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Review Article

Complications in Minimally Invasive Spine Surgery in the Last 10 Years: A Narrative Review

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Objective: Minimally invasive spine surgery (MISS) employs small incisions and advanced techniques to minimize tissue damage while achieving similar outcomes to open surgery. MISS offers benefits such as reduced blood loss, shorter hospital stays, and lower costs. This review analyzes complications associated with MISS over the last 10 years, highlighting common issues and the impact of technological advancements.
Methods: A systematic review following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines was conducted using PubMed, MEDLINE, Embase via OVID, and Cochrane databases, covering publications from January 2013 to March 2024. Keywords related to MISS and complications were used. Studies on adult patients undergoing MISS with tubular, uniportal, or biportal endoscopy, reporting intraoperative or postoperative complications, were included. Non-English publications, abstracts, and small case series were excluded. Data on MISS approach, patient demographics, and complications were extracted and reviewed by 2 independent researchers.
Results: The search identified 880 studies, with 137 included after screening and exclusions. Key complications in cervical MISS were hematomas, transient nerve root palsy, and dural tears. In thoracic MISS, complications included cerebrospinal fluid leaks and durotomy. In lumbar MISS, common complications were incidental dural injuries, postoperative neuropathic conditions, and disc herniation recurrences. Complications varied by surgical approach.
Conclusion: MISS offers reduced anatomical disruption compared to open surgery, potentially decreasing nerve injury risk. However, complications such as nerve injuries, durotomies, and hardware misplacement still occur. Intraoperative neuromonitoring and advanced technologies like navigation can help mitigate these risks. Despite variability in complication rates, MISS remains a safe, effective alternative with ongoing advancements enhancing its outcomes.

Keywords: Minimally invasive spine surgery, Complications, Systematic review

INTRODUCTION

Minimally invasive spine surgery (MISS) involves using small incisions, minimizing tissue destruction, and respecting tissue planes to achieve the same surgical goals as open spine surgery.[1] MISS came about in the 20th century as surgical instrumentation and imaging techniques for spine surgery continued to develop. The Williams microdiscectomy, described in 1978, mod-

ified the traditional 6-inch incision open approach for lumbar discectomy to a much less invasive procedure.[2] In recent years, the development of MISS has significantly expanded. Tubular retractors are commonly used in MISS and allow surgeons to operate on the spine through small ports. Endoscopic spine surgery is often dubbed the future of MISS and involves using an endoscope and associated instruments through one or 2 subcentimeter ports. Advanced imaging techniques such as magnetic resonance imaging and computed tomography (CT) scans, computer-assisted navigation, and robotics have also made minimally invasive approaches to spine surgery easier and safer for patients.[3-5]

With small incisions and respecting tissue planes, MISS aims to minimize damage to muscle and surrounding structures. Improved patient-reported outcomes and faster recovery periods have been associated with the MISS approach. Pokorny et al.[6] concluded that MISS reduced blood loss, hospitalization time, complications, and surgical costs compared to open spine surgery. Droeghaag et al.[7] also confirmed the cost-effectiveness of MISS by concluding that minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) is more cost-effective compared to open transforaminal lumbar interbody fusion (O-TLIF). The reduction in postoperative care that follows MISS contributes to its cost-effectiveness.[8] As technology and surgeon experience evolved, MISS techniques have been successfully used to treat complex conditions such as pediatric and adult scoliosis cases with significant curves.[9,10] Intradural extramedullary and metastatic tumors have also been treated safely and effectively with MISS.[11-13]

Despite the many benefits of MISS, it is important to understand its potential complications in order to improve clinical outcomes. Research describing MIS-TLIF for degenerative disc disease, spondylolisthesis, and vertebral canal stenosis describes over 89 specific complications, with the most common being radiculopathy (range, 2.8%–57.1%), screw malposition (0.3%–12.7%), and incidental durotomy (0.3%–8.6%).[14] Recent literature suggests complications associated with endoscopic spine surgery include dural tears, iatrogenic cord injury, incomplete decompression or recurrence, postoperative hematoma, and postoperative mechanical implant failures.[15-17] A literature review and meta-analysis assessing outcomes of open versus MIS-TLIF concluded that MIS-TLIF led to decreased tissue injury, blood loss, and length of hospital stay.[18] The authors also state that MIS-TLIF is a safe substitute for open spine surgery in obese patients. Ultimately, patient selection, surgeon experience, and the evolution of MISS technologies and techniques, such as augmented reality (AR) and intraoperative navigation, will continue to impact the incidence of patient complications.

METHODOLOGY

1. Literature Search

A comprehensive systematic literature review followed the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (ref), utilizing the databases PubMed, MEDLINE, Embase via OVID, and Cochrane. The review spanned publications from January 2013 through March 2024. We employed a strategic combination of MeSH (medical subject headings) and keywords to encompass a wide array of studies addressing MISS techniques and associated complications. Keywords included "Minimally invasive," "MISS," "Minimally Invasive Surgical Procedures," "tubular," "biportal," "uniportal," "spine," "surgery," "complications," "lumbosacral region," "cervical," "thoracic," "lumbar," "postoperative complications," and "intraoperative complications." Targeted searches were also conducted to pinpoint studies on minimally invasive tubular, endoscopic tubular-assisted, uniportal endoscopic, or biportal endoscopic surgeries involving the cervical, thoracic, or lumbar regions. To ensure the inclusion of unique studies, duplicate records were systematically removed. The exact content and order of the search string queries can be found in Supplementary Material 1. Additionally, a Google Scholar hand-search was conducted to identify further articles that may have yet to be captured through the initial database searches.

2. Inclusion and Exclusion Criteria

Studies were selected if they involved adult patients undergoing MISS using tubular, uniportal endoscopy, or biportal endoscopy techniques and reported on intraoperative or postoperative complications. The review focused exclusively on studies quantifying the frequency of these complications. Excluded were non-English publications, abstracts, conference presentations, editorials, expert opinions, case reports, case series with less than 10 patients, and review articles. We also excluded papers on lateral techniques. For studies reporting overlapping patient cohorts, preference was given to the report with the larger cohort.

3. Study Selection Process

Fig. 1 is a PRISMA diagram that illustrates the study selection process. All articles resulting from the search were exported into Rayyan (Cambridge, MA, USA), where duplicates were

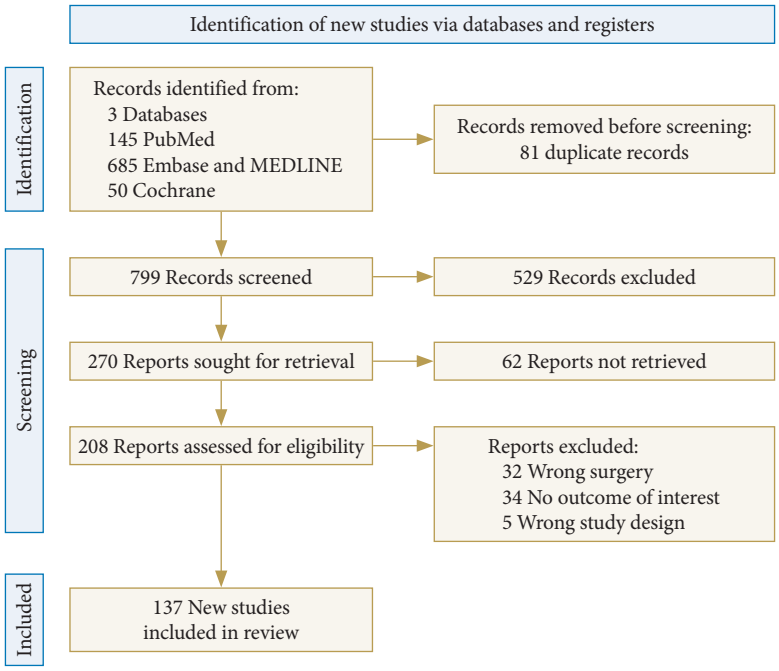

Fig. 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) flow diagram for study selection.

identified and deleted. Rayyan is professional research software widely used by collaborators for ease of study selection decisions. The study selection involved a systematic process where 2 reviewers independently screened titles and abstracts against the inclusion and exclusion criteria. The full texts of potentially relevant articles were then retrieved and assessed similarly. This screening was preceded by a pilot phase and a consensus meeting to ensure methodological rigor at each stage of the review process.

4. Data Extraction

Data regarding the type of MISS approach, patient demographics, complication rates, and detailed descriptions of complications were extracted using a structured form. Two researchers independently reviewed the data to ensure accuracy and consistency. Discrepancies were resolved through discussion, with unresolved issues referred to senior authors (GE).

RESULTS

After an electronic database search through PubMed, Embase, MEDLINE, and Cochrane, 880 references were identified. After removing 81 duplicate references, the titles and abstracts of 799 potentially relevant articles were reviewed, and 529 were excluded based on relevance. Subsequently, 270 reports were sought for retrieval, and 62 could not be retrieved. Out of the 208 reports assessed for eligibility, 71 were excluded based on the following criteria: 32 had the wrong surgery, 34 had no outcome of interest, and 5 had the wrong study design. Ultimately, 137 new studies were included in the review (Table 1). This process is illustrated in the PRISMA diagram (Fig. 1).

1. Cervical

1) Tubular

A comprehensive literature review identified 5 key studies reporting on tubular cervical spine surgery complications. The most frequently reported complications included hematomas (n = 3), transient nerve root palsy (n = 3), dural tears (n = 2), and transient hypesthesia (n = 2). Ross[19] conducted a retrospective analysis with the largest cohort (n = 262) and covered a 12-year period (2001–2013), noting complications such as C5 nerve root palsy (n = 3, 1.1%) and transient hypesthesia (n = 2, 0.7%).

2) Uniportal

Two studies examined complications associated with uniportal cervical spine surgery, involving a total of 63 patients. The most common complications reported were transient nerve root palsy/neurapraxia (n = 4) and recurrence of symptoms (n = 2). Kim et al.[20] included the largest cohort (n = 38) and found cases of transient nerve root palsy (n = 2, 5.3%) and symptom recurrence (n = 1, 2.6%).

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Table 1. A comprehensive review of clinical studies

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Vaishnav et al.[84]	A review of time-demand, radiation exposure and outcomes of skin-anchored intraoperative 3D navigation in minimally invasive lumbar spinal surgery	Retrospective	326	55	171:155	L	Tubular	Tubular: UTI (1, 1.1%), Postoperative sensory or motor deficit (2, 2.4%) respiratory depression (1, 1.3%) cardiac arrhythmia (1, 1.5%) nausea & vomiting (2, 2.7%), urinary retention requiring catheterization (7, 9.8%) incision-site edema (1, 1.3%) durotomy (1, 1.3%)
Lee et al.[85]	A Beginner's perspective on biportal endoscopic spine surgery in single-level lumbar decompression: a comparative study with a microscopic surgery	Retrospective	47	60.1	27:20	L	Biportal	Biportal: Dural tear (2, 4.26%), conversion to open surgery (2.13%)
Cahill et al.[86]	A comparison of acute hospital charges after tubular versus open microdiskectomy	Retrospective	48	45	25:23	L	Tubular	Tubular: Durotomy (1, 2.08%), postoperative diskitis (1, 2.08%)
Patel et al.[87]	A decade with micro-tubular decompression: peri-operative complications and surgical outcomes in single and multilevel lumbar canal stenosis	Retrospective	625	69.1	353:272	L	Tubular	Tubular: Intraoperative major building (1, 0.16%), dural tear (10, 1.6%), conversion to open surgery (3, 0.48%), UTI, prolonged catheterization (11, 1.76%), SIADH (7, 1.2%), new neurological deficit (7, 1.12%), paresthesia (11, 1.76%), pneumonia (2, 0.32%), ARDS (1, 0.16%), volume overload (transfusion related) (1, 0.16%), IHD (1, 0.16%), DVT (1, 0.16%), superficial infection (10, 1.6%), deep infection (2, 0.32%), wound dehiscence (1, 0.16%), fever (12, 1.92%)
Kumar et al.[88]	A hospital based prospective outcome assessment of minimally invasive spine decompression in lumbar spinal stenosis and intervertebral disc prolapse	Prospective	20	N/S, 21–40	12:8	L	Tubular	Tubular: CSF leak (1, 5%), superficial surgical site infection (1, 5%)
Dai et al.[89]	A new method for establishing operative channels in unilateral biportal endoscopic surgery: technical notes and preliminary results	Retrospective	50	34.48	34:16	L	Uniportal	Revision: 1 (2.0%), dura tear 1 (2.0%)
Wang et al.[90]	A single-arm retrospective study of the clinical efficacy of unilateral biportal endoscopic transforaminal lumbar interbody fusion for lumbar spinal stenosis	Retrospective	73	60.78	29:44	L	Biportal	Biportal: Postoperative epidural hematoma (3, 4.11%), dural tear (2, 2.74%), transient pain in the buttocks (2, 2.74%), temporary dysesthesia (1, 1.37%), transient muscle paralysis of both lower limbs (9, 12.33%)
Kim et al.[91]	Advantages of new endoscopic unilateral laminectomy for bilateral decompression (Ulbd) over conventional microscopic Ulbd	Retrospective	60	64.23	13:17	L	Biportal	Biportal: Cerebrospinal fluid leak (1, 3.33%)

(*Continued*)

Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Wu et al.[92]	Ambulatory uniportal versus biportal endoscopic unilateral laminotomy with bilateral decompression for lumbar spinal stenosis-cohort study using a prospective registry	Prospective	62	31.08	29:32	L	Uniportal, biportal	Uniportal: Conversion to open surgery due to bleeding (4, 13.8%), Incidental durotomy (3, 10.3%), one durotomy required conversion to open surgery (3.44%)
Thavara et al.[93]	Analysis of the surgical technique and outcome of the thoracic and lumbar intradural spinal tumor excision using minimally invasive tubular retractor system	Retrospective	12	48	5:7	T (8), L (4)	Tubular	Tubular: Surgical site infection (1, 8.33%), CSF leak (1, 8.33%), Pseudo meningocele (1, 8.33%)
Wu et al.[94]	Awake unilateral biportal endoscopic decompression under local anesthesia for degenerative lumbar spinal stenosis in the elderly: a feasibility study with technique note	Retrospective	31	70.49	13:18	L	Biportal	Biportal: Intraoperative neck pain (1, 3.23%), Transient lower limb numbness (3, 9.68%)
Wang et al.[95]	Biologics and minimally invasive approach to TLIFs: what is the risk of radiculitis?	Retrospective	174	58.39	92:92	L	Tubular	Tubular: radiculitis (22, 12.64%), infection/wound complication (2, 1.15%), pseudoarthrosis (7, 4.02%), unspecified postoperative complication (56, 32.18%)
Park et al.[96]	Biportal endoscopic approach for lumbar degenerative disease in the ambulatory outpatient vs inpatient setting: a comparative study	Retrospective	84	60	59:25	L	Biportal	Outpatient: postoperative radiculitis (10, 17.0%), postoperative weakness (1, 1.7%), wound drainage (1, 1.7%), reherniation (1, 1.7%), Inpatient: postoperative radiculitis (5, 19%), postoperative weakness (1, 3.8%), reherniation (1, 3.8%)
Wang et al.[97]	Biportal endoscopic decompression, debridement, and interbody fusion, combined with percutaneous screw fixation for lumbar brucellosis spondylitis	Retrospective	13	52	10:3	L	Biportal	Superficial incision infection (1, 76.9%)
Choi et al.[98]	Biportal endoscopic discectomy versus tubular microscopic discectomy for treating single-level lumbar disc herniation in obese patients: a multicenter, retrospective analysis	Retrospective	73	45.71	39:34	L	Tubular, biportal	Tubular: Asymptomatic hematoma (9, 25.6%), wound dehiscence (3, 6.9%), symptom aggravation due to remnant or recurrent disc herniation (18, 41.9%), reoperation due to remnant or recurrent disc herniation (8, 18.6%), Biportal: incidental durotomy (1, 3.3%), asymptomatic hematoma (6, 20.0%), symptom aggravation due to remnant or recurrent disc herniation (7, 23.3%), reoperation due to remnant or recurrent disc herniation (8, 18.6%)
Heo et al.[99]	Biportal endoscopic posterior cervical foraminotomy for adjacent 2-level foraminal lesions using a single approach (sliding technique)	Retrospective	12	57.8	10:2	C	Biportal	Temporary numbness of forearm (recovered spontaneously) (1, 8.33%), small bullae on chin area after surgery (1, 8.33%)

(*Continued*)

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Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Pérez et al.[100]	Biportal endoscopic spine surgery: clinical results for 163 patients	Retrospective	163	53	88:75	L	Biportal	Insufficient decompression (6, 3.7%), durotomy (2, 1.2%), CSF fistula (1, 0.6%), infection (1, 0.6%)
Jung et al.[101]	Biportal endoscopic spine surgery for cervical disk herniation: a technical notes and preliminary report	Retrospective	109	54.5	84:25	C	Biportal	One case of postoperative motor weakness of shoulder abduction and elbow flexion rated as MRC grade 2 from initial rating of grade 4 (resolved after 4 weeks)
Pao et al.[102]	Biportal endoscopic transforaminal lumbar interbody fusion using double cages: surgical techniques and treatment outcomes	Retrospective	89	64.7	17:72	L	Biportal	Dural tear (1, 1.1%), pedicle screw malposition (2, 2.2%), epidural hematoma (2, 2.2%), reoperation (2, 2.2%)
Park et al.[103]	Biportal endoscopic versus microscopic lumbar decompressive laminectomy in patients with spinal stenosis: a randomized controlled trial	Retrospective	34	66.2	18:14	L	Biportal	Biportal: Incidental durotomy (2, 7%), symptomatic hematoma with revision surgery (1, 3%)
Yuan et al.[104]	Clinical analysis of minimally invasive percutaneous treatment of severe lumbar disc herniation with UBE two-channel endoscopy and foraminal single-channel endoscopy technique	Retrospective	22	40	10:12	L	Biportal	Biportal: CSF leak (2, 9.09%)
Min et al.[105]	Clinical and radiological outcomes between biportal endoscopic decompression and microscopic decompression in lumbar spinal stenosis	Retrospective	54	65.74	27:27	L	Biportal	Biportal: Dural tear (2, 3.70%), postoperative epidural hematoma (1, 1.85%)
Kim and Choi[106]	Clinical and radiological outcomes of unilateral biportal endoscopic decompression by 30degree arthroscopy in lumbar spinal stenosis: minimum 2-year follow-up	Retrospective	55	70.7	26:29	L	Biportal	Biportal: Dural tear (2, 3.64%), epidural hematoma (1, 1.82%)
Park et al.[15]	Clinical and radiological outcomes of unilateral biportal endoscopic lumbar interbody fusion (ULIF) compared with conventional posterior lumbar interbody fusion (PLIF): 1-year follow-up	Retrospective	71	68	26:45	L	Biportal	Biportal: Dural tear (3, 4.2%), hematoma (1, 1.4%), infection (1, 1.4%)
Hao et al.[107]	Clinical comparison of unilateral biportal endoscopic discectomy with percutaneous endoscopic lumbar discectomy for single l4/5-level lumbar disk herniation	Retrospective	20	58.2	14:6	L	Biportal	Biportal: CSF leak (1, 5%), postoperative headache (1, 5%)
Ito et al.[108]	Clinical comparison of unilateral biportal endoscopic laminectomy versus microendoscopic laminectomy for single-level laminectomy: a single-center, retrospective analysis	Retrospective	139	68	18:14	L	Biportal	Biportal: Dural injury (2, 8.33%)

(*Continued*)

Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Kim et al.[109]	Clinical comparison of unilateral biportal endoscopic technique versus open microdiscectomy for single-level lumbar discectomy: a multicenter, retrospective analysis	Retrospective	60	65.74	37:23	L	Biportal	Biportal: Conversion to open surgery (3, 5%)
Guo et al.[110]	Clinical comparison of unilateral biportal endoscopic transforaminal lumbar interbody fusion verse 3D microscope-assisted transforaminal lumbar interbody fusion in the treatment of single-segment lumbar spondylolisthesis with lumbar spinal stenosis: a retrospective study with 24-month follow-up	Retrospective	26	64.15	12:14	L	Biportal	Biportal: Dural tear (2, 7.69%), Intracranial hypertension (1, 3.85%)
Hu et al.[111]	Clinical efficacy and imaging outcomes of unilateral biportal endoscopy with unilateral laminotomy for bilateral decompression in the treatment of severe lumbar spinal stenosis	Retrospective	50	68.52	20:30	L	Biportal	Dural tear (2, 4%)
Liu et al.[112]	Clinical outcomes of unilateral biportal endoscopic lumbar interbody fusion (ULIF) compared with conventional posterior lumbar interbody fusion (PLIF)	Prospective	27	63.89	12:15	L	Biportal	Biportal: Dural tear (1, 1.67%)
Heo and Park[41]	Clinical results of percutaneous biportal endoscopic lumbar interbody fusion with application of enhanced recovery after surgery	Prospective	23	61.4	7:16	L	Biportal	Biportal: Postoperative epidural hematoma (1, 2.17%), cage subsidence (1, 2.17%)
Lee et al.[113]	Comparative analysis between three different lumbar decompression techniques (Microscopic, tubular, and endoscopic) in lumbar canal and lateral recess stenosis: preliminary report	Retrospective	198	54.68	62:136	L	Uniportal, tubular	Uniportal: Dural tear (4, 2.44%), dysthesia (7, 4.27%), motor weakness (1, 0.61%), disc recur (1, 0.61%), Tubular: post-op hematoma (1, 2.94%), dysthesia (1, 2.94%), disc recur (1, 2.94%)
Kim et al.[114]	Comparative analysis of 3 types of minimally invasive posterior cervical foraminotomy for foraminal stenosis, uniportal-, biportal endoscopy, and microsurgery: radiologic and midterm clinical outcomes	Retrospective	118	56.49	80:38	C	Uniportal, biportal, tubular	Uniportal: transient nerve root palsy (2, 5.26%), recurrence (1, 2.63%), Biportal: recurrence (2, 6.67%), transient nerve root palsy (1, 3.33%), Tubular: recurrence (2, 4%), hematoma (2, 4%), dural tear (1, 3.33%), revision (1, 3.33%)
Heo et al.[115]	Comparative analysis of three types of minimally invasive decompressive surgery for lumbar central stenosis: biportal endoscopy, uniportal endoscopy, and microsurgery	Retrospective	64	66.95	26:38	L	Uniportal, biportal	Uniportal: Durotomy (1, 3.70%), transient weakness (1, 3.70%), postop hematoma (1, 3.70%), Biportal: Durotomy (1, 2.70%), postop hematoma (1, 2.70%)

(*Continued*)

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Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Kim et al.[116]	Comparative clinical and radiographic cohort study: uniportal thoracic endoscopic laminotomy with bilateral decompression by using the 1-block resection technique and thoracic open laminotomy with bilateral decompression for thoracic ossified ligamentum flavum	Retrospective	31	64	15:16	T	Uniportal, open	Uniportal: Incomplete decompression (1, 3.23%), incidental durotomy (1, 3.23%)
Antony et al.[117]	Case series of tubular retractor assisted minimally invasive extraforaminal l5/s1 microdiskectomy	Prospective	28	62	15:13	L	Tubular	Tubular: 2 (7.1%) (persistent or recurrent radicular pain (2))
He et al.[118]	Comparison of biportal endoscopic technique and uniportal endoscopic technique in Unilateral Laminectomy for Bilateral Decompression (ULBD) for lumbar spinal stenosis	Retrospective	65 (biportal, 33; uniportal, 32)	Biportal, 67.72; uniportal, 62.50	Biportal, 20:13; uniportal, 15:17	L	Uniportal, biportal	Uniportal: 3 (9.4%) (dural tear (1), transient leg numbness (2), infection (0)), Biportal: 1 (3.0%) (dural tear (0), transient leg numbness (1), infection (0))
Jung et al.[21]	Comparison of cervical biportal endoscopic spine surgery and anterior cervical discectomy and fusion in patients with symptomatic cervical disc herniation	Retrospective	162	54	113:49	C	Biportal	Biportal: 3 (1.9%) (motor weakness: 2, muscle soreness: 1)
Wang et al.[119]	Comparison of clinical outcomes and muscle invasiveness between unilateral biportal endoscopic discectomy and percutaneous endoscopic interlaminar discectomy for lumbar disc herniation at L5/S1 level	Retrospective	51	43.8	22:29	L	Biportal	Biportal: 3 (5.9%) (dura tear (1), nerve root injury (1), intervertebral infection (1))
Wu et al.[120]	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	Retrospective	31	58.5	16:15	L	Biportal	Biportal: 1 (3.2%) (dural tear (1))
Zhang et al.[121]	Comparison of endoscope-assisted and microscope-assisted tubular surgery for lumbar laminectomies and discectomies: minimum 2-year follow-up results	Retrospective	145	49.74	79:66	L	Tubular	Tubular: 14 (9.7%) (dural tear (8), wound infection (1), repeated surgery within 2 years (5))
Kotheeranurak et al.[122]	Comparison of full-endoscopic and tubular-based microscopic decompression in patients with lumbar spinal stenosis: a randomized controlled trial	Prospective	30	55.73	13:17	L	Tubular	Tubular: 6 (20.0%) (dural tear (1), infection (1), ipsilateral dysesthesia (1), contralateral dysesthesia (2), instability at 12 months postsurgery (1))
Özer et al.[123]	Comparison of lumbar microdiscectomy and unilateral biportal endoscopic discectomy outcomes: a single-center experience	Retrospective	54	Not available	30:24	L	Biportal	Biportal: 2 (3.7%) (temporary blindness in one eye due to retinal hemorrhage (1), dural tear (1))

(*Continued*)

Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Librianto et al.[124]	Comparison of microscopic decompression and biportal endoscopic spinal surgery in the treatment of lumbar canal stenosis and herniated disc: a one-year follow-up	Retrospective	102 (biportal, 54; tubular, 48)	Biportal, 46.33; tubular, 44.93	Biportal, 34:20; tubular, 27:19	L	Biportal, tubular	Biportal: 0 (0%), Tubular: 10 (27.8%) (residual leg pain (3), recurrent leg pain (6), segment instability (1))
Kim et al.[125]	Comparison of minimal invasive versus biportal endoscopic transforaminal lumbar interbody fusion for single-level lumbar disease	Retrospective	87 (biportal, 32; tubular, 55)	Biportal, 70.5; tubular, 67.3	Biportal, 17:15; tubular, 25:30	L	Biportal, tubular	Biportal: 2 (6.3%) (transient palsy (1), postoperative hematoma (1)), Tubular: 3 (5.5%) (transient palsy (2), postoperative hematoma (1))
Wang et al.[126]	Comparison of outcomes between unilateral biportal endoscopic and percutaneous posterior endoscopic cervical keyhole surgeries	Retrospective	89	58.28	42:47	C	Biportal	Biportal: 3 (3.37%) (dural tear (2), nucleus pulposus residue (1))
Liu et al.[127]	Comparison of percutaneous transforaminal endoscopic discectomy and microscope-assisted tubular discectomy for lumbar disc herniation	Retrospective	60	53.4	32:28	L	Tubular	Tubular: 12 (20%) (dural tear (2), paresthesia (10))
Kang et al.[128]	Comparison of primary versus revision lumbar discectomy using a biportal endoscopic technique	Retrospective	81	50.56	46:35	L	Biportal	Biportal: 6 (7.4%) (incidental durotomy (3), epidural hematoma (2), local recurrence (1))
Huang et al.[129]	Comparison of surgical invasiveness, hidden blood loss, and clinical outcome between unilateral biportal endoscopic and minimally invasive transforaminal lumbar interbody fusion for lumbar degenerative disease: a retrospective cohort study	Retrospective	38	60.13	22:16	L	Biportal	Biportal: 2 (5.4%) (dural tear (2))
Xie et al.[130]	Comparison of the safety and efficacy of unilateral biportal endoscopic lumbar interbody fusion and uniportal endoscopic lumbar interbody fusion: a 1-year follow-up	Retrospective	60 (biportal, 30; uniportal, 30)	Biportal, 49.1; uniportal, 51.2	Biportal, 17:13; uniportal, 16:14	L	Uniportal, biportal	Uniportal: 1 (3.3%) (CSF leak (1)), Biportal: 2 (6.7%) (nerve root injury (2))
Süner et al.[131]	Comparison of the tubular approach and uniportal interlaminar full-endoscopic approach in the treatment of lumbar spinal stenosis: our 3-year results	Prospective	20 (tubular, 10; uniportal, 10)	Tubular, 69.7; uniportal, 73.5	Tubular, 4:6; uniportal, 4:6	L	Uniportal, tubular	Uniportal: 2 (20%) (incidental durotomy (2)), Tubular: 2 (20%) (wound dehiscence (1), postop epidural hematoma (1)) --> no infection or CSF fluid fistula in either group
Ross[19]	Complications of minimally invasive, tubular access surgery for cervical, thoracic, and lumbar surgery	Retrospective	1,231 (cervical, 262; thoracic, 40; lumbar, 929)	53 (only overall avg age is available)	NA	C, T, L	Tubular	Tubular: C: 5 (1.9%) (durotomy (0), C5 nerve root palsy (3), transient increased hypesthesia in the dermatomal distribution of an operated nerve root (2), infection (0)), T: 1 (2.5%) (durotomy (1), infection (0)), L: 33 (3.6%) ((durotomy (32), postop epidural hematoma (1), infection (0))

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Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Cheng et al.[132]	Contralateral translaminar endoscopic approach for highly down-migrated lumbar disc herniation using percutaneous biportal endoscopic surgery: original research	Retrospective	32	56	17:15	L	Biportal	Biportal: 1 (3.1%) (postoperative dysesthesia (1), nerve root injury (0), dural tear (0))
Sonawane et al.[133]	Conventional versus tubular microdiscectomy for lumbar disc herniation: a prospective randomized study	Prospective	31	42.8	20:11	L	Tubular	Tubular: 5 (16.1%) (dural tear (2), urinary tract infection (1), recurrent disc herniation at same level (2))
Kuo et al.[134]	Cortical bone trajectory-based dynamic stabilization	Retrospective	40	66	17:23	L	Tubular	Tubular: 20 (50%) (Incidental durotomy (2), intraoperative anterior migration of the cage without a neurological deficit (1), gradual posterior cage migration and had undergone revision surgery (1), radiographic adjacent segment disease: 24, screw loosening (16))
Tan et al.[135]	Decompression via unilateral biportal endoscopy for severe degenerative lumbar spinal stenosis: a comparative study with decompression via open discectomy	Retrospective	50	64.8	29:21	L	Biportal	Biportal: 1 (2%) (Dural sac tearing (1), incision infection (0))
Sharma et al.[136]	Does a high BMI affect the outcome of minimally invasive TLIF? A retrospective study of 207 patients	Retrospective	207	53.16	128:79	L	Tubular	Tubular: 31 (14.9%) (accidental durotomies (20), superficial infections (2), urinary tract infection (1), pneumonia (1), worsening of symptoms within a month of surgery (2), postoperative neurological deficit (2), developed recurrent symptoms after 6 months of surgery (3))
Altshuler et al.[137]	Does minimally invasive spine surgery reduce the rate of perioperative medical complications? A retrospective single-center experience of 1435 degenerative lumbar spine surgeries	Retrospective	961	60.34	427:534	L	Tubular	Tubular: 25 (2.6%) (Decompression: DVT (6), Pulmonary embolism (2), UTI (13), pneumonia (4))
Yu et al.[138]	Early efficacy and safety of unilateral biportal endoscopic lumbar interbody fusion versus minimal invasive in the treatment of lumbar degenerative diseases	Retrospective	29	64.62	13:16	L	Biportal	Biportal: 1 (3.4) (durotomy (1))
Ariffin et al.[139]	Early experience, setup, learning curve, benefits, and complications associated with exoscope and three-dimensional 4k hybrid digital visualizations in minimally invasive spine surgery	Prospective	35	NA	NA	L	Tubular	Tubular: 4 (11.4%) (dural tear (4))
Foocharoen et al.[140]	Early outcomes: a comparison between biportal endoscopic spine surgery and open lumbar discectomy for single-level lumbar disc herniation	Retrospective	43	39.1	17:26	L	Biportal	Biportal: 1 (2.3%) (postoperative spinal epidural hematoma (1))

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Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Kim et al.[141]	Effect of dorsal root ganglion retraction in endoscopic lumbar decompressive surgery for foraminal pathology: a retrospective cohort study of interlaminar contralateral endoscopic lumbar foraminotomy and discectomy versus transforaminal endoscopic lumbar foraminotomy and discectomy	Retrospective	100	61.97	48:52	L	Uniportal	Uniportal: 23 (23%) (incidental durotomy (3), postoperative dysesthesia (20))
Hsieh et al.[142]	Effectiveness of minimally invasive transforaminal lumbar interbody fusion in geriatric patients	Retrospective	138	66.12	57:81	L	Tubular	Tubular: 10 (7.2%) (incidental durotomy with cerebrospinal fluid leakage (5), postoperative spinal epidural hematoma (1), superficial surgical wound infection (4))
Choi et al.[143]	Efficacy of biportal endoscopic spine surgery for lumbar spinal stenosis	Retrospective	35	65.4	14:21	L	Biportal	Biportal: 3 (8.6%) (dural tear (2), root injury (1), infection (0))
Kostysyn et al.[144]	Efficiency of interlaminar uniportal endoscopic lumbar discectomy	Prospective	95	41.6	53:42	L	Uniportal	Uniportal: 9 (9.5%) (reoperation: 6 (6.3%), haematoma: 0 (0%), surgical site infection: 0 (0%), CSF leakage: 1 (1.1%), sensory lesions: 2 (2.1%), motor deficit: 0 (0%))
Claus et al.[145]	Elderly as a predictor for perioperative complications in patients undergoing multilevel minimally invasive transforaminal lumbar interbody fusion: a regression modeling study	Retrospective	467	65.61	220:247	L	Tubular	Tubular: 201 (43.0%) (urinary tract infection (11), urinary retention (40), anemia requiring transfusion (59), confusion (22), ileus (12), hypotensive episodes (7), durotomy (6), deep venous thrombosis (1), arrhythmias (6), transient hypoxia (11), fracture (1), pneumonia (8), respiratory distress (2), acute kidney injury (6), epidural abscess/osteomyelitis (0), pulmonary embolism (2), wound seroma/hematoma (7))
Rao et al.[146]	Endoscopic lumbar discectomy vs microdiscectomy: early results, complications and learning curve an Australian perspective	Retrospective	30	53.6	21:9	L	Uniportal	Uniportal: 3 (10%) (dural tear (1), recurrent disc prolapse (1), recurrence at 20 weeks postop requiring reoperation (1))
Heo et al.[147]	Endoscopic treatment of extraforaminal entrapment of l5 nerve root (far out syndrome) by unilateral biportal endoscopic approach: technical report and preliminary clinical results	Retrospective	14	59.5	4:10	L	Biportal	Biportal: 3 (21.4%) (abdominal pain (2), perirenal fluid collection (1))
Guo et al.[148]	Evaluation of the learning curve and complications in unilateral biportal endoscopic transforaminal lumbar interbody fusion: cumulative sum analysis and risk-adjusted cumulative sum analysis	Retrospective	184	65.53	104:80	L	Biportal	Biportal: 11 (6.0%) (cage subsidence (2), dural tear (3), epidural hematomas (2), nerve root injury (1), residual symptom (3))

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Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Ahn et al.[149]	Extraforaminal approach of biportal endoscopic spinal surgery: a new endoscopic technique for transforaminal decompression and discectomy	Retrospective	21	64.2	10:11	L	Biportal	Biportal: 1 (4.8%) (dural tear (1))
Wang et al.[150]	Feasibility and efficacy of spinal microtubular technique for resection of lumbar dumbbell-shaped tumors	Retrospective	46	49 (median)	24:22	L	Tubular	Tubular: CSF leakage (2, 4.3%), wound infection (3, 6.5%), cavity effusion (5, 10.9%)
Kulkarni and Das[151]	Feasibility and outcomes of tubular decompression in extreme stenosis	Retrospective	325	61.8	175:150	L	Tubular	Tubular: 8 (2.5%) (incidental dural tears (4), urinary retention (3), Syndrome of inappropriate antidiuretic hormone secretion (1))
Huang et al.[152]	Full endoscopic uniportal unilateral laminotomy for bilateral decompression in degenerative lumbar spinal stenosis: highlight of ligamentum flavum detachment and survey of efficacy and safety in 2 years of follow-up	Prospective	106	70.2	45:61	L	Uniportal	Uniportal: 4 (3.8%) (residual stenosis (1), iatrogenic durotomy (1), delay wound healing (2))
Ruetten et al.[22]	Full-endoscopic uniportal decompression in disc herniations and stenosis of the thoracic spine using the interlaminar, extraforaminal, or transthoracic retropleural approach	Prospective	55	56	23:32	T	Uniportal	Uniportal: 10 (19%) (dural tear (2), epidural hematoma (2), transient arm dysesthesia (1), transient intercostal neuralgias (2), deterioration of myelopathy (1), transient deterioration of myelopathy (1), transient leg dysesthesia (1))
Vasilikos et al.[153]	How safe is minimally invasive transforaminal lumbar interbody fusion for octogenarians?: a perioperative complication analysis	Retrospective	21	84.1	13:8	L	Tubular	Tubular: 14 (66.6%) patients with complications, total of 30 individual complication events (cage dislocation (1), cage subsidence with stenosis (1), abscess (1), pulmonary embolism (2), sepsis (1), postoperative confusion (5), anemia requiring transfusion (5), sacroiliac joint syndrome (3), minor neurologic deficit (3), durotomy (2), urinary tract infection (2), transient mild hypoxia (2), liver insufficiency (1), depressive episode (1))
Kruger et al.[154]	Impact of morbid obesity (BMI > 40 kg/m^2) on complication rate and outcome following minimally invasive transforaminal lumbar interbody fusion (MIS TLIF)	Retrospective	28	60.4	10:18	L	Tubular	Epidural hemorrhage (2, 7.1%)
Goertz et al.[155]	Impact of obesity on complication rates, clinical outcomes, and quality of life after minimally invasive transforaminal lumbar interbody fusion	Retrospective	71	64.6	21:50	L	Tubular	Dural tear (9, 12.7%), Wound infection (1, 1.4%), rebleeding (1, 1.4%), neurological deficits (4, 5.6%), cage migration (5, 5.5%), screw avulsion or breakage (5, 7.0%), Both (2, 2.8%), revision surgery (13, 18.3%)

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Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Martens et al.[156]	Implantation of a bone-anchored annular closure device in conjunction with tubular minimally invasive discectomy for lumbar disc herniation: a retrospective study	Retrospective	60	42	25:35	L	Tubular	Symptomatic reherniation (2, 3%), reoperation (3, 5%)
Kim et al.[157]	Learning curve and clinical outcome of biportal endoscopic-assisted lumbar interbody fusion	Retrospective	57	68.5	28:29	L	Biportal	Post op spinal epidural hematoma (1, 1.7%), cage subsidence (1, 1.7%), transient paralysis (1, 1.7%)
Xu et al.[158]	Learning curve and complications of unilateral biportal endoscopy: cumulative sum and risk-adjusted cumulative sum analysis	Retrospective	197	64.8	107:90	L	Biportal	Residue (3, 1.5%), dural tear (4, 2.0%), epidural hematoma (2, 1.2%), nerve root injury (3, 1.5%)
Choi et al.[159]	Learning curve associated with complications in biportal endoscopic spinal surgery: challenges and strategies	Retrospective	68	58	28:40	L	Biportal	Dural tear (2, 2.9%), nerve root injury (1, 1.5%), incomplete decompression (4, 5.9%)
Kang et al.[160]	Learning curve for biportal endoscopic posterior cervical foraminotomy determined using the cumulative summation test	Retrospective	50	52.68	36:14	C	Biportal	incomplete decompression (2, 4%), epidural hematoma (2, 4%)
Park et al.[161]	Learning curve for lumbar decompressive laminectomy in biportal endoscopic spinal surgery using the cumulative summation test for learning curve	Retrospective	60	67.6	31:29	L	Biportal	Dural tear (3, 5%), hematoma (1, 2%), incomplete decompression (2, 3%)
Jain et al.[162]	Learning curve of microendoscopic discectomy in single-level prolapsed intervertebral disc in 120 patients	Retrospective	120	42.5	75:45	L	Tubular	Dural tear (4, 3.3%), guidewire migration (5, 4.2%), postoperative leg pain (4, 3.3%), foot drop (1, 0.8%), post-op wound infection (2, 1.7%), recurrence (2, 1.7%)
Sommer et al.[163]	Lumbar giant disk herniations treated with a unilateral approach for bilateral decompression	Retrospective	23	49	14:9	L	Tubular	Dural tear (1, 4.3%), reoperation (2, 9.0%)
Keerthan et al.[164]	Microdiscectomy and minimally invasive discectomy using a tubular retractor system for lumbar disc herniation: a comparative study	Prospective	41	41.78	22:19	L	Tubular	Dural tear (8, 19.5%), surgical site infection (1, 2.4%), hamstring tightness (5, 12.2%)
Bhatia et al.[165]	Microdiscectomy or tubular discectomy: is any of them a better option for management of lumbar disc prolapse	Retrospective	109	39	64:45	L	Tubular	Dural tear (9, 8.3%), residual disc (5, 4.6%), extensor hallucis longus weakness (1, 0.9%)
Fukushima et al.[166]	Microendoscope-assisted versus open posterior lumbar interbody fusion for lumbar degenerative disease: a multicenter retrospective cohort study	Prospective	57	65.2	31:26	L	Tubular	Cage loosening (1, 1.8%), infection (1, 1.8%), screw loosening (1, 1.8%)

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Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Murata et al.[167]	Microendoscopic decompression for lumbar spinal stenosis caused by facet-joint cysts: a novel technique with a cyst-dyeing protocol and cohort comparison study	Retrospective	48	69.1	30:18	L	Tubular	Dural tear (4, 11.1%)
Patil et al.[168]	Microendoscopic discectomy for lumbar disc herniations	Prospective	300	NR	187:113	L	Tubular	Discitis (2, 0.7%), dysesthesia (2, 0.7%), recurrent prolapse (6, 2.0%), recurrent disc (4, 1.3%), dural tear (3, 1.0%)
Shibayama et al.[169]	Microendoscopy-assisted extraforaminal lumbar interbody fusion for treating single-level spondylodesis	Retrospective	55	62.7	17:38	L	Tubular	Cage migration with symptoms (3, 5.5%)
Xu et al.[170]	Microscopic keyhole technique for surgical removal of thoracic spinal meningiomas	Retrospective	17	60.5	2:15	T	Tubular	CSF leak (2, 11.8%)
Kumar et al.[171]	Minimally invasive discectomy and decompression for lumbar spine using tubular retractor system: technique, learning curve and outcomes	Retrospective	40	44.9	15:25	L	Tubular	Reoperation (2, 5%), dural tear (4, 10%)
Alimi et al.[172]	Minimally invasive laminectomy for lumbar spinal stenosis in patients with and without preoperative spondylolisthesis: clinical outcome and reoperation rates	Retrospective	110	68.5	58:52	L	Tubular	Dural tears (16, 14.5%), reoperation (11, 10.0%)
Papavero et al.[173]	Minimally invasive posterior cervical foraminotomy for treatment of radiculopathy: an effective, time-tested, and cost-efficient motion-preservation technique	Retrospective	103	50	63:40	C	Tubular	CSF leak (1, 1%), wound hematoma (1, 1%), radiculitis (1, 1%)
Del Curto et al.[174]	Minimally invasive posterior cervical microforaminotomy in the lower cervical spine and C-T junction assisted by O-arm-based navigation	Retrospective	14	49.8	13:1	C	Tubular	Dural tear (1, 7.1%)
Regev et al.[175]	Minimally invasive spinal decompression surgery in diabetic patients: perioperative risks, complications and clinical outcomes compared with non-diabetic patients' cohort	Retrospective	199	55.8	102:97	L	Tubular	Incidental durotomies (16, 8.0%), surgical site infection (2, 1.0%), revision (15. 7.5%)
Ahmed et al.[176]	Minimally invasive surgical management of symptomatic lumbar disc herniation: can the endoscope replace the microscope?	Retrospective	20	48.4	18:2	L	Tubular	Incidental durotomies (1, 5%), neurological deficit (1, 5%)
Tender et al.[177]	Minimally invasive transforaminal lumbar interbody fusion: comparison of two techniques	Retrospective	43	48.2	30:23	L	Tubular	Incidental durotomies (1, 4.7%), reoperation (1, 2.3%)

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Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Kang et al.[178]	Minimally invasive transforaminal lumbar interbody fusion using the biportal endoscopic techniques versus microscopic tubular technique	Retrospective	79	66.67	34:45	L	Tubular, biportal	Tubular: Incomplete decompression (1, 2.1%), hematoma (2, 4.3%), dural tear (3, 6.4%), Biportal: Incomplete decompression (2, 6.3%), hematoma (1, 3,1%), dural tear (1, 3,1%), infection (1, 3.1%)
Evaniew et al.[179]	Minimally invasive tubular lumbar discectomy versus conventional open lumbar discectomy: an observational study from the canadian spine outcomes and research network	Prospective	339	45.2	178:161	L	Tubular	Incidental durotomy (12, 4%), wound complications (10, 3%), infection (4, 1%), wound drainage (1, 0.3%), hematoma (1, 0.3%), reoperation within 12 months (23, 7%)
Hubbe et al.[180]	Minimally invasive tubular microdiscectomy for recurrent lumbar disc herniation	Retrospective	30	49.4	15:15	L	Tubular	Incidental durotomy (5, 16.7%), instability (2, 6.7%), facet joint syndrome (2, 6.7%)
Birch et al.[181]	Minimally invasive tubular resection of lumbar synovial cysts: report of 40 consecutive cases	Retrospective	40	65	13:27	L	Tubular	Dural tear (2, 5%)
Yolcu et al.[182]	Minimally invasive versus open surgery for degenerative spine disorders for elderly patients: experiences from a single institution	Retrospective	59	72	35:24	L	Tubular	Incidental durotomy (1, 1.7%)
Zhang et al.[183]	One-hole split endoscopy technique versus unilateral biportal endoscopy technique for L5-S1 lumbar disk herniation: analysis of clinical and radiologic outcomes	Retrospective	70	49.1	42:28	L	Tubular	Dural tear (1, 1.4%), transient hypoesthesia (1, 1.4%)
Ruetten et al.[184]	Operation of soft or calcified thoracic disc herniations in the full-endoscopic uniportal extraforaminal technique	Prospective	26	58	10:16	T	Uniportal	Epidural hematoma (1, 3.8%), persistent intercoastal neuralgia (2, 7.7%), anterior dural leak (1, 3.8%), postop myelopathy (1, 3.8%)
Eum et al.[185]	Percutaneous biportal endoscopic decompression for lumbar spinal stenosis: a technical note and preliminary clinical results	Retrospective	58	63.4	18:40	L	Biportal	Headache (3, 5.0%), durotomy (2, 3.4%), transient leg numbness (2, 3.4%), hematoma (1, 1.7%)
Lee et al.[25]	Percutaneous endoscopic laminotomy with flavectomy by uniportal, unilateral approach for the lumbar canal or lateral recess stenosis	Retrospective	213		61:152	L	Uniportal	Transient dysesthesia (12, 5.60%), lower extremity motor weakness (1.97%), durotomy (3.94%)
Kim et al.[186]	Percutaneous full endoscopic bilateral lumbar decompression of spinal stenosis through uniportal-contralateral approach: techniques and preliminary results	Retrospective	48	62.4	15:33	L	Uniportal	Durotomy (3, 6.2%), of 3 cases, (1, 2.1%) dural tear was converted to open surgery
Kang et al.[187]	Percutaneous full-endoscopic versus biportal endoscopic posterior cervical foraminotomy for unilateral cervical foraminal disc disease	Retrospective	33	52.68	11:22	C	Biportal	Incomplete decompression (1.3%), durotomy (1.3%), epidural hematoma (1.3%), persistent dysesthesia (1.3%)

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Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Jiang[188]	Pin-assisted retraction technique in unilateral biportal endoscopic discectomy: a retrospective cohort study	Retrospective	57	27	35:22	L	Biportal	Dural tear (2, 3.5%), hematoma (3, 5.3%)
Kim et al.[189]	Pooled analysis of unsuccessful percutaneous biportal endoscopic surgery outcomes from a multi-institutional retrospective cohort of 797 cases	Retrospective	797	59	491:306	L	Biportal	Hematoma (5, 0.62%), lesion recurrence (16, 2%), incomplete operation (8, 1%), dural tear (3, 0.37%), instability (2, 0.25%), infection (0.13%)
Wu et al.[190]	Posterior endoscopic cervical foramiotomy and discectomy: clinical and radiological computer tomography evaluation on the bony effect of decompression with 2 years follow-up	Retrospective	25	51.8	16:9	C	Uniportal	motor deficits (2, 8%), recurrent symptoms due to prolapsed disc (1, 4%)
Wu et al.[191]	Prospective cohort study with a 2-year follow-up of clinical results, fusion rate, and muscle bulk for uniportal full endoscopic posterolateral transforaminal lumbar interbody fusion	Prospective	35	64	10:25	L	Uniportal	Durotomy (6%)
Staartjets et al.[24]	Recurrent lumbar disc herniation after tubular microdiscectomy: analysis of learning curve progression	Retrospective	1,241	44.8	661:580	L	Tubular	Durotomy (47, 3.8%), spondylodiscitis (4, 0.3%), iatrogenic nerve root lesion (3, 0.2%), wound infection (1, 0.1%), wrong side (incision only) (1, 0.1%), conversion to open (2, 0.2%), excessive blood loss >500 mL (1, 0.1%), phlebitis (1, 0.1%)
Kong et al.[192]	Retrospective analysis of paraspinal muscle-splitting microscopic-assisted discectomy versus percutaneous endoscopic lumbar discectomy for the treatment of far-lateral lumbar disc herniation	Retrospective	26	38.4	21:5	L	Tubular	Tubular: Temporary dysesthesia (1, 3.85%)
Sim et al.[193]	Single-level endoscopic TLIF has decreased surgery duration, blood loss, and length of hospital stay while achieving similar 1-year clinical and radiological outcomes compared with conventional minimally invasive TLIF	Retrospective	34	66.3	17:17	L	Tubular	Tubular: Dural tear (1, 2.9%), 1 case of meralgia paresthetica (1, 2.9%)
Khashan et al.[194]	Stable low-grade degenerative spondylolisthesis does not compromise clinical outcome of minimally invasive tubular decompression in patients with spinal stenosis	Retrospective	96	69.05	53:43	L	Tubular	Durotomy (7, 7.3%), neurological (1, 1.0%), surgical site infection (2, 2.1%), pneumonia (1, 1.0%), residual stenosis (3, 3.1%), other complications (1, 1.0%)
Singhatanadgige et al.[195]	Surgical outcomes of minimally invasive transforaminal lumbar interbody fusion using surgical microscope vs surgical loupes: a comparative study	Retrospective	100	64.79	NA	L	Tubular	New postoperative lower extremity sensory changes (transient paresthesia) (3, 3%)

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Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Kim et al.[196]	Technical considerations of uniportal endoscopic posterolateral lumbar interbody fusion: a review of its early clinical results in application in adult degenerative scoliosis	Retrospective	25	68.4	3:22	L	Uniportal	Incidental durotomy (1, 4%), mild grade subsidence (1, 4%)
Xu et al.[197]	The clinical effect of unilateral decompressive laminectomy plus fusion with unilateral biportal endoscopic technique for single level lumbar spinal stenosis	Retrospective	65	62.6	34:31	L	Biportal	Nerve root injury (1, 1.5%), infection (1, 1.5%)
Chen et al.[198]	The learning curve of unilateral biportal endoscopic (UBE) spinal surgery by CUSUM analysis	Retrospective	97	51.5	52:45	L	Biportal	Dural injury (2, 2.1%), residual nerve compression of intervertebral disc herniation (2, 2.1%)
Kim et al.[199]	The novel technique of uniportal endoscopic interlaminar contralateral approach for coexisting l5-S1 lateral recess, foraminal, and extraforaminal stenosis and its clinical outcomes	Retrospective	48	67.6	21:27	L	Uniportal	Revision (2, 4.2%), segmental instability (2, 4.2%), incidental durotomy (2, 4.2%), hematoma (1, 2.1%), postoperative dysesthesia (6, 12.5%)
Wu et al.[200]	Transforaminal unilateral biportal endoscopic spinal surgery for extraforaminal lumbar disc herniation: a retrospective observational study	Retrospective	17	65.8	11:6	L	Biportal	Dural tear (1, 5.9%)
Maduri et al.[201]	Transtubular anterior cervical foraminotomy for the treatment of compressive cervical radiculopathy: surgical results and complications in a consecutive series of cases	Retrospective	45	55.9	30:15	C	Tubular	4.4% of patients (n = 2) presented with transient Horner's syndrome
Abdelrahman et al.[202]	Trans-tubular translaminar microscopic-assisted nucleotomy for lumbar disc herniations in the hidden zone	Prospective	66	59	37:29	L	Tubular	Dural tear (1, 1.5%)
de Nijs et al.[203]	Tubular microdiscectomy for recurrent lumbar disc herniation: a valuable alternative to endoscopic techniques	Retrospective	15	39	8:7	L	Tubular	2 Patients (13.3%) presented with an iatrogenic durotomy and 2 patients (13.3%) had a second rLDH
Zhou et al.[204]	Unilateral Bi/multi-portal endoscopy for the treatment of complicated lumbar degenerative diseases with utilization of uniaxial spinal endoscope, instead of arthroscope: technique note and clinical results	Retrospective	44	55.97	20:22	L	Biportal	Postoperative dysesthesia (2, 4.8%), vertebral compression fracture (1, 2.4%)
Kim and Choi[205]	Unilateral biportal endoscopic decompression by 30degree endoscopy in lumbar spinal stenosis: technical note and preliminary report	Retrospective	105	71.2	46:59	L	Biportal	Dural tear (2, 1.9%), epidural hematoma (1, 1.0%)

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Table 1. A comprehensive review of clinical studies (Continued)

Study	Study title	Study type	No. of patients	Avg. age (yr)	Sex, M:F	Level(s)	Surgery	Complications (no., % of cohort)
Pao et al.[206]	Unilateral biportal endoscopic decompression for degenerative lumbar canal stenosis	Retrospective	81	70.2	38:43	L	Biportal	Dural tears (4, 4.9%), transient motor weakness (1, 1.2%), inadequate decompression (1, 1.2%), and epidural hematoma (1, 1.2%)
Deng et al.[23]	Unilateral biportal endoscopic decompression for symptomatic thoracic ossification of the ligamentum flavum: a case control study	Retrospective	14	59.4	8:6	T	Biportal	Hyperalgesia (2, 14.3%), head, neck pain (2, 14.3%), CSF leak (1, 7.1%)
Jiang et al.[207]	Unilateral biportal endoscopic discectomy versus percutaneous endoscopic lumbar discectomy in the treatment of lumbar disc herniation: a retrospective study	Retrospective	24	46.25	10:14	L	Biportal	Dural tear (1, 4.2%)
Zhu et al.[208]	Unilateral biportal endoscopic laminectomy for treating cervical stenosis: a technical note and preliminary results	Retrospective	19	65.2	13:6	C	Biportal	Epidural hematoma (1, 5.3%)
Huang et al.[209]	Unilateral biportal endoscopic lumbar interbody fusion assisted by intraoperative O-arm total navigation for lumbar degenerative disease: a retrospective study	Retrospective	44	58.5	13:31	L	Biportal	Dural tear (1, 2.3%), transient paraesthesis (1, 2.3%)
Shen et al.[210]	Unilateral versus bilateral pedicle screw instrumentation for single-level minimally invasive transforaminal lumbar interbody fusion	Retrospective	65	58	33:32	L	Tubular	False position of screws (1, 1.5%), incomplete relief of symptoms (1, 1.5%), dura tear (3, 4.6%), root irritation (1, 1.5%)
Wu et al.[211]	Uniportal thoracic endoscopic decompression using one block resection technique for thoracic ossified ligamentum flavum technical report	Retrospective	28	64	15:13	T	Uniportal	Incomplete decompression (1, 3.5%)
Venier et al.[212]	Use of intraoperative computed tomography improves outcome of minimally invasive transforaminal lumbar interbody fusion: a single-center retrospective cohort study	Retrospective	100	61	56:44	L	Tubular	Dural tear (5, 5%), Kirschner wire fracture (1, 1%), iCT-related problems (3, 3%), surgical infection (1, 1%), epidural hematoma (3, 3%), mortality (1, 1%)

L, lumbar; T, thoracic; C, cervical; 3D, 3-dimensional; UTI, urinary tract infection; SIADH, syndrome of inappropriate antidiuretic hormone; ARDS, acute respiratory distress syndrome; IHD, ischemic heart disease; DVT, deep vein thrombosis; CSF, cerebrospinal fluid; MRC, Medical Research Council; NA, not available; iCT, intraoperative computed tomography.

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3) Biportal

Eight studies investigated the complications associated with biportal cervical spine surgery, involving 504 patients. The most common complications reported were dural tears (n = 4), epidural hematomas (n = 4), motor weakness (n = 3), and incomplete decompression (n = 3). Jung et al.[21] included the largest cohort (n = 162) and reported 3 complications: motor weakness (n = 2, 1.2%) and muscle soreness (n = 1, 0.6%).

2. Thoracic

1) Tubular

Three studies examined complications associated with tubular thoracic spine surgery. Across all of the 69 patients included, there were observed instances of cerebrospinal fluid (CSF) leak (n = 3), pseudomeningocele formation (n = 1), and durotomy (n = 1). The largest study by Ross[19] included 40 patients and reported a single durotomy (n = 1, 2.5%).

2) Uniportal

Four studies examined complications associated with uniportal thoracic spine surgery involving 140 patients. The most common complications were dural tears (n = 4), epidural hematomas (n = 3), incomplete decompression (n = 2), and transient intercostal neuralgias (n = 2). Ruetten et al.[22] included the largest cohort (n = 55) and found that 10 patients experienced at least one adverse event. The reported complications included dural tear (n = 2), epidural hematoma (n = 2), transient arm dysesthesia (n = 1), transient intercostal neuralgias (n = 2), deterioration of myelopathy (n = 1), transient deterioration of myelopathy (n = 1), transient leg dysesthesia (n = 1).

3) Biportal

One study examined complications associated with biportal thoracic spine surgery. In their cohort of 14 patients, Deng et al.[23] found complications of hyperalgesia (n = 2, 14.3%), head and neck pain (n = 2, 14.3%), and CSF leak (n = 1, 7.1%).

3. Lumbar

1) Tubular

Fifty-seven studies examined complications associated with tubular lumbar surgery. Across all 7,495 patients, the most common complications recorded were incidental dural injuries (n = 266), postoperative neuropathic conditions (n = 59), disc herniation recurrences (n = 30), and urinary tract infections (n = 27). Staartjes et al.[24] included the largest cohort of patients (n = 1,241) within the tubular lumbar surgery group and recorded the following complications: durotomy (n = 47, 3.8%), spondylodiscitis (n = 4, 0.3%), iatrogenic nerve root lesion (n = 3, 0.2%), wound infection (n = 1, 0.1%), wrong side incision (n = 1, 0.1%), conversion to open surgery (n = 2, 0.2%) excessive blood loss > 500 mL (n = 1, 0.1%), and phlebitis (n = 1, 0.1%).

2) Uniportal

Sixteen studies examined complications associated with uniportal lumbar surgery. Across the 1,146 patients included, the most common complication recorded was incidental dural injury (n = 29). Lee et al.[25] included the largest cohort of patients (n = 213) and reported the following complications: transient dysesthesia (n = 12, 5.6%), motor weakness (n = 3, 1.4%), and durotomy (n = 6, 2.8%).

3) Biportal

Fifty-six studies examined complications associated with biportal endoscopic surgery. Across the 4,002 patients included, the most common complications recorded included incidental dural injuries (n = 69), hematomas (n = 39), and neuropathic conditions (n = 34). Kim et al.[19] included the largest cohort of patients (n = 797) and recorded the following complication: hematoma (n = 5, 0.62%), lesion recurrence (n = 16, 2%), incomplete operation (n = 8, 1.0%), dural tear (n = 3, 0.4%), instability (n = 2, 0.3%), and infection (n = 1, 0.1%).

Table 2 summarizes the common complications in MISS.

DISCUSSION

1. Intraoperative

1) Nerve injury

Nerve injuries arising from spinal surgery can be transient or permanent. They can have direct causes, such as trauma, which may include unintentional nerve contact with instruments, or indirect causes, such as hematomas or swelling. Patients often report pain, weakness, or numbness when experiencing a nerve injury. Compared to traditional open spinal surgery, a MISS approach provides the advantage of decreased anatomical disruption, which should theoretically diminish the probability of disturbing spinal nerves. On the other hand, MISS can sometimes provide a limited field of view and a smaller working field, hypothetically contributing to an increased risk of nerve damage. One systematic review and meta-analysis revealed 9 instances (0.24%) of transient nerve root injury complications in 3,673 biportal endoscopic spine cases.[16] A comprehensive review and meta-analysis evaluating MISS versus traditional open surgery

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Table 2. Common complications in minimally invasive spine surgery

Complication	Tubular	Uniportal	Biportal
Intraoperative			
Cervical	(n = 480)	(n = 63)	(n = 504)
Nerve injury	2 (0.42)	4 (6.35)	5 (0.99)
Dural tears	2 (0.42)	NR	4 (0.79)
Hematomas	3 (0.63)	NR	4 (0.79)
CSF leak	1 (0.21)	NR	NR
Thoracic	(n = 69)	(n = 140)	(n = 14)
Nerve injury	NR	9 (6.43)	NR
Dural tears	1 (1.45)	4 (2.85)	NR
Hematomas	NR	3 (2.14)	NR
CSF leak	3 (4.35)	1 (0.70)	1 (7.14)
Lumbar	(n = 7,495)	(n = 1,146)	(n = 4,002)
Nerve injury	65 (0.87)	53 (4.62)	34 (0.85)
Dural tears	266 (3.55)	29 (2.53)	69 (1.72)
Hematomas	20 (0.27)	2 (0.17)	39 (0.97)
CSF leak	8 (0.11)	2 (0.17)	3 (0.07)
Postoperative			
Cervical	(n = 480)	(n = 63)	(n = 504)
Disc herniation recurrences	2 (0.42)	2 (3.17)	2 (0.40)
Incomplete decompression	NR	NR	3 (0.20)
Thoracic	(n = 69)	(n = 140)	(n = 14)
Incomplete decompression	NR	2 (1.43)	NR
Lumbar	(n = 7,495)	(n = 1,146)	(n = 4,002)
Disc herniation recurrences	30 (0.40)	3 (0.26)	32 (0.80)
Incomplete decompression	3 (0.04)	1 (0.09)	21 (0.52)
Urinary tract infection	27 (0.36)	NR	NR

CSF, cerebrospinal fluid; NR, not reported.

for cervical and lumbar discectomy in 1,590 patients found that MISS had a higher incidence of nerve root injury compared to open surgery.[26]

Given the small corridors that MIS surgeons work through, intraoperative neuromonitoring (IONM) can be critical for detecting potential nerve injury or damage in advance. IONM can track nerve function in real-time throughout a procedure. A recent retrospective study assessed the feasibility of using IONM for dysesthesia prophylaxis in endoscopic spine surgery. An experimental group underwent IONM with somatosenory evoked potentials and transcranial motor evoked potentials, while a control group did not. Postoperative dysesthesia occurred in 2 patients in the experimental group with IONM evidence of compression of the exiting nerve root's dorsal root ganglion and in 6 patients in the control group. The authors believe this compression was due to the initial placement or manipulation of the endoscopic working cannula and instruments.[27] Li et al.[28] demonstrated that IONM is feasible within Kambin's triangle using a stimulation probe under fluoroscopic and robotic guidance in 34 TLIFs. Vitale et al.[29] developed a checklist for items to consider in response to patient IONM changes. Overall, Laratta et al.[30] detected a 296% increase in the use of IONM in spine surgery between 2008 and 2014, relating the rise to 1 in every 200 IONM cases in which a consequent neurological deficit is avoided, and an estimated $120,000 is saved.

2) Durotomy

The literature points to a slightly higher incidence of symptomatic durotomies in open spinal surgery when compared with MISS. Lower durotomy rates in MISS could be due to the preservation of the paraspinal musculature with the smaller resultant dead space allowed for CSF to collect.[31] A systematic review assessing complications between MIS-TLIF and O-TLIF in 14 studies found 6 out of 455 and 7 out of 446 cases of dural tears, respectively.[32] Another study documented 6.4% versus 15.9% risk of durotomy ($p < 0.05$) in 240 patients undergoing MISS and open spinal surgery, respectively.[33] One 10-year systematic review on unintended durotomies in lumbar degenerative spinal surgery reported a 7.20% risk in MISS versus 7.02% rate in open surgery; however, this difference was not statistically significant.[34]

Ruban and O'Toole[35] reported on their management of incidental durotomies in MISS. They devised and followed a repair and management system for unintended durotomies. A primary repair was attempted using 4-0 Nurolon Ethicon sutures for full-thickness durotomies. Fibrin glue was used if a watertight closure could be achieved; otherwise, a muscle graft or collagen matrix was employed with fibrin glue. If primary repair was not feasible, blood-soaked gel foam and fibrin glue were used. For partial-thickness tears, only fibrin glue was applied. Two modified needle drivers and a bayoneted Chitwood Knot Pusher were used for all primary repairs, with bed rest emphasized for all cases.

Additionally, Boukebir et al.[36] reported that 9.9% of patients experienced incidental durotomies during tubular procedures. These tears were repaired intraoperatively with fibrin glue, DuraSeal, or direct closure, resulting in no postoperative CSF leaks or infections. The study highlighted a significant learning curve, with earlier procedures having higher dural injury rates (27.3%) than later ones (1.8%). Effective techniques included using a

ball-tip instrument to separate the dura from the ligamentum flavum and the Scanlan endoscopic dural repair set with a 4-0 Nurolon TF-5 suture for primary repairs.

A multicenter study on managing dural tears in lumbar endoscopic surgery documented 698 durotomies in 64,470 cases (~1%).[37] Most durotomies were repaired with sealants, with DuraSeal being the most commonly used sealant. Two-thirds of endoscopic spine surgeons who used sealants reported an uneventful postoperative course in their patients after an incidental dural tear. The remaining one-third observed issues related to durotomy in their patients but at a low incidence.

Telfeian et al.[38] reported 4 incidental durotomies in 907 patients who underwent transforaminal endoscopic spine surgery over 4 years. Of the 4, one was treated with the Durepair Regeneration Matrix (Medtronic, Minneapolis, MN, USA), and another with a Duragen patch (Integra, Princeton, NJ, USA). Of the remaining 2 durotomies, one was treated with 24-hour bed rest, and the other was left untreated because it was considered too small. No subsequent CSF leaks were reported.

Nam et al.[31] reviewed 3 incidental durotomies from endoscopic lumbar decompressions. All tears were repaired with TachoSil (Corza Medical, Westwood, MA, USA). They reported that all 3 patients improved after durotomy repair with TachoSil, and no complications occurred after discharge during follow-up. Derman et al.[39] discussed 3 cases of incidental durotomies during uniportal endoscopic spine surgery successfully repaired with collagen matrix inlay graft. In a retrospective review of 27 patients with incidental durotomy following endoscopic stenosis lumbar decompression, Kim et al.[40] recommended endoscopic patch blocking for patients with less severe dural tears and good prognosis, and consideration of conversion to open repair in patients with more serious tears and with fair to poor prognosis. Heo et al.[41] reported successful dural tear repairs with nonpenetrating titanium vascular anastomosis clips in biportal endoscopic lumbar surgery.

With innovative materials and technologies, MIS surgeons have been able to treat incidental durotomies with much reported success. However, the difficulty of such repairs must be considered in that MIS is performed through a small tube, which limits the use of standard dural repair instruments.[42] Furthermore, minor tears may not always be identified by the surgeon and not require incidental durotomy repair kits. This leads to the potential underreporting of durotomy within the minimally invasive setting.[43]

3) Hardware malplacement

Not much has been reported on the incidence of suboptimally placed instrumentation when comparing MISS and open spinal surgery. Schmidt et al.[44] reported a 90% screw placement accuracy with the use of a navigated MIS Single Step Pedicle Screw System. Other MIS studies have reported high screw placement accuracies when comparing preoperatively planned to implanted screws using imaging.[45] A recent review on long-term reoperation rates after open versus MIS surgery documented a 28% versus 14% rate.[46]

Navigation is also a valuable tool that can prevent reoperation. Navarro-Ramirez et al.[47] reported using a portable intraoperative CT 3-dimensional (3D) navigation system for 117 cases of various indications in all spine regions. The authors achieved a pedicle screw placement accuracy of 99%.

Navigation also requires collaboration among surgeons, nurses, and technicians. The burden of set-up and calibration of equipment and verification of imaging data accuracy and surgical tool functionality is shared, making the technology quite easy to use over time. Virk and Qureshi demonstrate this increased accuracy in addition to decreasing intraoperative radiation exposure.[48]

With respect to navigation and robotics, Guillotte et al.[49] reported 100% of pedicle screws and 100% of interbodies were placed satisfactorily using the Globus Excelsius GPS. No instrumentation required replacement or revision intraoperatively. Saway et al.[50] concluded that single and multilevel robotic endoscopic TLIF is a safe and efficacious approach with comparable outcomes to open and other minimally invasive approaches. AR is the newest technology on the market that can assist with accurate hardware placement in addition to multiple other benefits.

2. Postoperative

1) Infection

Spinal surgical site infections (SSIs) can be difficult to manage and may require multiple hospitalizations, prolonged antibiotic therapy, repeated surgeries for wound debridement, or implant removal.[51] MISS studies have documented favorable outcomes regarding SSIs. Kulkarni et al.[51] retrospectively reviewed 1,043 patients who underwent 763 noninstrumented MISSs and 280 MIS-TLIF procedures for an overall SSI rate of 0.29%. Mueller et al.[52] retrospectively reviewed 961 MIS and 481 open cases and reported statistically different SSI rates of 0.5% and 3.3% ($p = 0.0003$).

Intraoperatively, intravenous antibiotic prophylaxis is effec-

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tive for SSI reduction.[53] The administration of a broad-spectrum antibiotic such as cefazolin half an hour before the skin incision with readministration every 4 hours during long surgeries is standard practice.[54] Skin antisepsis also reduces the probability of patients developing SSIs.[55] Proven closure and dressing protocol and the reduction of intraoperative blood loss can also reduce the risk of SSIs.[56] O'Toole et al.[57] propose 4 possible intraoperative causes of reduced infection rates in MISS compared to open spinal surgery: reduced contamination surface area, prevention of skin flora contamination via tubular retractors, smaller incisions decreasing skin dehiscence risk, and reduced operative site dead space limiting postoperative wound seromas or hematomas, thereby potentially lowering the chance of SSIs.

2) Pain

An important objective of MISS is to decrease postoperative pain with smaller incisions and reduced tissue disruption. Hockley et al.[58] retrospectively reviewed 172 TLIF cases (109 open, 63 MIS) and reported a shorter operative time, decreased blood loss, and less inpatient opioid usage for MIS-TLIF. A systematic literature review that sought to assess return to work and narcotic use following MIS and open lumbar spinal fusions concluded that patients who underwent MISS generally returned to work quicker than patients who had open spinal surgery. MISS patients also required less postoperative narcotic use for pain control.[59] A subsequent narrative review reported improved outcomes with MIS-TLIF compared to open-TLIF regarding intraoperative bleeding, hospital stay, time to ambulation, postoperative narcotic use, and time to resume work.[19] Three Quality Outcome Database (QOD) studies have assessed MIS versus open approaches for fusions and decompressions. Mooney et al. reported that an MIS approach to lumbar spinal fusions was associated with a greater decrease in leg and back pain at three- and twelve-month follow-up time points.[60] A statistically significant decrease in leg pain was reported in MIS compared to open fusion for grade 1 degenerative lumbar spondylolisthesis.[61] The final QOD study assessing MIS versus open decompression for low-grade spondylolisthesis reported no significant differences in back or leg pain outcomes. However, both approaches led to favorable patient outcomes.[62]

3) Long-term

With decreased muscle, bony and ligamentous disruption, MIS surgeons believe that a minimally invasive approach should decrease the risk of adjacent segment disease (ASD). Despite this, a systematic review assessing the long-term outcomes of MIS-TLIF and open-TLIF in 16 studies reported no significant difference in ASD at a minimum follow-up of 2 years (12.6% vs. 12.40%, $p = 0.50$).[63] However, a separate study by Li et al.[28] reviewed 9 trials comprising 770 patients and reported a significantly lower adjacent segment pathology (ASP) incidence rate in patients who underwent an MIS procedure compared with an open procedure ($p = 0.0001$). Single-level lumbar interbody fusion was performed in 6 trials of 408 patients, and Li et al.[28] reported a lower ASP incidence rate in the MIS group ($p = 0.002$) for these studies. Their pooled data analysis favored the MIS approach for ASD and adjacent segment degeneration avoidance.

A systematic review of 24 studies, including 2,496 patients evaluating open laminectomies and minimally invasive bilateral canal enlargement, reported that instability was observed most frequently in those with preexisting spondylolisthesis (12.6%) and those treated with an open laminectomy (12%).[64] The review also concluded that instability following lumbar decompressions would likely occur less frequently using minimally invasive techniques.

Another recent review reported the following percentages for recurrent disc herniations: open discectomy: 4.8%, microdiscectomy: 5.1%, microendoscopic discectomy: 3.9%, and full endoscopic discectomy: 3.5%.[65] These numbers do not vary significantly. Therefore, no clear indication of which technique reduces recurrent disc herniation incidence exists.

4) AR in MISS

In MISS, AR is used to overlay relevant anatomical landmarks and preplanned screw trajectories on actual patient anatomy. Surgeons can experience real-time feedback of instruments in space and in relation to real anatomy.[66] AR projections can be displayed on wearable headsets or directly into the surgeon's microscope with AR application software.[11] The advent of AR in spine surgery began with the development of the head-up display (HUD) system, which overlayed CT imaging on the eyepiece of the operating microscope.[67] The visualization of spinal tumor resection planes, in osteotomies, and during MIS transvertebral cervical foraminotomies with the HUD system has been well documented.[68,69] To address some of the HUD system's constraints, AR-head-mounted displays (HMDs) were subsequently developed. The Augmedics Xvision Spine system is the first and only AR-HMD to have been approved by the U.S. Food and Drug Administration.[70,71] Companies like Brainlab have taken a similar approach to HUD systems utilizing special software to display AR projections into the operative mi-

croscope's field of view.

AR can be combined with intraoperative navigation to facilitate surgical precision and drastically reduce the need for fluoroscopy. With Brainlab software, for example, AR anatomical and screw trajectory planning can be completed on a preoperative CT scan. Preoperative data can be fused with an intraoperative CT scan using elastic fusion software with digital correction. Following fusion, the planned imaging is projected into the operative microscope and adjusted according to the surgeon's preferences.[11] Brainlab's software provides 3D intraoperative navigation, which enhances visibility and effectively orients the surgeon. Using a navigated pointer, surgeons can verify exactly where they are located within a patient's spine at any given moment. This feature is especially crucial for complex MIS cases.

Sommer et al.[11] combined the use of AR with "total 3D navigation" using Brainlab software to perform 10 MIS-TLIFs. Total 3D navigation, coined by Lian et al.,[72] refers to the use of navigation for all steps of an MIS procedure, from pathology localization, incision planning to screw placement, tubular decompression, cage placement, and rod measurement without the need for any intraoperative fluoroscopy. The operating surgeon could observe all preoperatively planned imaging in the microscopic field of view. AR implementation added only 1.3 ± 0.37 minutes to the overall procedure time, and there were no reported intraoperative or postoperative complications. All 10 patients reported favorable outcomes at an average of 8.4 ± 2.4 months. In a separate study, Sommer et al.[11] also reported on using AR with navigation for MIS and open resection of benign intradural extramedullary tumors—preoperative AR planning involved marking tumor margins with the Brainlab "smart brush" function. All surgeries were successful as with the TLIF cases performed with AR and navigation.

5) Avoiding complications with AR in MISS

AR's surgical mapping feature is perhaps the strongest tool that can be used in the surgeon's attempt to avoid intraoperative and postoperative complications. As mentioned, MIS surgeons can use software such as Brainlab Elements to study patient images in 3D and accurately mark or outline tumors and structures at risk, and plan trajectories. Anatomy varies between patients; therefore, experience with approaches to spinal pathology can fall short. With the added benefit of in-depth interaction with and reviewing patient anatomy and disease preoperatively, surgeons can foresee potential intraoperative difficulties and be prepared for challenges.

With the projection of these preoperatively planned models into a microscope or headset, MIS surgeons can be precise with their techniques—many complications in MISS stem from unnecessary contact with unaffected anatomy. For example, screws placed not completely within the pedicle can cause serious neurologic or vascular injury or a CSF leak.[73,74] With enhanced preoperative study and intraoperative visualization of vertebral body anatomy, surgeons are more likely to be more accurate with screw implantation and avoid lateral, medial, cranial, or caudal breaches.[70,75,76] Butler et al.[77] discuss the potential of minimizing damage to key structures surrounding the level(s) operated on in the prevention of ASD. AR can easily facilitate that objective. In complex cases such as tumor resections where the risk of complication is higher, AR has been proven to be a valuable tool.[11,78]

With AR in MISS, surgeons can observe patient anatomy in 3D projected over the standard field of view. An enhanced perception of critical structures, including nerve roots and the dura, can give surgeons a better sense of confidence and control in complex cases where the probability of compromising such delicate structures is higher. AR can also be coupled with intraoperative navigation to improve surgical workflow further and avoid complications.

In addition to its direct operative benefit, AR is a valuable resource for surgical education. Schmidt et al.[79] assessed the utility, accuracy, efficiency, and precision of AR-guided MIS-TLIF and sought to determine the technology's impact in spine surgery training. Twelve neurosurgical residents at 2 sites performed a 1-level TLIF on a high-fidelity lumbar spine simulation model, each with and without AR projection (which included highlighted landmarks) into a microscope. The National Aeronautics and Space Administration (NASA) task load index was administered to all residents postoperatively. Results demonstrated that AR-guided procedures consistently impacted resident anatomical orientation and workload experience. According to the NASA task load index, procedures completed without AR required a significantly higher mental demand ($p = 0.003$) than with AR. Residents also reported that it was significantly more difficult for them to accomplish their level of performance without AR ($p = 0.019$). Virtual reality (VR) also has important educational value. In a separate study, neurosurgery residents completed minimally invasive lateral interbody fusions using a VR system for 3 simulations over 6 weeks. Performance scores improved for the majority of participants. All participants also demonstrated improved comfort with important surgical landmarks and confidence in performing the procedure without supervision.[80]

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The adjustment to using AR in MISS is the toughest challenge of implementing the technology into practice. Kann et al.[81] have completed extensive research on the use of the AR-HMD. They describe the biggest challenge of its integration into practices as the limited number of experienced surgeons proficient in its usage since the technology is relatively new. To become experienced with AR technology, surgeons need to undergo extensive training. No standardized curricula for AR/VR surgical tools are endorsed by major neurosurgery or orthopedic specialty organizations. Those more advanced in their careers and have built successful practices without modern technology like AR may also be more reluctant to implement it. Adopting AR into surgical workflow also challenges operating room (OR) staff. OR anesthesiologists, nurses, and techs must also consider their role with newly implemented technology and how their routine will change.

Acquiring and maintaining AR/VR systems is expensive. Software, training, and technical support can become burdens for hospitals, especially those not well-resourced or funded. High initial costs associated with high-fidelity simulators have already led to significant variability in simulator availability across institutions in the United States.[82] While AR is costly, there are clearly significant benefits to its adoption. AR devices can also challenge patient data safety.[83] These systems can collect and store vast patient information on company servers. Given the novelty of these systems, there is also a lack of developed safeguards against attacks on sensitive patient information. More work must be done to do so.

STRENGTHS AND LIMITATIONS

The primary strength of this narrative review is its comprehensive evaluation of complications in MISS across cervical, thoracic, and lumbar regions. By incorporating data from a wide range of studies, the review provides a detailed understanding of complication profiles associated with different MISS techniques, including tubular, uniportal, and biportal endoscopic surgeries, at each spine region. The reviewed literature includes data from various countries, surgical settings, and patient populations over the past decade, providing a broad and diverse perspective.

Despite its strengths, this review has several limitations. Many included studies were retrospective, introducing selection bias and limiting causal inferences. Heterogeneity among studies regarding patient populations, surgical techniques, and outcome measures poses a challenge in drawing definitive conclusions. Furthermore, variability in surgeon experience with MISS techniques, particularly for newer approaches like biportal endoscopy, complicates the assessment of complication rates. The subjective nature of some reported complications, such as postoperative headaches, introduces potential interviewer bias. Additionally, some studies' lack of detailed patient demographics and clinical characteristics limits understanding of their impact on complication rates. Future research should incorporate prospective, randomized controlled trials with standardized complication reporting and detailed patient characteristics.

CONCLUSION

Complications in any surgical procedure are inevitable. With MISS, surgeons recognize this fact and seek to diminish this risk with approaches that preserve anatomy and stability while targeting indicated degenerative pathology. Various studies demonstrate that MISS provides many benefits to patients that, in many cases, are superior to open surgery. With MISS, there is ample room for innovation to minimize potential complications, as demonstrated by novel, proven approaches like endoscopy and technological advancements such as AR/AR and robotics. As MISS develops rapidly, surgeons and industry partners must continue to reassess aids and technologies and keep the consequential mission of providing patients with the best spine care preeminent in all considerations.

NOTES

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SUPPLEMENTARY MATERIAL

Search Strategy

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1. "Minimally invasive"[All Fields] OR "MISS"[All Fields] OR "Minimally Invasive Surgical Procedures"[MeSH Terms] AND "tubular"[All Fields] OR "biportal"[All Fields] OR "uniportal"[All Fields]
2. "spin*"[All Fields] OR "Spine"[MeSH Terms] OR "spine surger*"[All Fields]
3. "Lumbosacral Region"[MeSH Terms] OR "Cervical"[All Fields] OR "thoracic"[All Fields] OR "lumbar"[All Fields]
4. "Postoperative Complications"[MeSH Terms] OR "Intraoperative Complications"[MeSH Terms] OR "complication*"[All Fields]

1 AND 2 AND 3 AND 4 - 185

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Embase <1974 to 2024 March 29>
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1. (((Minimally invasive or MISS).af. or exp Minimally Invasive Surgical Procedures/) and tubular.af.) or biportal.af. or uniportal.af. 6821
2. spin*.af. or exp Spine/ or spine surger*.af. 2077336
3. 1 and 2 2194
4. exp Lumbosacral Region/ or Cervical.af. or thoracic.af. or lumbar.af. 2107173
5. exp Postoperative Complications/ or exp Intraoperative Complications/ or complication*.af. 7489485
6. 4 and 5 511290
7. 3 and 6 1215
8. limit 7 to yr = "2013-2024" 1051
9. remove duplicates from 8 685

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1. (Complications):ti,ab,kw AND ("Minimally invasive Surgery"):ti,ab,kw AND (Spine):ti,ab,kw (Word variations have been searched) with Cochrane Library publication date Between Jan 2013 and Mar 2024 50