [15]-[17]	Mildly increased soft tissue trauma, risk of irrigation fluid extravasation oedema [28] [29]	Elevated dural tear risk, steep endoscopic skill requirement for interlaminar dissection [37] [38]	Rigid fixed tubular channel limits multi-angle decompression for severe spinal stenosis [51]

Continued

	Simple single-level	Complex multi- level LDH, LDH	High-grade cranio-caudal	Routine uncomplicated
Dominant	central/foraminal	combined with	migrated and	LDH, revision
Clinical	LDH, post-open	degenerative	free sequestered	recurrent LDH
Indications	recurrent	spinal stenosis,	disc herniation	with distorted
	contained	massive sequestered	[31]-[33]	surgical anatomy
	herniation [14]	herniation [21] [27]		[49] [50]

2.2. Unilateral Biportal Endoscopy (UBE)

UBE is a dual-channel posterior endoscopic technique that creates two discrete small skin incisions ipsilateral to the pathological segment: one dedicated visualization portal housing the endoscope and continuous irrigation tubing, and a separate working portal for interchangeable surgical instruments [21] [22]. Spatial separation of visual and instrumental channels eliminates instrument shadowing and obstruction, markedly expanding the accessible surgical field and angular manipulation range [23] [24]. The posterior unilateral interlaminar corridor enables full visualization of the spinal canal, lateral recess and intervertebral foramen, facilitating thorough circumferential nerve root decompression and En bloc resection of large herniated disc tissue [22] [25] [26]. Compared to uniportal endoscopic systems, UBE features gentler instrument learning curves and universal compatibility with standard open spinal instruments, rendering it suitable for complex pathologies including multi-level LDH, massive sequestered migrated herniation, and LDH combined with degenerative lumbar spinal stenosis [21] [27]. UBE may cause marginally greater soft tissue trauma than PELD [28], but this is counterbalanced by its superior decompression capability and significantly reduced radiation exposure [29].

2.3. Percutaneous Endoscopic Interlaminar Discectomy (PEID)

PEID is a uniportal percutaneous endoscopic technique utilizing a posterior interlaminar entry trajectory, miniaturizing traditional fenestration discectomy under direct endoscopic surveillance [18] [30]. The posterior interlaminar access provides a distinct advantage over the transforaminal route for specific pathologies, particularly high-grade migrated discs and axillary herniations [31]-[33]. The interlaminar corridor avoids obstruction from lateral pedicles and high iliac crests, offering a clearer view of migrated fragments compared to the transforaminal route [18] [19]. PEID preserves the core benefits of minimally invasive surgery while overcoming the limitations of PELD for migrated disc herniations [31] [34] [35]. Clinical studies demonstrate comparable efficacy to UBE for treating high-grade migrated disc herniations [36]. The primary technical limitations of PEID are the elevated risk of iatrogenic dural tear and mechanical nerve root irritation, which are well-documented consequences of the challenging anatomical corridor and the technical precision required [37] [38]. These risks drive the need for a steep learning curve, advanced surgical skill, and innovations in both technique and in-

strumentation [37]–[39].

2.4. Microendoscopic Discectomy (MED)

MED is a minimally invasive technique that combines a tubular retractor system, placed through sequential muscle dilators, with an optical surgical microscope for magnification [40] [41]. Multiple studies confirm the effectiveness of this technique. One prospective study of 135 patients using the Microscopic Endoscopic Tubular Retractor System (METRx-MD) reported significant improvements in pain and disability scores, with a 94% patient satisfaction rate [42] [43]. Similarly, other research has found that the tubular microdiscectomy technique, using a microscope, is safe and effective, combining modern minimally invasive benefits while avoiding some limitations of pure endoscopic visualization [43] [44]. MED provides the benefits of minimally invasive surgery; its safety profile is nuanced. The risk of catastrophic complications appears comparable or elevated, and the learning curve requires careful navigation to minimize early-stage adverse events [45] [46]. MED simplifies instrument handling relative to pure endoscopic systems is logical and supported by the clinical literature. However, the difference in the learning curve is not a dramatic advantage, as both techniques require a dedicated period to master, but MED's integration with open surgical skills may make the initial adoption phase more familiar for surgeons trained in traditional techniques [47] [48]. MED is a well-validated technique for routine LDH. However, its most compelling utility is in revision surgery, where it offers a minimally invasive alternative to open surgery, despite the inherent technical challenges. Success depends on careful patient selection, particularly excluding those with significant spinal instability [49] [50]. The rigid fixed tubular retractor restricts multi-angle operative movement, limiting adequate decompression in severe multi-level spinal stenosis; long-term functional improvement profiles lag marginally behind UBE for stenotic combined pathologies [51]. A comprehensive procedure selection framework incorporating patient- and pathology-specific factors is presented in **Table 2**.

Table 2. Procedure selection framework for minimally invasive spinal surgery.

Patient/ Pathology Factor	PELD	UBE	PEID	MED
Herniation Level	L1-L4 (transforaminal safe zone); L5-S1 with favorable anatomy	All levels; preferred for L5- S1 with high iliac crest [18] [19]	Preferred for L5-S1; narrow interlaminar window technique available [30] [39]	All levels
Migration Direction & Grade	Suitable for contained, mild (<6 mm) migration [14] [53]	All migration patterns; excellent for large sequestered fragments [36]	Preferred for high-grade (>6 mm) caudally migrated fragments [20] [31] [34]	All migration patterns; revision cases [49] [50]

Continued

Foraminal Anatomy	Requires adequate foraminal width; high iliac crest contraindication [15]	Posterior approach avoids foraminal constraints [22]	Posterior approach; narrow interlaminar window technique available [39]	Posterior approach
Concomitant Stenosis	Limited lateral recess decompression capability [15]-[17]	Ideal for combined stenosis; comprehensive canal decompression [21] [27] [54] [55]	Limited; primarily disc-focused [19] [31]	Suitable for mild-moderate stenosis; rigid tube limits multi-level [51] [56]
Recurrent Herniation	Suitable for contained recurrent herniation after prior surgery [14]	Excellent for revision; superior adhesiolysis visualization [22] [57]	Limited evidence; challenging due to scarring	Well-established for revision [49] [50]
Instability	Avoid; may require fusion	May require adjunct fusion	Avoid	May require adjunct fusion
Surgeon Expertise	Steep learning curve; requires dedicated endoscopic training [15]	Moderate learning curve; compatible with open instruments [23] [24] [27]	Steep learning curve; high technical precision required [37] [38]	Gentlest learning curve; familiar to open surgeons [47] [48] [58]
Preferred Anesthesia	Local/conscious sedation [10]	General/epidural [22] [25] [26]	Local/epidural [31]-[33]	General/epidural [45] [46]

3. Comparative Analysis of Four Minimally Invasive Surgical Modalities

Two standardized comparative tables are constructed to quantify basic technical characteristics (**Table 1**) and procedural selections (**Table 2**) for Minimally Invasive Spinal Surgery.

Selection Guidance: The optimal technique should be selected through comprehensive patient assessment integrating disc pathology morphology, spinal segment anatomy, patient comorbidity burden, and anesthetic tolerance thresholds [59]-[63]. Surgeon expertise and institutional resources should be considered alongside patient-specific factors, as outcomes are strongly influenced by procedural volume and experience [37] [38] [47]. For uncomplicated single-level LDH without stenosis, PELD offers the least tissue trauma and fastest recovery [13] [64]. For complex, multi-level, or stenotic pathologies, UBE provides the most comprehensive decompression [54] [55] [65] [66]. For high-grade migrated discs, PEID offers superior access [31] [34]. For surgeons in training or revision cases, MED provides a familiar and safe option [49] [50] [67].

4. Discussion

Following decades of iterative technical advancement in spinal minimally invasive surgery, PELD, UBE, PEID and MED constitute the four primary surgical standards for LDH treatment, with all four platforms capable of achieving adequate neural decompression and sustained relief of radicular symptomatic burden [60] [62] [68]. However, it is essential to recognize that the evidence base for these techniques derives from heterogeneous patient populations. The strongest evidence for isolated, single-level LDH without concomitant stenosis comes from randomized controlled trials and prospective cohort studies specifically enrolling such patients [13] [60] [64] [69]. In contrast, evidence for UBE and MED in the context of lumbar spinal stenosis [26] [51] [54] [55] [65] [66], for PEID in highly migrated fragments [20] [31] [34], and for revision surgery [22] [49] [50] [70] comes from separate populations with distinct pathoanatomy and surgical goals. Outcomes from these different populations, particularly regarding complication rates, reherniation risk, and long-term functional recovery that should not be directly extrapolated to isolated LDH cases. This discussion carefully distinguishes evidence by clinical context, and our conclusions are stratified accordingly. The literature is deeply focused on navigating a complex landscape where each technique: PELD, UBE, PEID, and MED, presents a unique profile of strengths and weaknesses. The evidence confirms that all four techniques are effective for their respective indications, but meaningful progress relies on careful patient selection, a thorough understanding of each procedure's distinct challenges, and a commitment to advancing surgical technology and training [59] [63]. When interpreting comparative data, readers must consider whether the study population comprises isolated LDH, LDH with stenosis, recurrent LDH, or mixed cohorts, as these groups differ substantially in baseline characteristics and expected outcomes.

The evidence confirms that PELD provides definitive advantages in minimal soft tissue injury, very early mobilization, and short hospitalization due to its design and use of local anesthesia [71]-[73]. Direct comparative evidence from prospective controlled trials [13] [64] demonstrates statistically superior early post-operative VAS back/leg pain scores and Oswestry Disability Index (ODI) functional recovery metrics in PELD cohorts relative to matched MED and UBE patient groups for isolated single-level LDH. On this basis, PELD may be considered a first-line intervention for suitable patients with uncomplicated LDH morphology [72] [73], although this designation is supported primarily by indirect comparison and technical rationale rather than head-to-head superiority trials. PELD has advantages over open surgery [13], but inadequate decompression is a major cause of failure of the procedure, especially with high-grade migrations [53]. A more recent 2024 study comparing it to the interlaminar approach for lateral recess stenosis also notes that PELD is often “technically demanding” for this condition [74]. PELD outcomes provide a comprehensive view of patient demographics and ideal surgical candidates. The patients in this study had a mean age of 37 years, supporting the technique's application in a younger demographic. The most common lev-

els treated were L5-S1 (50%) and L4-L5 (45%), representing the vast majority of cases [75].

UBE's dual-channel design delivers a clear, wide surgical field and full instrument mobility, enabling more effective and comprehensive decompression for complex stenotic pathologies compared to uniportal systems [54] [55] [65]. This is supported by direct comparative data showing better objective outcomes like dural sac expansion, superior patient-reported outcomes, and a lower risk of reoperation in LDH with concomitant stenosis [55] [66]. UBE for two-level Lumbar Spinal Stenosis (LSS) reported a combined excellent/good rate of 95.12% at a mean follow-up of 17.4 months [66]. Other studies also report high rates, such as 98.25% at 6 months for recurrent disc herniation [70]. UBE's advanced visualization and enhanced dexterity make it particularly well-suited for the demanding task of revision surgery, where dense scarring is a major obstacle [22] [57]. However, claims of UBE's "definitive superiority" for all complex LDH presentations should be tempered, as direct head-to-head comparisons with PELD for non-stenotic LDH remain limited [63] [64], and its advantages are most clearly demonstrated for stenotic and multi-level pathologies [51] [55].

PEID functions as a targeted complementary uniportal endoscopic technique designed to resolve the longstanding clinical limitation of transforaminal PELD for caudally migrated free disc fragments [20] [31]. A large 2024 study of 328 patients reported a success rate of 94.7% according to the modified MacNab criteria for PEID in treating high-grade migrated LDH [34]. The interlaminar approach can avoid obstruction from lateral pedicles and high iliac crests, offering a clearer view of the migrated fragment compared to the transforaminal route [18] [19]. This makes PEID comparable in efficacy to UBE for treating high-grade migrated disc herniations [36]. The strongest evidence for PEID comes from a 2023 study reporting high efficacy for highly downward-migrated disc herniation, with a 97.43% good-to-excellent outcome rate according to MacNab criteria [31]. On the basis of these comparative cohort data, PEID may be considered the preferred approach for high-grade migrated discs, although this reflects its unique technical suitability for this specific pathology rather than general superiority over other techniques [20] [52].

MED occupies a valuable middle ground in spine surgery, providing the minimally invasive benefits of a tubular retractor system while maintaining a surgical environment that is more familiar and has a gentler learning curve than full-endoscopic techniques [46] [47] [58] [67]. This is supported by studies demonstrating comparable clinical outcomes to open discectomy and endoscopic techniques [56] [58] [67]. However, claims that MED offers the "highest intraoperative safety margin" are based primarily on its familiarity to surgeons trained in open techniques [48] rather than direct comparative safety data [45]. The neurological complication rate for MED was 4.5% in the 2022 review [45], which is comparable to endoscopic techniques rather than definitively lower. MED is a safe and effective procedure for Decompression for Lumbar Spinal Stenosis (DLSS), the rigid tubu-

lar retractor presents technical limitations that make it less flexible than UBE for complex decompressions. However, when single-level DLSS is treated effectively with MED, long-term functional recovery is comparable to UBE. The primary advantages of UBE lie in its superior perioperative metrics (shorter surgery, less blood loss, quicker discharge) rather than a dramatic long-term functional superiority [56].

When comparing long-term efficacy and reherniation rates across techniques, several important methodological caveats must be acknowledged. The cited studies [13] [60] [69] [76] [77] vary substantially in patient populations (isolated LDH vs. mixed degenerative disease), follow-up durations (ranging from 12 months to 10 years), outcome measures (VAS, ODI, MacNab, and composite scores), and definitions of recurrence (ranging from radiological findings alone to symptomatic reherniation requiring reoperation). These differences preclude direct comparison of reported rates across studies. For example, reherniation rates in the available literature range from 3% - 8% for PELD [14] [76] and 2% - 6% for MED [49] [69], but these figures derive from studies with different follow-up periods and recurrence definitions. The available meta-analyses [60] [62] [76] suggest comparable long-term functional outcomes (≥ 5 years) between endoscopic techniques and MED [69], but this conclusion is based on limited long-term data and should be interpreted cautiously. Until large-cohort, multi-center prospective trials with standardized follow-up and recurrence definitions are completed, comparisons of long-term efficacy and reherniation risk must be considered provisional rather than definitive.

All four techniques are effective for LDH, the evidence suggests a potential trade-off between the short-term advantages of endoscopic techniques and the long-term durability of more established methods like MED [60] [62] [76] [77]. MISS modalities preserve the multifidus muscle and posterior ligament complex far better than traditional open laminectomy, leading to sustained improvements in patient quality of life and reduced risk of post-operative instability. However, the complete elimination of instability risk is not guaranteed in all cases or with all techniques; patient selection and the specific surgical approach remain important factors [69] [78] [79]. The broader context of comparable long-term outcomes and the importance of individualized patient selection are both strongly supported by current meta-analyses. The literature does not advocate for one single best technique, but rather for a nuanced approach based on the specific details of each case [60] [62] [80].

The evidence shows significant effort in developing simpler, safer, and more efficient navigation and foraminoplasty techniques to overcome the traditional limitations of PELD, particularly its steep learning curve and radiation exposure [81]-[83]; UBE developmental work is indeed targeting low-pressure closed-circuit irrigation systems as a key method to reduce soft tissue edema, making the procedure safer and improving patient outcomes [84]-[88]; The engineering of PEID instrumentation is clearly focused on safety. The introduction of transpar-

ent working channels and techniques like laminoplasty are concrete examples of modifications that enhance visualization and create a safer working corridor, thereby reducing the risk of iatrogenic dural injury during the procedure [39] [89]; MED platforms integrate intraoperative 3D navigation with tubular retractor surgery is a real and documented practice aimed at improving the accuracy of retractor placement and the safety of neural decompression [90] [91]. Current technological advances in spinal surgery are primarily focused on improving precision in complex deformity correction cases rather than routine discectomy, with two key innovations leading the way: patient-specific 3D-printed guides, which have demonstrated high accuracy for pedicle screw placement (with success rates reaching 95.97% in recent studies, particularly valuable in severely distorted anatomy like congenital scoliosis), and AI-assisted navigation systems, which not only enhance surgical precision and efficiency but also significantly reduce radiation exposure by up to 90% during certain procedures [92]-[96].

5. Conclusions

Based on evidence derived primarily from isolated LDH populations, PELD serves as the first-line ultra-minimally invasive intervention for uncomplicated, single-level, central and foraminal contained LDH, providing the fastest early mobilization and resulting in the least measurable soft tissue trauma. UBE demonstrates definitive superiority in complex, multi-level LDH concurrent with degenerative spinal stenosis, enabling complete circumferential neural decompression and offering the broadest overall clinical indication spectrum. PEID constitutes the optimal procedural choice for high-grade, cranio-caudally migrated and sequestered free disc herniations, effectively overcoming the anatomical access limitations inherent to the transforaminal approach of PELD. MED offers the highest intraoperative safety margin and the gentlest learning curve for surgical trainees, making it well suited for routine LDH and revision cases of recurrent herniation with distorted postsurgical anatomy, thereby facilitating widespread clinical implementation in training hospitals.

Collectively, all four modalities outperform conventional open laminectomy discectomy across key perioperative endpoints, including reduced intraoperative blood loss, shortened hospital stays, accelerated functional rehabilitation, and low long-term rates of reherniation and major complications. No single minimally invasive technique qualifies as a universal gold standard for all LDH clinical presentations. Accordingly, operative surgeons must perform a holistic patient assessment that integrates disc pathology morphology, spinal segment anatomy, patient comorbidity burden, and anesthetic tolerance thresholds to formulate personalized surgical plans, thereby maximizing therapeutic efficacy while minimizing avoidable soft tissue trauma.

It is important to emphasize that these conclusions are drawn from evidence for isolated LDH populations unless otherwise specified. Outcomes from studies of lumbar spinal stenosis, recurrent herniation, or fusion procedures should be

interpreted within their specific clinical contexts and should not be generalized to all LDH presentations without careful consideration of population differences. The comparative long-term outcome data, particularly regarding reherniation rates, must be interpreted with caution given heterogeneity across studies in patient selection, follow-up duration, and recurrence definitions.

Author Contributions

Conceptualization, Fatima and Arjun Sinkemani; methodology, Fatima; software, Shuang Zhang; validation, Arjun Sinkemani; investigation, Arjun Sinkemani; resources, Fatima; data curation, Shuang Zhang; writing—original draft preparation, Fatima; writing—review and editing, Arjun Sinkemani; visualization, Shuang Zhang; supervision, Arjun Sinkemani; project administration, Arjun Sinkemani; funding acquisition, Arjun Sinkemani. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Pojskic, M., Bisson, E., Oertel, J., Takami, T., Zygorakis, C. and Costa, F. (2024) Lumbar Disc Herniation: Epidemiology, Clinical and Radiologic Diagnosis WFNS Spine Committee Recommendations. *World Neurosurgery*, **X**, **22**, Article ID: 100279. <https://doi.org/10.1016/j.wnsx.2024.100279>
- [2] Hamed, A., Al-Qiami, A., Alsali, H., Almansi, A., Massoud, M., Alzawahreh, A., *et al.* (2024) Surgical vs. Conservative Management of Chronic Sciatica (>3 Months) Due to Lumbar Disc Herniation: Systematic Review and Meta-Analysis. *Cureus*, **16**, e59617. <https://doi.org/10.7759/cureus.59617>
- [3] Uri, O., Alfandari, L., Folman, Y., Keren, A., Smith, W., Paz, I., *et al.* (2023) Acute Disc Herniation Following Surgical Decompression of Lumbar Spinal Stenosis: A Retrospective Comparison of Mini-Open and Minimally Invasive Techniques. *Journal of Orthopaedic Surgery and Research*, **18**, Article No. 974. <https://doi.org/10.1186/s13018-023-04457-2>
- [4] Li, L., An, J., Guo, L., Shan, X.Q., Sun, Y.P., Li, J.Q., *et al.* (2025) Comparison of Percutaneous Endoscopic Lumbar Discectomy (PELD) and Unilateral Biportal Endoscopic (UBE) Discectomy in the Treatment of Far Lateral Lumbar Disc Herniation (FLLDH): A Retrospective Study. *Journal of Orthopaedic Surgery and Research*, **20**, Article No. 510. <https://doi.org/10.1186/s13018-025-05906-w>
- [5] Hu, Z.X., Han, J., Sun, Y.F. and Tian, X.L. (2022) Comparison of Percutaneous Endoscopic Lumbar Discectomy vs. Minimally Invasive Transforaminal Lumbar Interbody Fusion for the Treatment of Single-Segment Lumbar Disc Herniation: A Meta-Analysis. *European Review for Medical and Pharmacological Sciences*, **26**, 6678–6690.
- [6] Shao, J., Fan, Z., Meng, H. and Fei, Q. (2024) Learning Curve and Complications of Unilateral Biportal Endoscopy Unilateral Laminectomy Bilateral Decompression for Lumbar Spinal Stenosis. *Videosurgery and Other Miniinvasive Techniques*, **19**, 489–497. <https://doi.org/10.20452/wiitm.2024.17905>
- [7] Li, W., Yan, Q. and Cong, L. (2022) Comparison of Endoscopic Discectomy versus

- Non-Endoscopic Discectomy for Symptomatic Lumbar Disc Herniation: A Systematic Review and Meta-Analysis. *Global Spine Journal*, **12**, 1012-1026. <https://doi.org/10.1177/21925682211020696>
- [8] Ahn, Y. and Lee, S. (2023) Uniportal versus Biportal Endoscopic Spine Surgery: A Comprehensive Review. *Expert Review of Medical Devices*, **20**, 549-556. <https://doi.org/10.1080/17434440.2023.2214678>
- [9] Ma, X., Li, W., Gao, S., Cao, C., Li, C., He, L., et al. (2022) Comparison of Unilateral Biportal Endoscopic Discectomy versus Percutaneous Endoscopic Lumbar Discectomy for the Treatment of Lumbar Disc Herniation: A Systematic Review and Meta-Analysis. *Medicine*, **101**, e30412. <https://doi.org/10.1097/md.00000000000030612>
- [10] Kambin, P. and Gellman, H. (1983) Percutaneous Lateral Discectomy of the Lumbar Spine. *Clinical Orthopaedics and Related Research*, **174**, 127-132. <https://doi.org/10.1097/00003086-198304000-00017>
- [11] Yeung, A., Roberts, A., Zhu, L., Qi, L., Zhang, J. and Lewandrowski, K. (2019) Treatment of Soft Tissue and Bony Spinal Stenosis by a Visualized Endoscopic Transforaminal Technique under Local Anesthesia. *Neurospine*, **16**, 52-62. <https://doi.org/10.14245/ns.1938038.019>
- [12] Perez-Roman, R.J., Basil, G.W., Boddu, J.V., Bashti, M. and Wang, M.Y. (2022) Size Matters—From the Working Channel to the Wavelength of Light: Optimizing Visualization in Endoscopic Spine Surgery. *Journal of Clinical Neuroscience*, **105**, 73-78. <https://doi.org/10.1016/j.jocn.2022.08.024>
- [13] Shi, R., Wang, F., Hong, X., Wang, Y., Bao, J., Liu, L., et al. (2019) Comparison of Percutaneous Endoscopic Lumbar Discectomy versus Microendoscopic Discectomy for the Treatment of Lumbar Disc Herniation: A Meta-Analysis. *International Orthopaedics*, **43**, 923-937. <https://doi.org/10.1007/s00264-018-4253-8>
- [14] Meng, B. (2020) Percutaneous Endoscopic Lumbar Discectomy: Indications and Complications. *Pain Physician*, **1**, 49-56. <https://doi.org/10.36076/ppj.2020/23/49>
- [15] Kim, H.S., Raorane, H.D., Wu, P.H., Yi, Y.J. and Jang, I.T. (2020) Evolution of Endoscopic Transforaminal Lumbar Approach for Degenerative Lumbar Disease. *Journal of Spine Surgery*, **6**, 424-437. <https://doi.org/10.21037/jss.2019.11.05>
- [16] Bertonha, C.L., Bertonha, L.M., Telles, S.L.R., Bertonha, J.M., Ferreira Neto, I.R., Aciole, M.A., et al. (2024) Translaminar Full Endoscopic Technique with Tom Shidi Needles for Highly- and Dorsally-Migrated Lumbar Disc Herniations. *World Neurosurgery*, **181**, 6-12. <https://doi.org/10.1016/j.wneu.2023.10.001>
- [17] Wang, C., Wong, K., Wu, P., Chen, K., Chang, W., Chien, C., et al. (2025) Full Decompression of Spinal Stenosis in Stable Adult Isthmic Spondylolisthesis with a Combination of Full Endoscopic Spine Surgery and Unilateral Biportal Endoscopic Spine Surgery: A Case Report. *International Journal of Spine Surgery*, **19**, 598-603. <https://doi.org/10.14444/8800>
- [18] Kim, C.H., Chung, C.K. and Woo, J.W. (2016) Surgical Outcome of Percutaneous Endoscopic Interlaminar Lumbar Discectomy for Highly Migrated Disk Herniation. *Clinical Spine Surgery: A Spine Publication*, **29**, E259-E266. <https://doi.org/10.1097/bsd.0b013e31827649ea>
- [19] Liu, W., He, J., Liu, M., Ge, H., Wan, G., Xu, D., et al. (2026) Comparative Efficacy of Posterior versus Lateral Endoscopic Approaches in the Management of Complex Lumbar Disc Herniation: A Retrospective Cohort Study. *Orthopaedic Surgery*, **18**, 695-709. <https://doi.org/10.1111/os.70279>
- [20] Zheng, S., Zhao, Q., Hu, Z., Wang, B., Zhu, Z., Qiu, Y., et al. (2026) Comparison of Clinical Effectiveness between Interlaminar and Transforaminal Endoscopic Lumbar

- Discectomy for L4/5 Highly Migrated Lumbar Disc Herniation: A Retrospective Study with a Minimum One Year Follow-Up. *BMC Musculoskeletal Disorders*, **27**, Article No. 654. <https://doi.org/10.1186/s12891-026-10027-4>
- [21] Kazarian, E.R., Yang, J.I., Kazarian, G.S. and Kim, Y.H. (2026) Primer on Unilateral Biportal Endoscopic Spine Surgery: Technical Overview for Beginners. *The Spine Journal*, **26**, 450-456. <https://doi.org/10.1016/j.spinee.2025.06.003>
- [22] Kim, H., Lee, J.Y., Cho, H.G., Park, J.W., Han, S. and Ko, Y. (2024) Advanced Technique of Unilateral Biportal Endoscopy on Revision Surgery for Recurred Herniated Intervertebral Disc: A Technical Note. *Case Reports in Orthopedics*, **2024**, Article ID: 4095518. <https://doi.org/10.1155/2024/4095518>
- [23] Wu, W., Xie, Y., Xue, Y., Cui, M., Zeng, X., Zhang, Y., *et al.* (2025) Advantages of 12° Endoscope in Unilateral Biportal Endoscopic Surgery for Lumbar Disc Herniation. *International Journal of Spine Surgery*, **19**, 569-577. <https://doi.org/10.14444/8771>
- [24] Wu, P.H., Kim, H.S., Choi, D.J. and Gamaliel, Y.T. (2021) Overview of Tips in Overcoming Learning Curve in Uniportal and Biportal Endoscopic Spine Surgery. *Journal of Minimally Invasive Spine Surgery and Technique*, **6**, S84-S96. <https://doi.org/10.21182/jmisst.2020.00024>
- [25] Tian, D., Zhu, B., Liu, J., Chen, L., Sun, Y., Zhong, H., *et al.* (2022) Contralateral Inclinator Approach for Decompression of the Lateral Recess and Same-Level Foraminal Lesions Using Unilateral Biportal Endoscopy: A Technical Report. *Frontiers in Surgery*, **9**, Article 959390. <https://doi.org/10.3389/fsurg.2022.959390>
- [26] Bui, A.T., Trinh, G.M., Wu, M., Hoang, T.T., Hu, M. and Pao, J. (2023) Indications for and Outcomes of Three Unilateral Biportal Endoscopic Approaches for the Decompression of Degenerative Lumbar Spinal Stenosis: A Systematic Review. *Diagnostics*, **13**, Article 1092. <https://doi.org/10.3390/diagnostics13061092>
- [27] Liu, Y., Li, X., Tan, H., Hao, X., Zhu, B., Yang, Y., *et al.* (2025) Learning Curve of Uniportal Compared with Biportal Endoscopic Techniques for the Treatment of Lumbar Disc Herniation. *Orthopaedic Surgery*, **17**, 513-524. <https://doi.org/10.1111/os.14312>
- [28] Choi, K., Shim, H., Hwang, J., Shin, S.H., Lee, D.C., Jung, H.H., *et al.* (2018) Comparison of Surgical Invasiveness between Microdiscectomy and 3 Different Endoscopic Discectomy Techniques for Lumbar Disc Herniation. *World Neurosurgery*, **116**, e750-e758. <https://doi.org/10.1016/j.wneu.2018.05.085>
- [29] Zhang, Y., Ju, J. and Wu, J. (2025) Comparison of Unilateral Biportal Endoscopic Decompression and Percutaneous Endoscopic Lumbar Decompression for Single-Level Degenerative Lumbar Spinal Stenosis: A Systematic Review and Meta-Analysis. *Journal of Orthopaedic Surgery and Research*, **20**, Article No. 952. <https://doi.org/10.1186/s13018-025-06338-2>
- [30] Li, Z., Liu, B. and Su, L. (2025) Effect and Safety of Percutaneous Endoscopic Interlaminar Discectomy for L5-S1 Disc Herniation: Direct Inferior Endplate Approach versus Indirect Approach. *European Spine Journal*, **34**, 1115-1122. <https://doi.org/10.1007/s00586-025-08667-6>
- [31] Li, R., Fu, D., Han, H., Zhan, Z., Wu, Y. and Meng, B. (2023) Comparative Analysis of Percutaneous Endoscopic Interlaminar Discectomy for Highly Downward-Migrated Disc Herniation. *Journal of Orthopaedic Surgery and Research*, **18**, Article No. 602. <https://doi.org/10.1186/s13018-023-04090-z>
- [32] Liu, H., Zhang, S., Zhang, K., Zhou, J. and Qian, C. (2026) Clinical and Radiological Outcomes of Unilateral Biportal Endoscopy and Percutaneous Endoscopic Interlaminar Discectomy for Highly Downward-Migrated Lumbar Disc Herniation: A Retrospec-

- tive Study. *BMC Surgery*, **26**, Article No. 559.
<https://doi.org/10.1186/s12893-026-03933-w>
- [33] Amato, M., Aprile, B. and de Oliveira, C. (2018) Radiation Exposure during Percutaneous Endoscopic Lumbar Discectomy: Interlaminar versus Transforaminal. *Arquivos Brasileiros de Neurocirurgia: Brazilian Neurosurgery*, **38**, 31-35.
<https://doi.org/10.1055/s-0038-1672576>
 - [34] Ma, H., Shen, M., Tang, Z., Li, K., Zhou, H., Sun, X., et al. (2024) Percutaneous Endoscopic Interlaminar Discectomy for High-Grade Migrated Lumbar Disc Herniation: Clinical Efficacy and Safety Assessment. *International Orthopaedics*, **48**, 2455-2463.
<https://doi.org/10.1007/s00264-024-06246-w>
 - [35] Zheng, S., Zhao, Q., Hu, Z., Li, H., Wang, B., Zhu, Z., et al. (2025) Large-Channel Interlaminar Endoscopic Discectomy for Highly Migrated Lumbar Disc Herniation: Effectiveness and Safety. *Journal of Pain Research*, **18**, 3821-3832.
<https://doi.org/10.2147/jpr.s537181>
 - [36] Wu, S., Zhong, D., Zhao, G., Liu, Y. and Wang, Y. (2024) Comparison of Clinical Outcomes between Unilateral Biportal Endoscopic Discectomy and Percutaneous Endoscopic Interlaminar Discectomy for Migrated Lumbar Disc Herniation at Lower Lumbar Spine: A Retrospective Controlled Study. *Journal of Orthopaedic Surgery and Research*, **19**, Article No. 21. <https://doi.org/10.1186/s13018-023-04484-z>
 - [37] Guo, W., Guo, S., Zhang, X., Zhang, W., Xia, G. and Liao, B. (2025) Comparative Study of the Learning Curves for Percutaneous Endoscopic Interlaminar Lumbar Discectomy and Unilateral Biportal Endoscopy Techniques. *BMC Surgery*, **25**, Article No. 210.
<https://doi.org/10.1186/s12893-025-02951-4>
 - [38] Ma, X., Zhang, H., Li, Z. and Zhang, W. (2026) Learning Curves and Clinical Outcomes of Interlaminar vs Transforaminal Endoscopic Lumbar Discectomy: A Single-Surgeon CUSUM Analysis. *Current Problems in Surgery*, **82**, Article ID: 102110.
<https://doi.org/10.1016/j.cpsurg.2026.102110>
 - [39] Wu, T., Yuan, J., Jia, J., He, D., Miao, X., Deng, J., et al. (2021) Percutaneous Endoscopic Interlaminar Discectomy via Laminoplasty Technique for L₅-S₁ Lumbar Disc Herniation with a Narrow Interlaminar Window. *Orthopaedic Surgery*, **13**, 825-832.
<https://doi.org/10.1111/os.12978>
 - [40] Perez-Cruet, M.J., Foley, K.T., Isaacs, R.E., Rice-Wyllie, L., Wellington, R., Smith, M.M., et al. (2002) Microendoscopic Lumbar Discectomy: Technical Note. *Neurosurgery*, **51**, S2-129-S2-136. <https://doi.org/10.1097/00006123-200211002-00018>
 - [41] Marappan, K., Jothi, R. and Paul Raj, S. (2018) Microendoscopic Discectomy (MED) for Lumbar Disc Herniation: Comparison of Learning Curve of the Surgery and Outcome with Other Established Case Studies. *Journal of Spine Surgery*, **4**, 630-637.
<https://doi.org/10.21037/jss.2018.06.14>
 - [42] Palmer, S. (2002) Use of a Tubular Retractor System in Microscopic Lumbar Discectomy: 1 Year Prospective Results in 135 Patients. *Neurosurgical Focus*, **13**, 1-4.
<https://doi.org/10.3171/foc.2002.13.2.6>
 - [43] Kunert, P., Kowalczyk, P. and Marchel, A. (2010) Minimally Invasive Microscopically Assisted Lumbar Discectomy Using the Metrx X-Tube System. *Neurologia i Neurochirurgia Polska*, **44**, 554-559. [https://doi.org/10.1016/s0028-3843\(14\)60152-3](https://doi.org/10.1016/s0028-3843(14)60152-3)
 - [44] Kogias, E., Jimenez, P.F. and Hubbe, U. (2015) Microendoscopic Lumbar Discectomy: Technique and Results of 188 Cases. *Indian Journal of Orthopaedics*, **49**, 262-263.
<https://doi.org/10.4103/0019-5413.152551>
 - [45] Bombieri, F.F., Shafafy, R. and Elsayed, S. (2022) Complications Associated with Lumbar Discectomy Surgical Techniques: A Systematic Review. *Journal of Spine Surgery*,

- 8, 377-389. <https://doi.org/10.21037/jss-21-59>
- [46] Eldin, M.M., Hassan, A.S.E.D., AboHamed, O.Y.A., Hassan, A.A.N. and Omar, A.H. (2025) Inter-Laminar Micro-Endoscopic Discectomy versus Microdiscectomy in Single-Level Posterolateral Lumbar Disc Herniation: A Comparative Study. *Journal of Craniovertebral Junction and Spine*, **16**, 142-147. https://doi.org/10.4103/jcvjs.jcvjs_32_24
- [47] Nowitzke, A.M. (2005) Assessment of the Learning Curve for Lumbar Microendoscopic Discectomy. *Neurosurgery*, **56**, 755-762. <https://doi.org/10.1227/01.neu.0000156470.79032.7b>
- [48] Martín-Láez, R., Martínez-Agüeros, J.Á., Suárez-Fernández, D., Montaña-Núñez, F. and Vázquez-Barquero, A. (2012) Complications of Endoscopic Microdiscectomy Using the EASYGO! System: Is There Any Difference with Conventional Discectomy during the Learning-Curve Period? *Acta Neurochirurgica*, **154**, 1023-1032. <https://doi.org/10.1007/s00701-012-1321-5>
- [49] Hou, T., Zhou, Q., Dai, F., Luo, F., He, Q., Zhang, J., *et al.* (2015) Repeated Microendoscopic Discectomy for Recurrent Lumbar Disk Herniation. *Clinics*, **70**, 120-125. [https://doi.org/10.6061/clinics/2015\(02\)09](https://doi.org/10.6061/clinics/2015(02)09)
- [50] Luhana, R.C., Doshi, J.N. and Khodifad, A. (2022) Role of Microendoscopic Discectomy for the Treatment of Recurrent Lumbar Disc Herniation. *Journal of Spinal Surgery*, **9**, 224-230. https://doi.org/10.4103/joss.joss_49_22
- [51] Zheng, B., Xu, S., Guo, C., Jin, L., Liu, C. and Liu, H. (2022) Efficacy and Safety of Unilateral Biportal Endoscopy versus Other Spine Surgery: A Systematic Review and Meta-Analysis. *Frontiers in Surgery*, **9**, Article 911914. <https://doi.org/10.3389/fsurg.2022.911914>
- [52] Maroun, R., Jamaledine, Y., Assi, C., Moucharafieh, R. and Badra, M. (2026) Endoscopic Discectomy for L4-L5 Disc Herniation: A Meta-Analysis Comparing Transforaminal and Interlaminar Approaches. *Brain and Spine*, **6**, Article ID: 105925. <https://doi.org/10.1016/j.bas.2026.105925>
- [53] Choi, G., Prada, N., Modi, H.N., Vasavada, N.B., Kim, J.S. and Lee, S.H. (2010) Percutaneous Endoscopic Lumbar Herniectomy for High-Grade Down-Migrated L4-L5 Disc through an L5-S1 Interlaminar Approach: A Technical Note. *MIN—Minimally Invasive Neurosurgery*, **53**, 147-152. <https://doi.org/10.1055/s-0030-1254145>
- [54] Liu, X. (2019) A Novel Biportal Full Endoscopy Technique for Lumbar Lateral Recess Stenosis. *Clinical Spine Surgery: A Spine Publication*, **32**, 51-56. <https://doi.org/10.1097/bsd.0000000000000667>
- [55] Sun, W., Wang, J., Hu, Y., Tao, J. and Yang, C. (2025) Efficacy and Safety of Unilateral Biportal Endoscopy Compared with Transforaminal Route Percutaneous Endoscopic Lumbar Decompression in the Treatment of Lumbar Spinal Stenosis: Minimum 1-Year Follow-Up. *Journal of Pain Research*, **18**, 1071-1080. <https://doi.org/10.2147/jpr.s493602>
- [56] Feng, X., Wang, B., Ding, J., Niu, B., Muhetaer, W., Yang, H., *et al.* (2025) Unilateral Biportal Endoscopic versus Microscopic Discectomy in Degenerative Lumbar Spinal Stenosis: A Prospective Cohort Study. *Medicine*, **104**, e42594. <https://doi.org/10.1097/md.00000000000042594>
- [57] Lee, C., Kim, Y. and Kim, J. (2026) Utility of the Scope Retractor for Adhesiolysis in Unilateral Biportal Endoscopic Lumbar Surgery: Illustrative Cases. *Journal of Neurosurgery: Case Lessons*, **11**, 1-6. <https://doi.org/10.3171/case26223>
- [58] Son, S., Ahn, Y., Lee, S.G. and Kim, W.K. (2020) Learning Curve of Percutaneous Endoscopic Interlaminar Lumbar Discectomy versus Open Lumbar Microdiscectomy

- at the L5-S1 Level. *PLOS ONE*, **15**, e0236296. <https://doi.org/10.1371/journal.pone.0236296>
- [59] Merter, A., Özyıldırım, M., Shibayama, M., Ito, Z., Nakamura, S. and Ito, F. (2025) Comparison of 3 Different Endoscopic Techniques for Lumbar Spinal Stenosis: Comprehensive Radiological and Clinical Study. *Neurospine*, **22**, 276-285. <https://doi.org/10.14245/ns.2448864.432>
- [60] Liu, S., Zhang, X., Xiong, Y. and He, H. (2025) Minimally Invasive Surgery for Lumbar Disc Herniation: A Meta-Analysis of Efficacy and Safety. *International Journal of Surgery*, **111**, 5623-5636. <https://doi.org/10.1097/jis9.0000000000002434>
- [61] Yong, J.H., Wang, E., Chin, B.Z. and Hey, H.W.D. (2026) Full-Endoscopic versus Microscopic Lumbar Discectomy for Lumbar Disc Herniation: A Systematic Review and Meta-Analysis of 4,186 Cases. *The Spine Journal*, **26**, 981-995. <https://doi.org/10.1016/j.spinee.2025.12.016>
- [62] Patel, T., Farhan, M., Nashaat Hamza, D., Daneshpazhouh, M., Nahar, O.A., Serafy, A.E., et al. (2025) Comparative Effectiveness of Minimally Invasive Endoscopic Discectomy versus Conventional Surgical Techniques for Lumbar Disc Herniation: A Systematic Review and Meta-Analysis. *Annals of Medicine & Surgery*, **87**, 6661-6674. <https://doi.org/10.1097/ms9.0000000000003689>
- [63] Ding, H., Han, X., Xing, Y., Liu, Y., He, D. and Han, X. (2025) Clinical and Radiological Comparison of Unilateral Biportal Endoscopic and Percutaneous Transforaminal Endoscopic Discectomy in the Treatment of Lumbar Spinal Degenerative Disease. *Orthopaedic Surgery*, **17**, 1105-1113. <https://doi.org/10.1111/os.14361>
- [64] Li, D., Tao, L., Zhang, X., Su, Q. and Yin, B. (2025) Unilateral Biportal Endoscopy versus Percutaneous Endoscopic Lumbar Discectomy for Lumbar Disc Herniation: A Comparative Study of Clinical Efficacy and Radiological Outcomes. *BMC Surgery*, **25**, Article No. 257. <https://doi.org/10.1186/s12893-025-02986-7>
- [65] Jin, X., Li, B. and Liu, L. (2025) Learning Curve Analysis of Unilateral Biportal Endoscopic Technique in the Treatment of the Lumbar Disc Herniation Combined with Spinal Stenosis. *BMC Surgery*, **25**, Article No. 617. <https://doi.org/10.1186/s12893-025-03370-1>
- [66] Xu, S., Wu, H., Liu, H., Xiang, J., Yang, J., Wang, C., et al. (2025) Unilateral Biportal Endoscopic Decompression for Two-Level Adjacent Lumbar Spinal Stenosis through a Single Sliding Approach: Technical Report and Early Follow-Up. *Journal of Orthopaedic Surgery and Research*, **20**, Article No. 1067. <https://doi.org/10.1186/s13018-025-06480-x>
- [67] Yadav, R.I., Long, L. and Yanming, C. (2019) Comparison of the Effectiveness and Outcome of Microendoscopic and Open Discectomy in Patients Suffering from Lumbar Disc Herniation. *Medicine*, **98**, e16627. <https://doi.org/10.1097/md.00000000000016627>
- [68] Cheng, Z., Sun, L., Tang, T., Wu, Q., Liang, L., Lu, H., et al. (2026) Comparison of Clinical Efficacy and Minimal Invasiveness between Unilateral Biportal Endoscopic and Percutaneous Endoscopic Lumbar Discectomy in the Treatment of Calcified Lumbar Disc Herniation: A Retrospective Analysis. *BMC Musculoskeletal Disorders*, **27**, Article No. 568. <https://doi.org/10.1186/s12891-026-09907-6>
- [69] Chen, Z., Zhang, L., Dong, J., Xie, P., Liu, B., Chen, R., et al. (2023) Percutaneous Transforaminal Endoscopic Discectomy versus Microendoscopic Discectomy for Lumbar Disk Herniation: Five-Year Results of a Randomized Controlled Trial. *Spine*, **48**, 79-88. <https://doi.org/10.1097/brs.0000000000004468>
- [70] Guo, C., Ding, T., Zheng, J., Fang, X., Feng, Z. and Xue, Y. (2025) Early Clinical and

- Radiologic Evaluation of Unilateral Biportal Spinal Endoscopy for Recurrent Lumbar Disc Herniation: A Retrospective Study. *World Neurosurgery*, **203**, Article ID: 124499. <https://doi.org/10.1016/j.wneu.2025.124499>
- [71] Yu, L., Zhu, B., Dong, H., Li, X., Liu, X., Yang, Y., *et al.* (2023) Does Immediate Post-operative Early Ambulation Affect Clinical Results of Full-Endoscopic Lumbar Discectomy? A Historical Control Study of Daytime Operation with a 8-Hour Hospital Stay versus Inpatient Operation. *Orthopaedic Surgery*, **15**, 2354-2362. <https://doi.org/10.1111/os.13814>
- [72] Cao, J., Huang, W., Wu, T., Jia, J. and Cheng, X. (2019) Percutaneous Endoscopic Lumbar Discectomy for Lumbar Disc Herniation as Day Surgery—Short-Term Clinical Results of 235 Consecutive Cases. *Medicine*, **98**, e18064. <https://doi.org/10.1097/md.00000000000018064>
- [73] Vemula, V.R.C., Thota, S., Chigurupalli, C.S., Papasani, A.K.R., Bodapati, C.P. and Middina, M. (2026) Early Biochemical Muscle Injury and One-Year Clinical and Imaging Outcomes Following Microsurgical *versus* Endoscopic Lumbar Discectomy: A Prospective Comparative Study. *The Indian Journal of Medical Research*, **163**, 399-405. https://doi.org/10.25259/ijmr_3114_2025
- [74] Chen, K., Luo, Y.C., Yang, F.G. and He, R.J. (2024) [Two Kinds of Percutaneous Endoscopic Lumbar Decompression in the Treatment of Single Level Lumbar Lateral Recess Stenosis]. *China Journal of Orthopaedics and Traumatology*, **37**, 338-344. (In Chinese)
- [75] Abohussein, M., Nabil, M., Elnoamany, H., Gaber, E., Habib, H.A., Dorrah, M., *et al.* (2025) Outcome of Percutaneous Endoscopic Surgery for Management of Lumbar Disc Herniation. *Egyptian Journal of Neurosurgery*, **40**, Article No. 146. <https://doi.org/10.1186/s41984-025-00488-5>
- [76] Zhao, K., Li, L., Li, T. and Xiong, Y. (2022) Percutaneous Endoscopic Lumbar Discectomy for the Treatment of Recurrent Lumbar Disc Herniation: A Meta-Analysis. *Bio-Med Research International*, **2022**, Article ID: 6488674. <https://doi.org/10.1155/2022/6488674>
- [77] Wang, R., Zeng, W., Hong, A.T., Cho, H., Khalid, S.I. and Mehta, A.I. (2026) Short-Term Outcomes and 2-Year Reoperations Following Endoscopic versus Microdiscectomy for Lumbar Disc Herniation: A Propensity-Matched Analysis. *World Neurosurgery*, **206**, Article ID: 124794. <https://doi.org/10.1016/j.wneu.2026.124794>
- [78] Du, C., Song, K., Hai, B. and Wang, X. (2023) Retrospective Study of Minimal Three-Year Follow-Up of Transforaminal Endoscopic Discectomy for Lumbar Disc Herniation: 5000 Multicenter Cases. *Cureus*, **15**, e50993. <https://doi.org/10.7759/cureus.50993>
- [79] Liu, Y., Zhao, H., Liu, F., Liu, W. and Wang, L. (2025) Comparison of Clinical Outcomes between Selective Fusion and Dual-Segment Fusion in Endoscopic Surgery for Bi-Segmental Lumbar Spinal Stenosis with Segmental Instability. *Journal of Orthopaedic Surgery*, **33**, 1-8. <https://doi.org/10.1177/10225536251399935>
- [80] Di, L., Wang, A., Stillman, K.E., Tierney, L.K., Jackson, S.G., Sasser, A.J., *et al.* (2025) A Systematic Review and Meta-Analysis of Preoperative Characteristics and Postoperative Outcomes in Patients Undergoing Endoscopic Spine Surgery: Part I Endoscopic Microdiscectomy. *Journal of Clinical Medicine*, **14**, Article 6757. <https://doi.org/10.3390/jcm14196757>
- [81] Li, Z. (2017) Modified Percutaneous Lumbar Foraminoplasty and Percutaneous Endoscopic Lumbar Discectomy: Instrument Design, Technique Notes, and 5 Years Follow-Up. *Pain Physician*, **1**, E85-E98. <https://doi.org/10.36076/ppj.2017.1.e85>
- [82] Zheng, W., Xia, W., Liu, C., Wu, Z., Liu, M., Zuo, R., *et al.* (2025) Whole Process Nav-

- igated Percutaneous Endoscopic Lumbar Discectomy Guided by a Novel X-Ray Instant Navigation: A Technical Report and Preliminary Clinical Outcomes. *BMC Musculoskeletal Disorders*, **26**, Article No. 985. <https://doi.org/10.1186/s12891-025-09084-y>
- [83] Liu, B., Li, Z.C., Zhang, Z.H. and Zhi, Z.G. (2026) Comparison of Novel Double-Needle Puncture Technique to the Conventional TESSYS Technique in Percutaneous Endoscopic Lumbar Discectomy: Enhanced Efficiency and Reduced Radiation Exposure. *BMC Surgery*, **26**, Article No. 197. <https://doi.org/10.1186/s12893-026-03584-x>
- [84] Hong, Y., Kim, S., Hwang, J., Eum, J., Heo, D., Suh, D., et al. (2021) Water Dynamics in Unilateral Biportal Endoscopic Spine Surgery and Its Related Factors: An *in Vivo* Proportional Regression and Proficiency-Matched Study. *World Neurosurgery*, **149**, e836-e843. <https://doi.org/10.1016/j.wneu.2021.01.086>
- [85] Tam, K., Li, H.Y., Lo, H.K. and Kam, W.L. (2026) A Protocol to Preserve the Dural Safety Margin during Simultaneous Hybrid Lumbar Unilateral Biportal Endoscopy and Cervical Laminoplasty. *World Neurosurgery*, **209**, Article ID: 124877. <https://doi.org/10.1016/j.wneu.2026.124877>
- [86] Park, D.K., Weng, C., Zakko, P. and Choi, D. (2023) Unilateral Biportal Endoscopy for Lumbar Spinal Stenosis and Lumbar Disc Herniation. *JBJS Essential Surgical Techniques*, **13**, e22.00020. <https://doi.org/10.2106/jbjs.st.22.00020>
- [87] Merter, A., Özyıldırım, M., Kurt, F. and Özçelik, M. (2025) Bispectral Index Monitoring in Endoscopic Lumbar Spine Surgery: Retrospective Analysis of Central Nervous System Complications. *World Neurosurgery*, **200**, Article ID: 124230. <https://doi.org/10.1016/j.wneu.2025.124230>
- [88] Wu, P.H., Kavishwar, R.A. and Kim, H.S. (2024) A Narrative Review of Current and Future of Unilateral Biportal Endoscopic (UBE) Transforaminal Lumbar Interbody Fusion. *Seminars in Spine Surgery*, **36**, Article ID: 101084. <https://doi.org/10.1016/j.semss.2024.101084>
- [89] Shi, W.R., Huang, Y., Sun, M.J. and Yuan, F. (2025) Clinical Efficacy Analysis of Transparent Fully Visualized Working Channel in Percutaneous Endoscopic Interlaminar Discectomy. *The Journal of Practical Medicine*, **41**, 1859-1866.
- [90] Ziechmann, R., Pathak, S.M. and Kim, B. (2024) Combined Microscopic Tubular and Endoscopic Approach for Calcified Midline Thoracic Disc Herniation: A Bridge to Endoscopic Discectomy. *Cureus*, **16**, e66948. <https://doi.org/10.7759/cureus.66948>
- [91] Schick, U. and Döhnert, J. (2002) Technique of Microendoscopy in Medial Lumbar Disc Herniation. *MIN—Minimally Invasive Neurosurgery*, **45**, 139-141. <https://doi.org/10.1055/s-2002-34345>
- [92] Ali, I.S., Bakaes, Y., MacLeod, J.S., Lee, T.Y., Cho, S. and Hsu, W.K. (2025) Artificial Intelligence in Planning for Spine Surgery. *Current Reviews in Musculoskeletal Medicine*, **18**, 627-634. <https://doi.org/10.1007/s12178-025-09992-5>
- [93] Lee, T.C., Chan, T.T., Tsang, C.Y., Cheung, C.C. and Cheung, P.H. (2025) Application of 3D Printing for Rod Bending in Long Construct Percutaneous Pedicle Screw Fixation Spinal Surgery. *Journal of Orthopaedics, Trauma and Rehabilitation*, **32**, 146-152. <https://doi.org/10.1177/22104917241303775>
- [94] Yang, W., Guo, W., Wu, W., Ma, R., Wang, Z., Zhang, H., et al. (2025) Accuracy and Cost Comparison of 3D-Printed Guides in Complex Spinal Deformity Correction: Direct vs Indirect Design. *Frontiers in Bioengineering and Biotechnology*, **13**, Article 1611998. <https://doi.org/10.3389/fbioe.2025.1611998>
- [95] Liawrungrueang, W. (2025) Advancing the Future of Endoscopic Spine Surgery. *Asian Spine Journal*, **19**, IX-X. <https://doi.org/10.31616/asj.2025.0327>

- [96] Weinberg, J., Bonamer, J., Kelhofer, N., Jawad-Makki, M.A., Zuckerbraun, R., Gonzalez, C., *et al.* (2026) Implications and Utility of Artificial Intelligence in Clinical Spine Surgical Practice. *Seminars in Spine Surgery*, **38**, Article ID: 101239.
<https://doi.org/10.1016/j.semss.2025.101239>

List of Abbreviations

DLSS—Decompression for Lumbar Spinal Stenosis;
Kambin triangle—Kambin triangular safe zone (foraminal surgical corridor);
LDH—Lumbar Disc Herniation;
LSS—Lumbar Spinal Stenosis;
Macnab—Macnab functional outcome grading scale;
MED—Microendoscopic Discectomy;
METRx-MD—Microscopic Endoscopic Tubular Retractor System;
MISS—Minimally Invasive Spinal Surgery;
MPLIF—Modified Posterior Lumbar Interbody Fusion;
ODI—Oswestry Disability Index;
PEID—Percutaneous Endoscopic Interlaminar Discectomy;
PELD—Percutaneous Endoscopic Lumbar Discectomy;
PRISMA—Preferred Reporting Items for Systematic Reviews and Meta-Analyses;
PTED—Percutaneous Transforaminal Endoscopic Discectomy (synonym of PELD);
UBE—Unilateral Biportal Endoscopy;
VAS—Visual Analogue Scale (pain score).