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Review Article

Minimally Invasive Spine Surgery for Degenerative Lumbar Diseases: Current Advances and Future Perspectives

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Abstract

Degenerative lumbar diseases (DLDs), encompassing lumbar disc herniation, lumbar spinal stenosis, degenerative spondylolisthesis and degenerative lumbar scoliosis, constitute a predominant global source of chronic low back pain and radiculopathy. Such conditions markedly degrade patients' quality of life and place a heavy socioeconomic burden on healthcare systems. Conventional open posterior lumbar surgery delivers satisfactory spinal decompression and interbody fusion, yet it is plagued by prominent drawbacks: severe paraspinal muscle injury, substantial intraoperative blood loss, intractable postoperative pain, longer hospital stays, and an increased risk of adjacent segment disease. Fueled by advances in surgical navigation, spinal endoscopy and intraoperative neuromonitoring, minimally invasive spine surgery (MISS) has achieved remarkable progress. These minimally invasive procedures retain the integrity of the posterior ligamentous complex, drastically lessen soft tissue trauma, and enable accelerated early postoperative rehabilitation. This narrative review was conducted to systematically characterize the state-of-the-art application of MISS for DLD management. High-quality peer-reviewed studies were retrieved and synthesized to summarize mainstream MISS techniques, operative workflows, perioperative clinical outcomes, surgical complications and inherent technical limitations. We further outline promising developmental directions for minimally invasive lumbar interventions. This work aims to furnish evidence-based references for clinical therapeutic decision-making and facilitate future translational research related to DLD minimally invasive treatment.

Keywords

Minimally Invasive Spine Surgery, Degenerative Lumbar Disease, Endoscopic Spine Surgery, Percutaneous Pedicle Screw Fixation, Lumbar Decompression, Lumbar Fusion

1. Introduction

Degenerative lumbar diseases are age-related progressive disorders caused by intervertebral disc degeneration, facet joint osteoarthritis, ligamentum flavum hypertrophy, and spinal instability, predominantly affecting middle-aged and elderly populations globally [1]. For patients with persistent symptomatic DLDs refractory to conservative management for more than 3–6 months, surgical intervention is indicated to relieve neural compression, restore spinal stability, and alleviate pain-related disability [2]. Traditional open lumbar laminectomy and fusion have long been the gold-standard treatment, yet they inevitably disrupt paraspinal muscle attachment, posterior osseoligamentous structures, and spinal kinematics, increasing the risk of chronic axial back pain and early adjacent segment degeneration [3].

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Therefore, there is an urgent need for surgical strategies that involve less trauma and faster recovery. Minimally invasive spine surgery has become a mainstream alternative to open surgery over the past decade, characterized by smaller incisions, less paraspinal muscle dissection, reduced intraoperative trauma, and rapid functional recovery [4]. With continuous technical innovation, representative MISS approaches for DLDs include percutaneous endoscopic lumbar discectomy (PELD), percutaneous transforaminal endoscopic lumbar discectomy (PTELD), microendoscopic discectomy (MED), minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF), oblique lateral interbody fusion (OLIF), and percutaneous pedicle screw fixation (PPSF)-assisted fusion. Recent technological improvements in biportal endoscopy, robotic navigation, and preoperative AI planning have further expanded the indications and improved surgical safety for complex multi-segment degenerative lumbar disorders [5, 6]. This review focuses on high-level clinical evidence, systematically evaluating the efficacy, safety, surgical indications, perioperative outcomes, and complications of current mainstream minimally invasive techniques in DLD management, and highlights emerging innovations and future research directions for clinical spine practice.

2. Main Minimally Invasive Surgical Modalities for Degenerative Lumbar Diseases

2.1. Percutaneous Endoscopic Lumbar Discectomy

PELD, including PTELD and percutaneous posterior endoscopic lumbar discectomy (PELD-posterior), remains the most widely adopted minimally invasive decompression technique for single-level lumbar disc herniation and mild central or lateral recess spinal stenosis [7]. Under fluoroscopic or 3D navigational guidance, the endoscope is percutaneously inserted through transforaminal or interlaminar corridors, allowing direct visualization of herniated disc tissue and precise nerve root decompression with minimal soft-tissue dissection [8]. Multiple recent cohort studies and meta-analyses have confirmed that PELD achieves equivalent short-term and mid-term pain relief and functional recovery compared with conventional open discectomy, with significantly reduced intraoperative blood loss, shorter hospital stay, and faster return to daily work and social activities [9]. For patients with far-lateral lumbar disc herniation, PTELD demonstrates superior clinical efficacy and fewer postoperative complications due to its direct anatomical access to the extraforaminal nerve root compartment [10]. Nevertheless, PELD is technically limited in severe central canal stenosis, complex multi-level degeneration, and highly unstable spondylolisthesis, mainly due to restricted working channel space and limited capacity for extensive bony decompression and spinal stabilization [11].

2.2. Microendoscopic Discectomy (MED)

MED serves as a transitional minimally invasive technique between conventional open discectomy and full-endoscopic spine surgery, utilizing a tubular retractor and high-definition endoscopic visualization to perform targeted discectomy and partial laminectomy under magnified direct vision [12]. Compared with open procedures, MED significantly preserves paraspinal muscle integrity and posterior ligamentous complex structure, effectively reducing the incidence of chronic postoperative axial low back pain and muscle atrophy [13]. A 2024 prospective randomized controlled trial demonstrated that MED yielded equivalent ODI and VAS pain scores at 1-year postoperative follow-up versus open discectomy, accompanied by lower overall complication rates and shorter postoperative rehabilitation time [14]. MED is most suitable for moderate lumbar spinal stenosis and contained disc herniation; however, its minimally invasive advantages are diminished in multi-segment decompression and severe degenerative spinal deformity cases [15].

2.3. Minimally Invasive Transforaminal Lumbar Interbody Fusion (MIS-TLIF)

MIS-TLIF combined with percutaneous pedicle screw fixation represents the mainstream minimally invasive fusion procedure for degenerative spondylolisthesis, unstable lumbar spinal stenosis, recurrent disc herniation with segmental instability, and mild degenerative lumbar scoliosis [16]. Through a unilateral paravertebral tubular retractor, facetectomy, interbody discectomy, endplate preparation, cage implantation, and bone grafting are performed, followed by percutaneous screw-rod fixation to achieve solid segmental spinal fusion and mechanical stability [17]. Compared with traditional open TLIF, MIS-TLIF markedly reduces paraspinal muscle trauma, intraoperative hemorrhage, postoperative infection risk, and length of hospitalization, while maintaining comparable fusion rates and mid-term clinical functional outcomes [18]. Navigation-assisted and robotic-guided MIS-TLIF further improve pedicle screw placement accuracy and reduce neurovascular injury risk in complex anatomical conditions, including high-grade spondylolisthesis and deformity-associated degenerative lumbar diseases [19].

2.4. Oblique Lateral Interbody Fusion (OLIF)

OLIF is a retroperitoneal lateral minimally invasive fusion technique that accesses the lumbar intervertebral disc space through an oblique anterolateral corridor between the psoas major muscle and abdominal great vessels, avoiding disruption of the posterior paraspinal muscles, posterior ligaments, and lumbar posterior osseous structures [20]. OLIF is primarily indicated for degenerative lumbar scoliosis, multi-segment spinal stenosis, low-grade degenerative spondylolisthesis, and revision lumbar degenerative pathologies [21]. Recent comparative studies have verified that OLIF allows placement of larger interbody fusion cages, provides better segmental lordosis correction, restores disc height more effectively, and achieves high fusion rates with lower posterior approach-related complication rates [22]. However, OLIF has clear anatomical limitations at the L5-S1 segment and carries potential risks of psoas muscle weakness, hip flexor pain, and major vascular injury, requiring rigorous preoperative radiological evaluation and standardized surgical training [23].

2.5. Unilateral Biportal Endoscopic (UBE) Lumbar Surgery

UBE lumbar endoscopic surgery has rapidly gained global popularity as an innovative hybrid minimally invasive technique combining the advantages of full endoscopy and open spinal surgery [24]. By establishing two separate small percutaneous working portals, UBE allows wide-range multi-segment decompression, foraminal release, and interbody fusion for complex degenerative lumbar disorders under direct endoscopic visualization [25]. Multiple systematic reviews and comparative studies have shown that UBE-assisted decompression and fusion achieves satisfactory long-term spinal alignment correction and pain relief, with less soft-tissue damage and faster early rehabilitation compared with traditional open and tubular minimally invasive approaches [26]. Despite its excellent clinical potential, UBE remains associated with a steep surgical learning curve and requires advanced endoscopic proficiency for safe clinical application [27].

2.6. Other Emerging Minimally Invasive Technologies

Additional innovative minimally invasive technologies recently applied in DLD management include AI-assisted preoperative surgical planning, robotic-assisted percutaneous screw fixation, expandable tubular retractor systems, and novel biodegradable interbody fusion cage materials [28]. Robotic-assisted MISS significantly improves surgical precision, reduces intraoperative fluoroscopic radiation exposure for surgeons and patients, and optimizes instrumentation accuracy in complex and revision degenerative lumbar cases [29]. Novel biomaterial bone graft substitutes and 3D-printed personalized fusion cages have demonstrated promising preliminary results in enhancing fusion quality and reducing cage subsidence complications in osteoporotic and elderly patient populations [30].

3. Perioperative Clinical Outcomes and Postoperative Complications of MISS for DLDs

3.1. Short-term and Mid-term Clinical Outcomes

Short-term perioperative clinical outcomes of all mainstream MISS modalities are consistently superior to conventional open surgery in terms of reduced intraoperative blood loss, lower postoperative VAS pain scores, shorter hospital stay, and accelerated early functional recovery and ambulation [31]. Mid-term follow-up studies confirm that MISS and open spinal surgery achieve equivalent improvements in ODI, JOA scores, and quality-of-life indexes for single-level degenerative lumbar diseases [32]. For multi-segment and complex degenerative lumbar disorders, UBE-assisted endoscopic fusion and OLIF demonstrate excellent long-term spinal alignment maintenance and sustainable pain relief when strict surgical indications and standardized operative protocols are followed [33]. Propensity-score-matched comparative analyses further validate that minimally invasive approaches provide comparable long-term clinical efficacy while significantly reducing perioperative surgical trauma and postoperative recovery time [34].

3.2. Complications and Independent Risk Factors

Common postoperative complications associated with MISS include transient nerve root irritation, incidental dural tear, interbody cage subsidence, pedicle screw malposition, superficial surgical site infection, and residual chronic axial back pain [35]. Endoscopic decompression techniques carry a slightly higher risk of transient postoperative radicular pain due to intraoperative nerve root manipulation and endoscopic workspace limitations [36]. Fusion-based minimally invasive procedures are mainly associated with cage subsidence, pseudarthrosis, and non-union complications, particularly in elderly osteoporotic patients with poor bone mineral density [37]. Advanced age, severe osteoporosis, multi-segment spinal degeneration, preoperative spinal deformity, and revision surgery history are well-documented independent risk factors for poor postoperative clinical outcomes and increased complication rates [38]. Strict preoperative patient selection, comprehensive bone quality assessment, and intraoperative navigation monitoring can effectively minimize overall surgical complication incidence and improve postoperative prognosis [39].

4. Current Clinical Limitations and Future Research Perspectives

Despite remarkable technical and clinical progress, MISS for degenerative lumbar diseases still faces several important clinical limitations and challenges. First, each minimally invasive technique has strict surgical indications, and inappropriate application in complex patient populations may lead to insufficient neural decompression, inadequate spinal stabilization, and poor long-term clinical results [40]. Second, most advanced minimally invasive endoscopic and robotic spine techniques have a steep learning curve, requiring long-term specialized surgical training and substantial clinical experience accumulation for safe and standardized popularization [41]. Third, high-quality long-term prospective randomized controlled trials comparing minimally invasive versus open surgery for complex multi-segment degenerative lumbar disorders remain limited in current global literature [42]. Fourth, the cost-effectiveness and long-term economic benefits of robotic and AI-assisted advanced MISS require further health economic evaluation for widespread clinical popularization [43].

Future development directions for MISS in degenerative lumbar disease management include: (1) further development and clinical application of AI-assisted preoperative planning and intraoperative real-time intelligent monitoring systems [44]; (2) research and clinical translation of novel biodegradable biomaterials and minimally invasive bone graft substitutes to improve spinal fusion quality [45]; (3) conduct of large-scale multi-center prospective cohort studies and RCTs to provide high-level clinical evidence for complex degenerative lumbar disease treatment [46]; (4) establishment of standardized global training systems to promote safe, standardized, and popularized clinical application of advanced minimally invasive spine surgical techniques [47].

5. Conclusion

Minimally invasive spine surgery has become an essential and indispensable treatment strategy for degenerative lumbar diseases worldwide, offering superior perioperative safety, minimal soft-tissue trauma, rapid postoperative rehabilitation, and comparable long-term clinical efficacy relative to conventional open spinal surgery [48]. Individualized minimally invasive surgical modality selection should be strictly based on comprehensive evaluation of patient age, bone quality, disease subtype, number of affected segments, spinal stability, and preoperative clinical symptoms. With continuous innovation in surgical instruments, navigational technology, artificial intelligence assistance, and novel biomaterial development, MISS will further expand clinical indications and continuously improve long-term clinical outcomes for patients with degenerative lumbar disorders. High-quality long-term clinical trials and standardized technical training systems are still required to further optimize surgical protocols and provide more robust evidence for future clinical spine surgical practice.

Abbreviations

DLDs	Degenerative Lumbar Diseases
MISS	Minimally Invasive Spine Surgery
PELD	Percutaneous Endoscopic Lumbar Discectomy
PTELD	Percutaneous Transforaminal Endoscopic Lumbar Discectomy
MED	Microendoscopic Discectomy
MIS-TLIF	Minimally Invasive Transforaminal Lumbar Interbody Fusion
OLIF	Oblique Lateral Interbody Fusion
PPSF	Percutaneous Pedicle Screw Fixation
VAS	Visual Analogue Scale
ODI	Oswestry Disability Index
JOA	Japanese Orthopaedic Association Scores
UBE	Unilateral Biportal Endoscopy
AI	Artificial Intelligence
RCT	Randomized Controlled Trial
MED	Microendoscopic Discectomy

Author Contributions

Zhi Liang: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing

Conflicts of Interest

The author declares no conflicts of interest.

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