Complications in Minimally Invasive Spine Surgery (2013–2024): Lumbar Spine—Tubular Minimally Invasive Techniques

A Proportional Meta-Analysis

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Study Design. Systematic review and proportional meta-analysis.

Objective. To quantify overall and specific complication rates associated with tubular minimally invasive spine surgery (MISS) for lumbar pathologies over the past decade.

Summary of Background Data. Tubular MISS is widely used for lumbar pathologies due to its reduced tissue disruption and faster recovery compared with open surgery. However, reported complication rates vary, and pooled estimates for specific complications remain limited.

Materials and Methods. A systematic search of PubMed, Medline, Embase, and the Cochrane Library (January 2013–March 2024) was conducted following PRISMA guidelines. Studies were included if they involved 10 adult patients undergoing tubular lumbar MISS and provided extractable complication data. A random-effects model was used to pool complication rates, and study quality was assessed using the Cochrane Risk of Bias Tool and Newcastle-Ottawa Scale. All analyses were done using R studio.

Results. Seventy-five studies involving ~12,600 patients were included in the analysis. The complication rate was 10% (95% CI: 8%–14%, $I^2=93\%$). Specific complication rates were: dural tears 4% (95% CI: 3%–5%, $I^2=69\%$) in 56 studies (6651 patients); nerve injuries 1% (95% CI: 1%–3%, $I^2=70\%$) in 41 studies (5278 patients); postoperative hematoma 1% (95% CI: 1%–2%, $I^2=31\%$) in 19 studies (2454 patients); surgical site infections 1% (95% CI: 0%–1%, $I^2=27\%$) in 46 studies (10,439 patients); revision surgeries 2% (95% CI: 2%–3%, $I^2=77\%$) in 43 studies (8948 patients); and disc reherniation 3% (95% CI: 1%–7%, $I^2=84\%$) in 14 studies (1928 patients).

Conclusion. This meta-analysis provides a comprehensive overview of complication rates in tubular lumbar MISS, revealing generally low rates but significant heterogeneity across studies. These findings offer valuable insights for patient counseling and surgical planning, though individual patient factors and surgeon experience should be considered.

Key Words: lumbar spine, tubular, MISS, surgical complications

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In the past two decades, minimally invasive spine surgery (MISS) has transformed the surgical management of spinal conditions, offering a less invasive alternative to traditional open procedures.[1] The core principle of MISS is minimizing collateral damage to paraspinal tissues, which reduces postoperative morbidity and accelerates recovery.[2–4] Among the techniques within MISS, tubular approaches have been widely adopted, utilizing tubular retractors to preserve muscle integrity while providing targeted access to the diseased anatomy.[2,3] Developed initially for lumbar disc herniation (LDH), these techniques have expanded to address conditions like lumbar spinal stenosis (LSS) and even multilevel pathologies.[1] The advantages of tubular MISS are well-documented, including decreased blood loss, shorter hospital stays, reduced postoperative pain, and quicker return to normal activities.[5–7] These benefits make tubular MISS an attractive option, particularly for patients with complex anatomic or physiological challenges, such as obesity, where minimizing surgical morbidity is paramount.[8–10]

As with any surgical technique, complications are a recognized concern with tubular MISS, particularly given

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its steep learning curve.[11,12] Dural tears are the most reported complication, with rates ranging from 6.4% to as high as 27.3% in some studies.[13–15] Other complications, such as nerve palsies, postoperative hematomas, surgical site infections, and implant malposition, have been reported at lower frequencies but with similar variability across studies.[16] Notably, the absence of pooled data makes it challenging to draw definitive conclusions about overall and specific complications.[16]

This systematic review and proportional meta-analysis, aims to address the knowledge gap regarding complication rates in lumbar tubular MISS by comprehensively evaluating overall and specific complications. By pooling data from studies published over the past decade, we offer an updated and consolidated perspective on the safety profile of tubular MISS, with a focus on key complications such as dural tears, nerve palsies, postoperative hematomas, surgical site infections (SSIs), and surgical revisions. This analysis is intended to support clinical decision-making, enhance patient safety, and optimize the use of tubular techniques in lumbar spine surgery.

MATERIALS AND METHODS

Literature Search

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines,[17] and was registered in PROSPERO (CRD42024570377). A comprehensive literature search across PubMed, Medline, Embase through OVID, and the Cochrane Library (January 2013–March 2024) utilized Medical Subject Headings and relevant keywords to broadly capture studies on lumbar tubular MISS and its associated complications. The "Minimally invasive," "MISS," "Minimally Invasive Surgical Procedures," "tubular," "biportal," "uniportal," "surgery," "complications," "lumbosacral region," "cervical," "thoracic," "lumbar," "postoperative complications," and "intraoperative complications." The broader search terms facilitated a comprehensive investigation of complications across multiple MISS techniques (biportal, tubular, uniportal) and spinal regions (cervical, thoracic, lumbar), ensuring consistency in screening while enabling the dis-

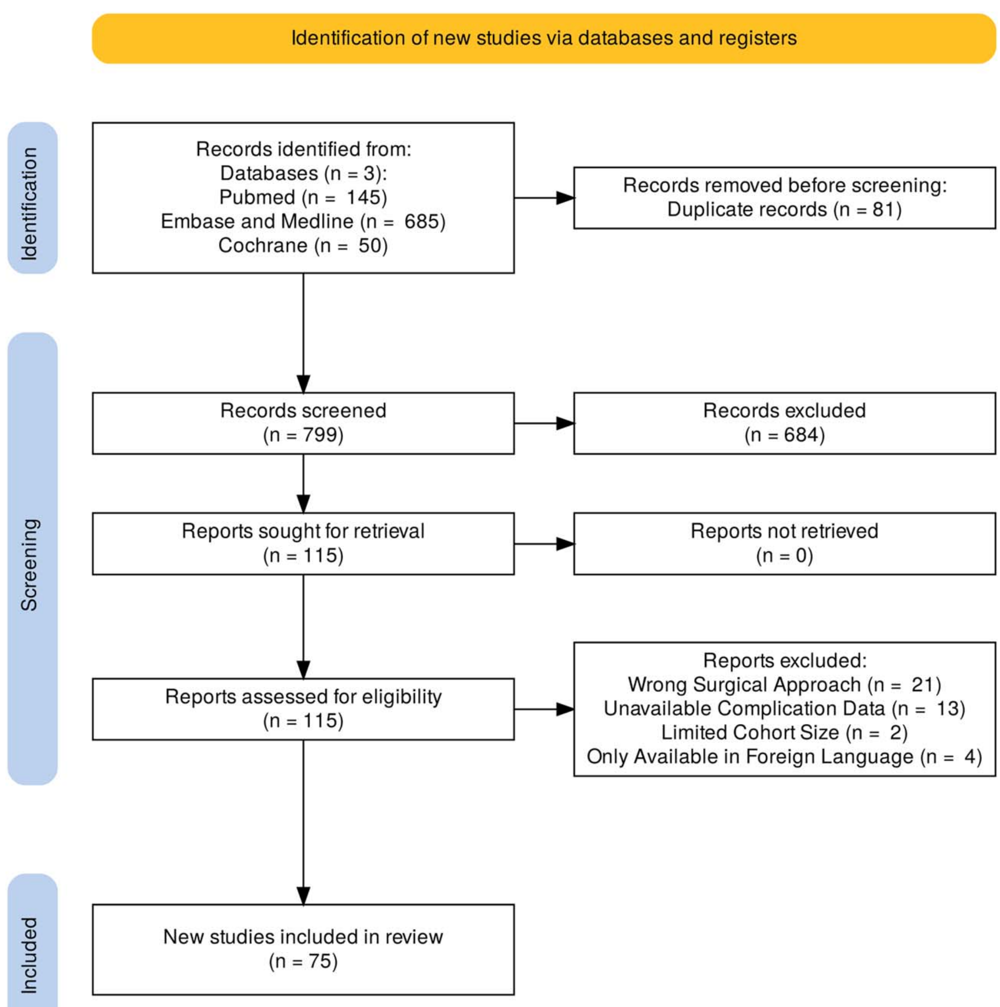

Figure 1. PRISMA flow diagram for study selection.

TABLE 1. Summary of Complications Across Studies in Lumbar Tubular Endoscopic Spine Surgery

References	Sample size	Total complications	Dural tears	Nerve palsies	Postoperative hematomas	Surgical site infections	Disc reherniations	Surgical revisions
Cahill *et al.*[24]	48	2	1	0	—	1	—	—
Patel *et al.*[25]	625	81	10	7	—	0	—	16
Kumar *et al.*[26]	20	2	—	—	—	1	—	—
Wang *et al.*[27]	174	99	—	22	—	2	—	12
Choi *et al.*[28]	43	38	0	—	0	0	18	8
Lee *et al.*[29]	34	3	0	1	1	—	1	0
Antony *et al.*[30]	28	2	—	2	—	—	—	1
Zhang *et al.*[31]	145	10	2	0	—	5	—	3
Kotheeranurak *et al.*[32]	30	8	1	3	—	1	—	2
Librianto *et al.*[33]	48	18	—	9	—	—	—	8
Kim *et al.*[34]	55	4	0	2	0	0	—	1
Liu *et al.*[35]	60	14	2	10	—	—	—	2
Süner *et al.*[36]	10	3	0	—	1	0	—	1
Ross *et al.*[6]	929	33	32	0	1	0	—	—
Sonawane *et al.*[37]	31	5	2	0	0	0	2	—
Kuo *et al.*[38]	40	4	2	0	—	0	—	1
Sharma *et al.*[39]	207	31	37	20	—	2	3	6
Altshuler *et al.*[40]	961	24	—	—	—	—	—	—
Hsieh *et al.*[41]	138	15	5	—	1	4	—	—
Claus *et al.*[42]	467	201	6	—	7	0	—	—
Wang *et al.*[43]	46	10	—	—	—	3	—	—
Kruger *et al.*[44]	28	2	2	0	2	0	—	2
Goertz *et al.*[45]	71	40	9	4	—	1	—	13
Martens *et al.*[46]	60	5	—	—	—	—	2	3
Jain *et al.*[47]	120	18	4	5	—	2	2	—
Nayak *et al.*[48]	41	15	8	0	—	1	—	—
Bhatia *et al.*[49]	102	21	9	1	—	1	—	5
Kumar *et al.*[49]	40	8	4	2	—	—	—	2
Alimi *et al.*[15]	110	27	16	—	—	—	—	11
Regev *et al.*[50]	199	33	16	—	—	2	—	15
Ahmed *et al.*[51]	20	2	1	1	—	0	—	—
Tender *et al.*[52]	43	2	1	—	1	—	—	0
Kang *et al.*[53]	32	5	1	0	1	1	—	—
Evaniew *et al.*[4]	339	51	12	0	1	4	—	23
Hubbe *et al.*[55]	30	12	5	—	—	—	1	2
Birch *et al.*[56]	40	2	2	—	—	—	—	—
Yolcu *et al.*[57]	59	1	1	—	—	—	—	0
Staartjes *et al.*[58]	1241	155	47	3	—	1	56	39
Kong *et al.*[59]	26	1	—	1	0	0	—	—
Sim *et al.*[60]	34	2	1	1	—	—	—	—
Khashan *et al.*[61]	96	22	7	1	—	2	—	6
Singhatanadgige *et al.*[62]	100	3	0	3	—	0	—	—
Abdelrahman *et al.*[63]	66	1	1	—	—	—	—	—
de Nijs *et al.*[64]	15	4	2	—	—	—	2	0
Shen *et al.*[5]	65	7	3	1	—	0	—	0
Venier *et al.*[66]	100	15	5	0	3	1	—	1
Bisson *et al.*[67]	71	11	0	—	—	—	—	10
Andrade Amos *et al.*[68]	48	3	1	—	—	1	—	—
Shousha *et al.*[69]	4280	8	—	—	—	4	—	4
Kogias *et al.*[70]	53	9	9	—	—	—	—	—
Heo *et al.*[71]	41	11	1	1	2	0	—	—
Oki *et al.*[72]	24	2	—	1	—	—	—	1

Bhatnagar *et al.*[73]	20	11	1	8	—	1	—	—
Wang *et al.*[74]	38	0	0	0	—	0	—	—
Sommer *et al.*[75]	10	0	—	0	—	0	—	0
Liu *et al.*[76]	28	1	0	—	—	0	—	—
Lv *et al.*[77]	48	0	0	0	—	0	—	0
Sanchez *et al.*[78]	33	2	—	—	—	—	1	—
Balasubramanian *et al.*[79]	14	1	0	1	0	0	0	0
Wang *et al.*[80]	122	4	2	—	—	0	—	0
Chan *et al.*[81]	72	7	2	1	1	0	—	1
Carrascosa-Granada *et al.*[82]	10	5	0	—	1	1	—	—
Wipplinger *et al.*[83]	13	1	—	—	—	—	—	0
Knio *et al.*[84]	68	25	6	—	—	—	—	12
Heo *et al.*[85]	42	3	1	—	2	0	—	—
Wang *et al.*[86]	58	10	—	—	—	—	—	—
Kulkarni *et al.*[87]	51	2	—	—	—	—	0	0
Alimi *et al.*[88]	33	6	—	—	—	—	—	3
Siu *et al.*[89]	24	0	—	0	—	—	—	—
Shen *et al.*[90]	65	6	3	1	—	0	—	—
Lian *et al.*[91]	33	0	—	—	—	—	—	—
Barbagallo *et al.*[92]	13	0	0	0	—	—	—	—
Sukkarieh *et al.*[93]	13	0	0	—	—	0	—	0
Alimi *et al.*[94]	32	3	1	—	—	—	1	1
Kulkarni *et al.*[95]	17	0	—	—	—	—	0	—

The value "0" indicates that the complication was explicitly noted not to have occurred. A "—" indicates that the complication was not explicitly mentioned in the study.

tinct identification of lumbar tubular studies in this review. Google Scholar was also used to conduct a hand search of additional articles found in the initial database search. Supplemental Digital Content 1, http://links.lww.com/BRS/C884 details the full search strategy for each database.

Inclusion and Exclusion Criteria

Studies were included if they examined lumbar tubular procedures in the lumbar spine and involved at least 10 adult patients. Only studies with extractable complication data, either reporting specific complication frequencies or explicitly stating the absence of complications, were eligible. Excluded were conference abstracts, reviews, meta-analyses, and studies without full-text availability in English. In addition, research utilizing microendoscopic techniques or oblique/lateral approaches was omitted. For overlapping patient cohorts, the study with the larger sample size was prioritized.

Study Selection and Data Extraction

All articles identified through the literature search were imported into Rayyan (Cambridge, MA) for screening. Duplicate records were removed before two independent reviewers (S.I. and E.G.) assessed titles and abstracts based on predefined inclusion and exclusion criteria. Full texts of potentially relevant studies were then reviewed using the same method and criteria. Data extraction was performed using a structured form to collect study characteristics, patient demographics, complication frequencies, and risk of bias. Two reviewers (S.I. and E.G.) conducted the extraction independently to ensure accuracy, resolving discrepancies through discussion or consultation with a third reviewer (C.I.) if needed.

Quality Assessment

Study quality was evaluated by using design-specific assessment tools. The Cochrane Risk of Bias Tool was applied to randomized controlled trials (RCTs),[18] while the Newcastle-Ottawa scale (NOS) was used for nonrandomized studies,[19] including cohort and case-control designs. A NOS score of ≥ 6 indicated good study quality, aligning with prior meta-analyses on complications in biportal endoscopic spine surgery.[20] Two researchers (S.I. and E.G.) independently conducted the assessments, with any discrepancies resolved through discussion. If consensus could not be reached, a third reviewer (C.I.) was consulted to ensure consistency in quality evaluation.

Data Management and Analysis

Overall complication rate for lumbar tubular MISS was the primary outcome, with secondary outcomes including dural tears, nerve palsies, postoperative hematomas, surgical site infections (SSIs), disc reherniations, and surgical revisions. Outcomes were selected based on their clinical relevance and frequency of reporting.

Heterogeneity among studies was evaluated using the I^2 statistic, though its interpretation was cautious, as high I^2 values are common in proportional meta-analyses and do not necessarily indicate inconsistency.[21] A random-effects model was used to account for expected variability across study settings.[21,22] Given the relatively low event rates, a generalized linear mixed model with a logit transformation was applied.[21,22] Sensitivity analyses were conducted by excluding studies with moderate to high risk of bias and comparing results using a fixed-effect model. Subgroup sensitivity analyses by age or underlying pathology were considered; however, most included studies reported complication data in aggregate without stratification by patient characteristics. Although the average age was available at the study level, it was not feasible to perform reliable patient-level analyses, as categorizing studies by mean age would risk ecological bias. Consequently, sensitivity analyses were restricted to study design and risk-of-bias assessments. Publication bias was assessed qualitatively with funnel plots (see Supplemental Digital Content 2–8, Supplemental Digital Content 2, http://links.lww.com/BRS/C885; Supplemental Digital Content 3, http://links.lww.com/BRS/C886; Supplemental Digital Content 4, http://links.lww.com/BRS/C887; Supplemental Digital Content 5, http://links.lww.com/BRS/C888; Supplemental Digital Content 6, http://links.lww.com/BRS/C889; Supplemental Digital Content 7, http://links.lww.com/BRS/C890; Supplemental Digital Content 8, http://links.lww.com/BRS/C891), as their validity in proportional meta-analyses remains uncertain.[21] Certainty of evidence for each pooled outcome was assessed using the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) framework. Evidence was rated across domains of study design, risk of bias (informed by our ROB assessment), inconsistency, indirectness, and imprecision, and categorized as high, moderate, low, or very low. A GRADE Summary of Findings table is provided in Supplemental Digital Content 9, http://links.lww.com/BRS/C892. Our proportional meta-analysis was conducted using the *metaprop* function from the *meta* package.[23] All statistical analyses and visualizations were performed using R version 4.4.1 (R Project for Statistical Computing, Vienna, Austria).

RESULTS

Characteristics of Included Studies and Quality Assessment

A total of 880 publications were returned in the initial database search, with 81 duplicates removed, leaving 799 studies for title and abstract screening. The PRISMA flow diagram for study selection is presented in Figure 1. Following this, 115 studies were selected for full-text review to identify the incidence of complications in cervical MISS. Seventy-five studies were eligible for inclusion, spanning 12,590 patients. Table 1 summarizes the study characteristics and complication data. Most of the studies were retrospective (58/75 77.3%), with seventy cohort studies, two RCTs, and three case-control studies. Of the cohort and case-control studies, the majority had a moderate risk of bias (51/73, 69.9%), while twenty studies were of good quality with a low risk of bias, and two studies had a high risk of bias (Table 2). For the RCTs, one study had an unclear risk of bias, while the second had a high risk of bias (Table 3).

The sample sizes ranged from 10 to 4280 patients, with the average age of participants ranging from 38.4 to 72.2 years. Males accounted for 54.2% of the participants in the 71 studies that reported gender distribution. Study follow-up periods ranged from 1 to 84 months. Most studies were from the United States (24.3%) and China (16.2%).

Meta-Analysis Results

Total Complications

Seventy-five studies, encompassing 12,590 patients, were included in the meta-analysis of total complications associated with lumbar procedures, with 1192 complication events reported. According to the random-effects model, the pooled incidence of total complications was 10% (95% CI: 8%–14%). Notable heterogeneity was observed among the included studies ($I^2 = 93\%$, $P < 0.01$) (Fig. 2). We did not perform a sensitivity analysis.

Dural Tears

Fifty-six studies, encompassing 6651 patients, were included in the meta-analysis of dural tear complications associated with lumbar procedures, with 284 dural tear events reported. According to the random-effects model, the pooled incidence of dural tears was 4% (95% CI: 3%–5%). Notable heterogeneity was observed among the included studies ($I^2 = 69\%$, $P < 0.01$) (Fig. 3). Several studies reported notably low rates of dural tear complications, such as Cahill *et al.*[24] with a rate of 2% (95% CI: 0%–11%), while Kogias *et al.*[70] reported higher rates of 17% (95% CI: 8%–30%).

Nerve Palsies

Forty-one studies, encompassing 5278 patients, were included in the meta-analysis of nerve injury complications associated with lumbar procedures, with 112 nerve injury events reported. The pooled incidence of nerve injuries was 1% (95% CI: 1%–3%) according to the random-effects model. Notable heterogeneity was observed among the included studies ($I^2 = 70\%$, $P < 0.01$) (Fig. 4).

Postoperative Hematomas

Nineteen studies, encompassing 2454 patients, were included in the meta-analysis of hematoma complications associated with lumbar procedures, with 25 hematoma events reported. According to the random-effects model, the pooled incidence of hematoma formation was 1% (95% CI: 1%–2%). Low heterogeneity was observed among the included studies ($I^2 = 31\%$, $P = 0.09$) (Fig. 5).

SSIs

Forty-six studies, encompassing 10,439 patients, were included in the meta-analysis of surgical site infection

TABLE 2. Study Evaluation Using the Newcastle-Ottawa Scale for Nonrandomized Studies*

References	Design	Selection	Comparability	Exposure	Total score
Cahill *et al.*[24]	Retrospective Cohort	3	0	1	4
Patel *et al.*[25]	Retrospective Cohort	3	0	3	6
Kumar *et al.*[26]	Prospective Cohort	3	0	2	5
Wang *et al.*[27]	Retrospective Cohort	3	0	3	6
Choi *et al.*[28]	Retrospective Cohort	3	0	3	6
Lee *et al.*[29]	Retrospective Cohort	3	0	2	5
Antony *et al.*[30]	Prospective Cohort	3	0	3	6
Zhang *et al.*[31]	Retrospective Cohort	3	0	3	6
Kotheeranurak *et al.*[32]	Prospective Cohort	3	0	2	5
Librianto *et al.*[33]	Retrospective Cohort	4	2	3	9
Kim *et al.*[34]	Retrospective Cohort	3	0	3	6
Liu *et al.*[35]	Retrospective Cohort	3	0	3	6
Süner *et al.*[36]	Prospective Cohort	3	0	2	5
Ross *et al.*[6]	Retrospective Cohort	3	0	2	5
Sonawane *et al.*[37]	Prospective Cohort	3	0	3	6
Kuo *et al.*[38]	Retrospective Cohort	3	0	3	6
Sharma *et al.*[39]	Retrospective Cohort	3	0	3	6
Altshuler *et al.*[40]	Retrospective Cohort	3	0	3	6
Hsieh *et al.*[41]	Retrospective Cohort	3	0	2	5
Claus *et al.*[42]	Retrospective Cohort	3	0	2	5
Wang *et al.*[43]	Retrospective Cohort	3	0	3	6
Kruger *et al.*[44]	Retrospective Case-Control	0	0	0	0
Goertz *et al.*[45]	Retrospective Cohort	3	0	3	6
Martens *et al.*[46]	Retrospective Cohort	3	0	3	6
Jain *et al.*[47]	Retrospective Cohort	3	0	3	6
Nayak *et al.*[48]	Prospective Cohort	4	2	3	9
Bhatia *et al.*[49]	Retrospective Cohort	4	2	3	9
Kumar *et al.*[49]	Retrospective Cohort	4	2	3	9
Alimi *et al.*[15]	Retrospective Cohort	3	0	3	6
Regev *et al.*[50]	Retrospective Cohort	3	0	3	6
Ahmed *et al.*[51]	Retrospective Cohort	4	2	3	9
Tender *et al.*[52]	Retrospective Cohort	4	2	3	9
Kang *et al.*[53]	Retrospective Cohort	4	2	3	9
Evaniew *et al.*[54]	Retrospective Cohort	4	2	3	9
Hubbe *et al.*[55]	Retrospective Cohort	3	0	3	6
Birch *et al.*[56]	Retrospective Cohort	3	0	3	6
Yolcu *et al.*[57]	Retrospective Cohort	4	2	3	9
Staartjes *et al.*[58]	Retrospective Cohort	3	0	3	6
Kong *et al.*[59]	Retrospective Cohort	4	2	3	9
Sim *et al.*[60]	Retrospective Cohort	4	2	3	9
Khashan *et al.*[61]	Retrospective Cohort	3	0	3	6
Singhatanadgige *et al.*[62]	Retrospective Cohort	3	0	3	6
Abdelrahman *et al.*[63]	Prospective Cohort	3	0	3	6
de Nijs *et al.*[64]	Retrospective Cohort	3	0	2	5
Shen *et al.*[65]	Retrospective Cohort	3	0	3	6
Venier *et al.*[66]	Retrospective Cohort	3	0	1	4
Bisson *et al.*[67]	Prospective Cohort	4	2	3	9
Andrade Amos *et al.*[68]	Prospective Cohort	3	0	0	3
Shousha *et al.*[69]	Retrospective Cohort	3	0	3	6
Kogias *et al.*[70]	Retrospective Case-Control	4	2	3	9
Heo *et al.*[71]	Retrospective Cohort	4	2	3	9
Oki *et al.*[72]	Retrospective Cohort	3	0	0	3
Bhatnagar *et al.*[73]	Prospective Cohort	3	0	3	6
Wang *et al.*[74]	Retrospective Cohort	4	2	3	9
Sommer *et al.*[75]	Prospective Cohort	3	0	3	6
Liu *et al.*[76]	Retrospective Cohort	4	2	3	9
Sanchez *et al.*[78]	Retrospective Cohort	3	0	3	6
Balasubramanian *et al.*[79]	Retrospective Cohort	3	0	3	6

TABLE 2. (*continued*)

References	Design	Selection	Comparability	Exposure	Total score
Wang *et al.*[80]	etrospective Cohort	3	0	3	6
Chan *et al.*[81]	etrospective Cohort	4	2	2	8
Wipplinger *et al.*[83]	rospective Case-Control	3	0	3	6
Knio *et al.*[84]	etrospective Cohort	3	0	3	6
Heo *et al.*[85]	rospective Cohort	4	2	3	9
Wang *et al.*[86]	etrospective Cohort	3	0	3	6
Kulkarni *et al.*[87]	rospective Cohort	3	0	2	5
Alimi *et al.*[88]	rospective Cohort	3	0	3	6
Siu *et al.*[89]	etrospective Cohort	3	0	3	6
Shen *et al.*[90]	etrospective Cohort	4	2	3	9
Lian *et al.*[91]	Retrospective Cohort	3	0	1	4
Barbagallo *et al.*[92]	Retrospective Cohort	3	0	3	6
Sukkarieh *et al.*[93]	Retrospective Cohort	3	0	3	6
Alimi *et al.*[94]	Retrospective Cohort	3	0	3	6
Kulkarni *et al.*[95]	Retrospective Cohort	3	0	3	6

*Studies scoring 7–9 were considered low risk of bias, 5–6 moderate risk, and 0–4 high risk.

TABLE 3. Study Evaluation Using the Cochrane Risk of Bias Tool for Randomized Clinical Trials

Study	Design	Random sequence generation	Allocation concealment	Blinding	Incomplete outcome data	Selective reporting	Other biases
Lv *et al.*[77]	Randomized Clinical Trial	Low	Unclear	High	Low	Low	Low
Carrascosa-Granada *et al.*[82]	Randomized Clinical Trial	Unclear	Unclear	Low	Low	Low	Low

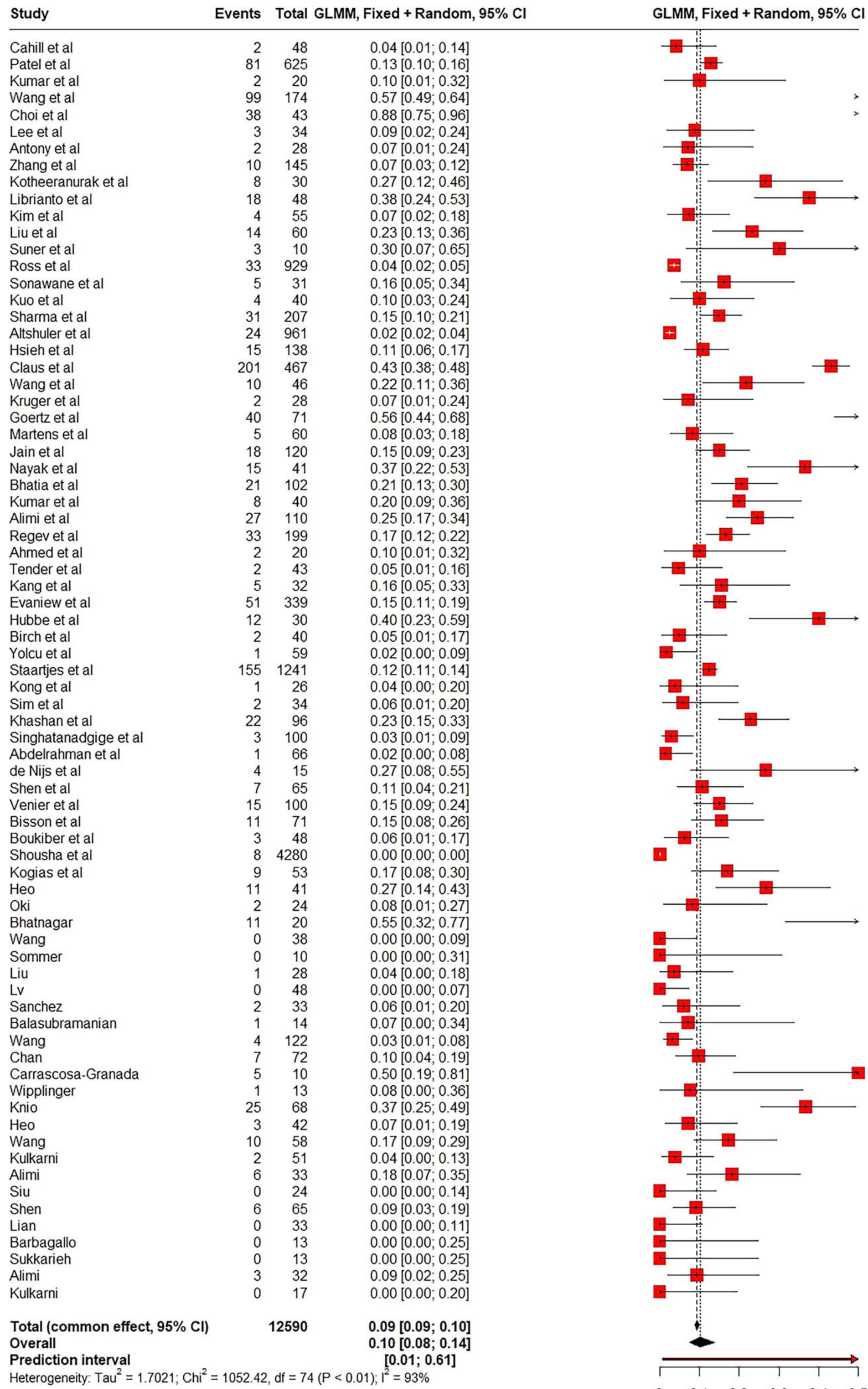

Figure 2. Forest plot for the incidence of total complications in lumbar tubular spine surgery.

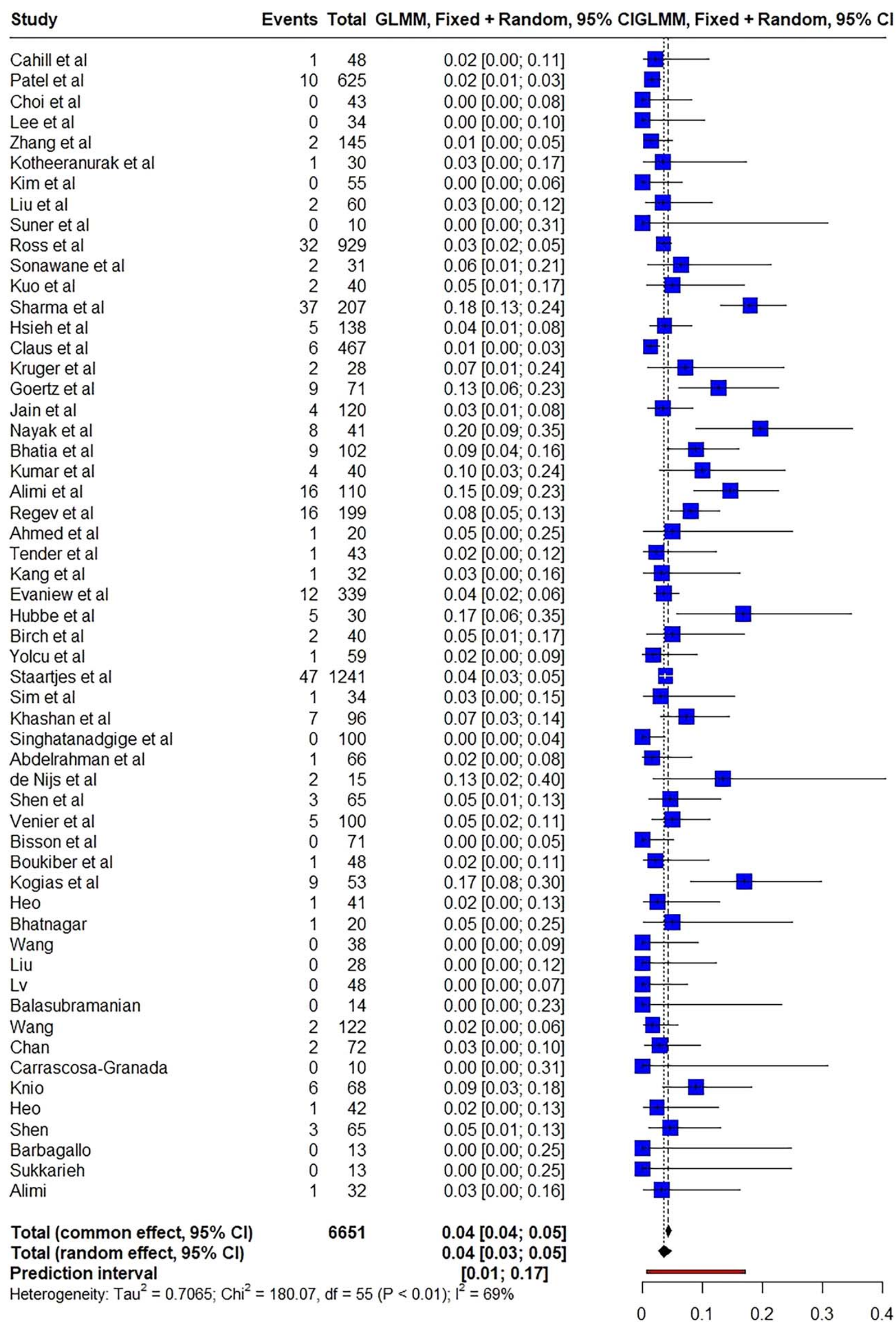

Figure 3. Forest plot for the incidence of dural tears in lumbar tubular spine surgery.

(SSI) complications associated with lumbar procedures, with 42 SSI events reported. The pooled incidence of SSIs was 1% (95% CI: 0%–1%) according to the random-effects model. Low heterogeneity was observed among the included studies ($I^2 = 27\%$, $P = 0.05$) (Fig. 6).

Disc Reherniations

Fourteen studies, encompassing 1928 patients, were included in the meta-analysis of disc reherniation following lumbar procedures, with 89 reherniation events reported. The pooled incidence of disc recurrence was 3%

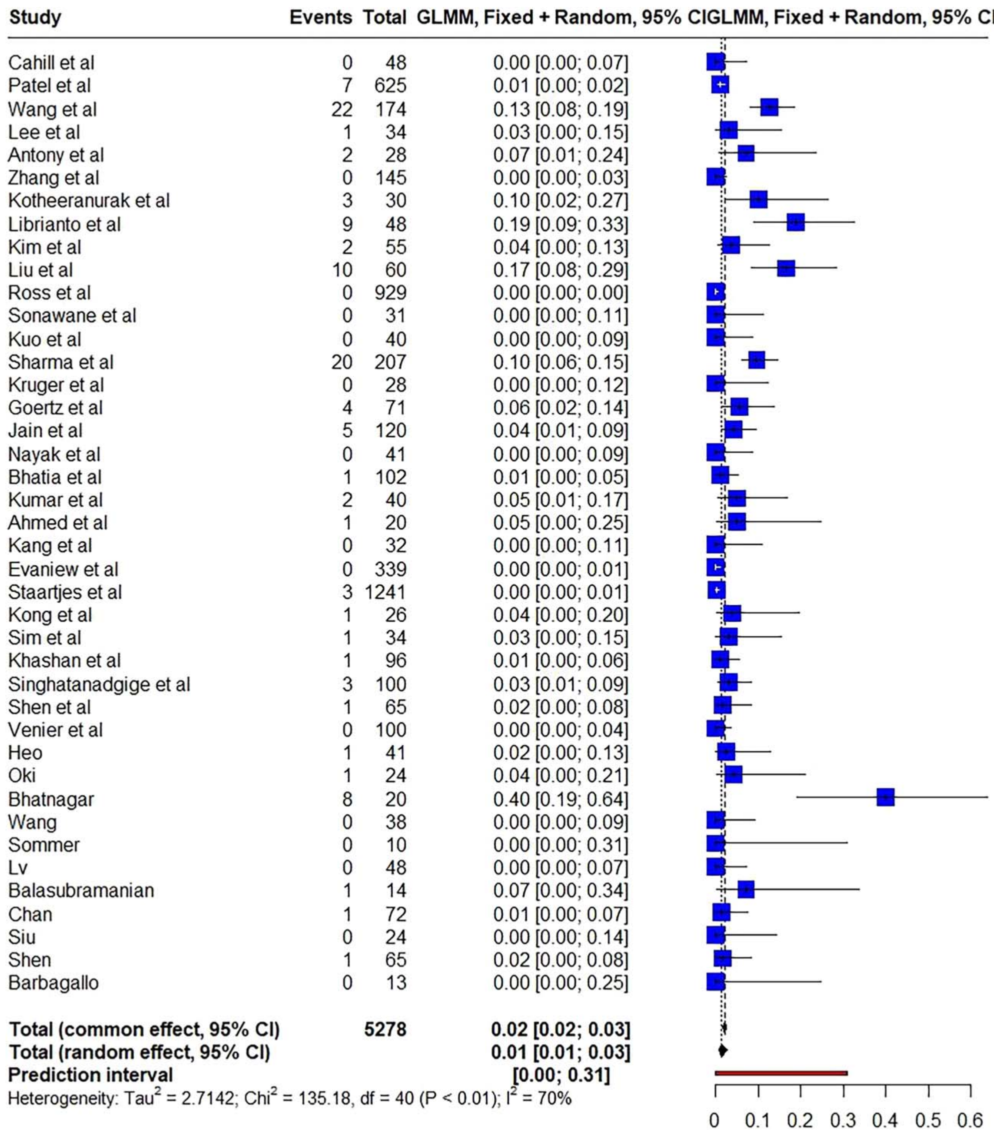

Figure 4. Forest plot for the incidence of nerve palsies in lumbar tubular spine surgery.

(95% CI: 1%–7%) according to the random-effects model. Significant heterogeneity was observed among the included studies ($I^2 = 84\%$, $P < 0.01$) (Fig. 7).

Surgical Revisions

Forty-three studies, encompassing 8948 patients, were included in the meta-analysis of revision surgery rates associated with lumbar procedures, with 196 revision events reported. The pooled incidence of revision surgeries was 2% (95% CI: 2%–3%) according to the random-effects model. Significant heterogeneity was observed among the included studies ($I^2 = 77\%$, $P < 0.01$) (Fig. 8).

Illustration depicting potential hematoma, dural tear and CSF leak, and nerve injury during tubular minimally invasive lumbar spine surgery (Fig. 9).

DISCUSSION

Tubular spine surgery has emerged as one of the options for minimally invasive approaches to treating lumbar spine conditions. It is used in discectomies, foraminotomies, laminotomies, and fusion procedures to treat focal compressive and unstable spinal lesions while preserving normal osteoligamentous structures and muscles.[14] They offer enhanced 3D visualization through an operating microscope, allowing for effective management of degenerative, traumatic, and even tumor-related spinal pathologies. Unlike open techniques, tubular approaches provide faster recovery, reduced blood loss, and lower infection rates, making them a key component of minimally invasive spine surgery.[96,97] Associated complications remain a critical consideration when selecting a surgical approach to treat a spinal disease. Common complications of tubular MISS are nerve palsy, dural tears, hematomas, cerebrospinal fluid leak, and disc recurrences.[16]

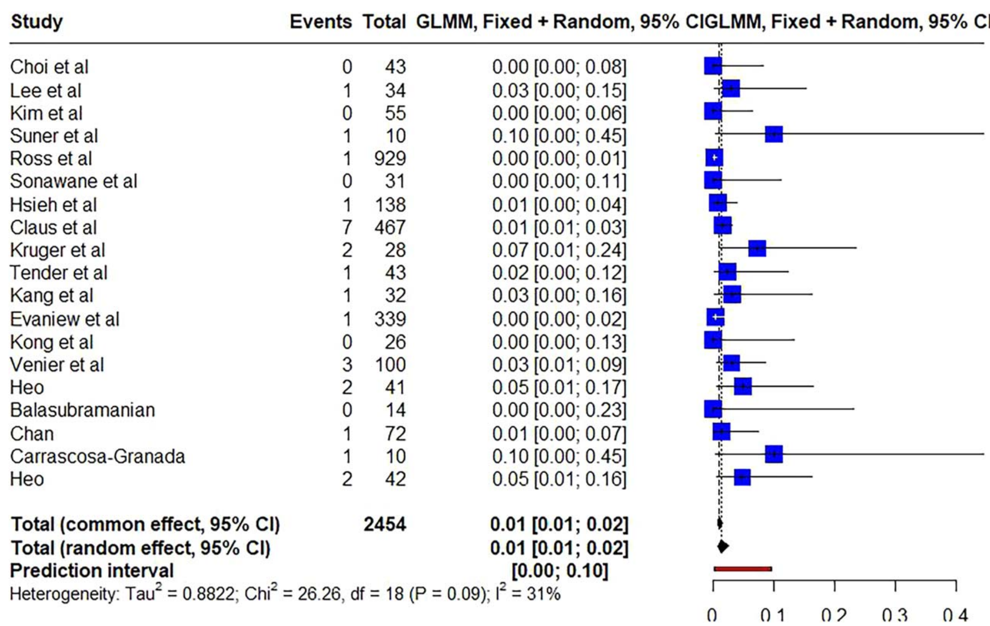

Figure 5. Forest plot for the incidence of postoperative hematomas in lumbar tubular spine surgery.

Our proportional meta-analysis, encompassing 75 studies and 12,950 patients, found a pooled complication rate of 10% from 1192 total complications. Our rate is similar to that reported in other studies. A systematic review evaluating the learning curve for MI-TLIF reported a pooled complication rate of 11.2%.[98] Similarly, a systematic review comparing open and minimally invasive posterior fusion approaches found a total complication rate of 10.9% for MIS fusion.[99] Complication rates for minimally invasive lumbar discectomy vary widely. A review reported total complication rates ranging from 2.4% to 20.8%.[100] A recent single-center study also reported a 10% complication rate for decompression (9.3% minor, 0.7% major).[101] It should be noted that the total complication rate, as our primary outcome, is particularly sensitive to how complications were defined across studies. Some studies included both minor and major complications, whereas others only reported major events. This variability likely contributes to the observed heterogeneity and limits direct comparability across studies.

Our meta-analysis demonstrated substantial heterogeneity ($I^2 = 93\%$), indicating that complication rates are likely influenced by multiple factors, including technical variations between lumbar pathologies and differences in how complications are defined across studies. This level of heterogeneity is generally expected in proportional meta-analyses, as studies often differ in patient populations, surgical techniques, complication reporting standards, and follow-up durations. Furthermore, there are currently no standardized statistical tests specifically designed to assess heterogeneity in proportional meta-analyses, and researchers must rely on judicious interpretation of available methods.[21]

Comparison to Endoscopic Spine Surgery (ESS)

ESS and tubular surgery demonstrate comparable complication rates, with approach-specific differences. However, these comparisons should be interpreted with caution, as the studies reporting on endoscopic surgery and other minimally invasive techniques may differ substantially in patient populations, inclusion criteria, follow-up, and complication definitions. Dural tears are reported more frequently in tubular than ESS, likely due to greater soft tissue and dural manipulation during exposure.[102] However, ESS may have a higher risk of transient neural irritation, given the smaller working space and technical demands of endoscopic instrumentation.[103] Continuous saline irrigation in ESS helps protect neural structures and reduce adhesion-related dural injuries.[104] A randomized controlled trial looking at outcomes of decompression for lumbar spinal stenosis found no significant difference in perioperative and postoperative complication rates between ESS (10%) and tubular surgery (20%) ($P = 0.278$).[32] In addition, a systematic review showed that ESS had a lower risk of surgical site infections, likely due to reduced soft tissue damage, continuous irrigation, and decreased inflammatory response.[105,106] However, ESS has been associated with higher recurrence rates and instability, mainly due to differences in the extent of decompression compared with tubular MI-TLIF.[107] While both techniques are effective, ESS requires a longer learning curve, even for experienced spine surgeons.[108,109]

Dural Tears

Dural tears are a recognized complication of lumbar spine surgery. Our meta-analysis of 6651 patients across 56 studies reports a pooled incidence of 4%. Prospective data from 14 UK institutions indicate that

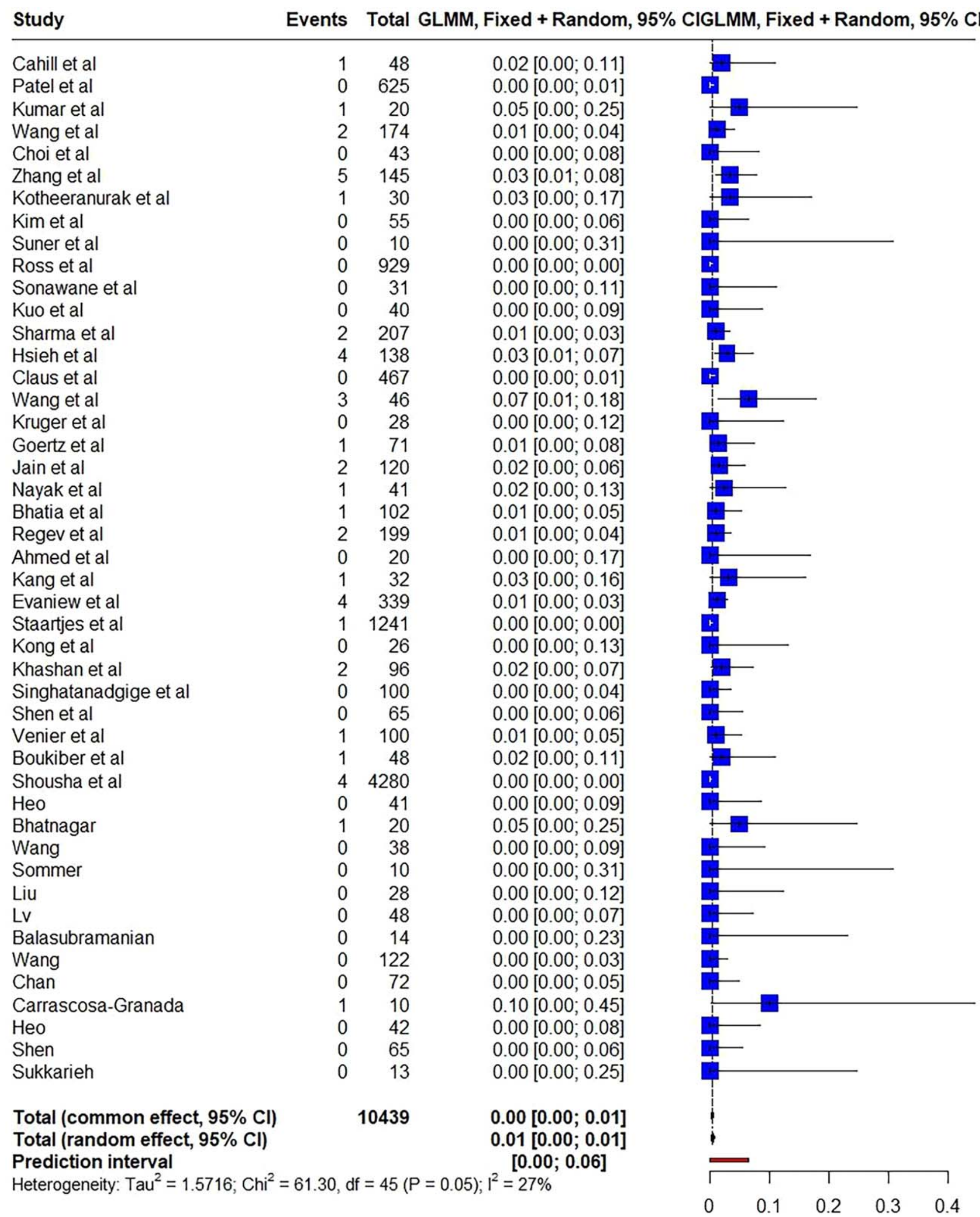

Figure 6. Forest plot for the incidence of surgical site infections in lumbar tubular spine surgery.

dural tear rates vary depending on the type of procedure, with rates of 3.5% for primary discectomy, 8.5% for spinal stenosis surgery, and up to 13.2% for revision discectomy.[110] Studies have shown comparable or lower dural tear rates in tubular MISS compared with open surgeries. A systematic review found rates of 7.2% for tubular MISS *versus* 7.02% for open surgery, while another study demonstrated a significantly lower risk with MISS (6.4%) compared with open surgery (15.9%).[13,111] Dural tears typically occur caudally and contralaterally in tubular procedures when removing thickened ligamentum flavum (LF), often due to dural adhesion to LF.[14] Prevention strategies include careful dissection with a ball-tip instrument before using Kerrison rongeurs, employing 90° Kerrison rongeurs, and testing the bite beforehand to avoid dural entrapment.[14] When dural tears occur, management depends on the size and presence of extruding nerve roots. Small tears can be treated with fibrin glue or DuraSeal, while larger defects may require primary repair with 4-0 Nurolon sutures, supported by muscle grafts or collagen matrices if necessary.[112] Postoperatively, the duration of bed rest can vary. Still, early mobilization within 24–48 hours has shown favorable outcomes, likely due to minimal dead space in MISS procedures, reducing the risk of cerebrospinal fluid (CSF) leaks.[14]

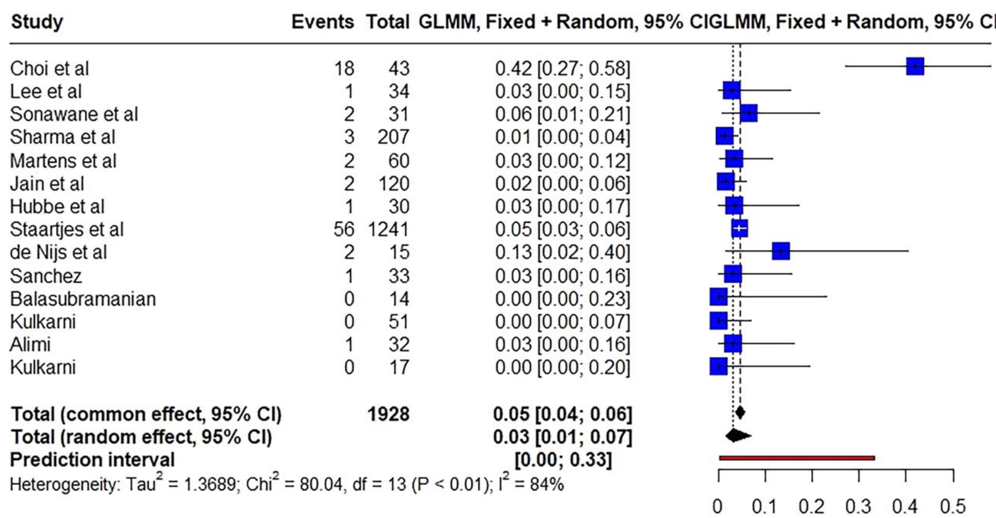

Figure 7. Forest plot for the incidence of disc reherniations in lumbar tubular spine surgery.

Nerve Palsies

Nerve injuries are a known complication of lumbar spine surgery, with our meta-analysis of 5278 patients from 41 studies reporting a pooled incidence of 1%. For lumbar microdiscectomies, a systematic review found a 0.9% incidence for tubular discectomies, significantly lower than the 2.6% rate for open discectomy.[113] For tubular MI-TLIF, a study reported that transient postoperative neuralgia was noted in 2.1% of cases.[114] A systematic review found no significant difference in nerve injury risk between MI-TLIF and open TLIF.[115] Endoscopic procedures report a wider range of incidence (0.1%–4%).[116,117] Limited visualization, neural retraction, anatomic variations, prolonged surgery, and interbody device placement often cause nerve injuries in tubular surgery.[118] Prevention strategies focus on ensuring clear visualization of nerve roots, utilizing navigation, optimizing cage placement, and employing intraoperative neurophysiological monitoring (IONM). When injuries occur, mild cases are managed conservatively with pain control, while hardware-related compression may necessitate revision surgery. Continued advancements in surgical techniques, navigation, and real-time monitoring are expected to further reduce nerve injury rates in minimally invasive lumbar procedures.[119,120]

Postoperative Hematomas

Hematoma formation is a recognized complication of lumbar spine surgery, with our meta-analysis of 2454 patients across 19 studies reporting a pooled incidence of 1%. Literature estimates suggest tubular surgeries have a higher hematoma risk than open surgery (1.94% *vs.* 0.42%).[121] Biportal endoscopic spine surgery (BESS) shows even higher rates, with 8.4% compared with 1.4% in conventional procedures.[122] The increased hematoma risk in minimally invasive procedures arises from continuous irrigation masking intraoperative bleeding, limited surgical visualization, and difficulty controlling bone bleeding.[40,122,123]

Prevention strategies include meticulous intraoperative hemostasis and careful bone bleeding management. Postoperative anticoagulation should be managed cautiously, as it is a significant independent risk factor.[124] If a hematoma occurs, early diagnosis with MRI is critical, and emergent surgical evacuation is required for symptomatic cases with neurological deficits. Small, asymptomatic hematomas may resolve conservatively with careful monitoring, while postoperative pain management and bed rest may be necessary in mild cases.

Surgical Site Infections

Surgical site infections (SSIs) are a known complication of lumbar spine surgery, with our meta-analysis of 10,439 patients across 46 studies reporting a pooled incidence of 1%. A systematic review and meta-analysis showed that MISS significantly reduces SSI risk compared with open surgery, with rates of 1.5% *versus* 3.8%.[125] Furthermore, a large single-center study showed that for lumbar degenerative pathology, SSI for MISS was 0.5% in a meta-analysis and 0.5% *versus* 3.3% in open procedures.[126] In endoscopic spine procedures, the rates have been reported to be even lower. A study by Mahan *et al.*[127] comparing full endoscopic spine surgery (FESS) to nonendoscopic procedures reported rates as low as 0.001% compared with 1.1% in a propensity-matched cohort. Patient factors like diabetes, chronic pulmonary disease, coronary artery disease, and osteoporosis contribute to SSI risk after spine surgery.[128] Prevention includes preoperative optimization, *Methicillin-Resistant Staphylococcus aureus* (MRSA) decolonization, prophylactic antibiotics, vancomycin powder application, and negative pressure wound therapy (NPWT). Management involves antibiotics for superficial infections and surgical debridement for deep infections.

Disc recurrence

Regarding lumbar disc, our meta-analysis of 1928 patients across 14 studies reported a pooled recurrence

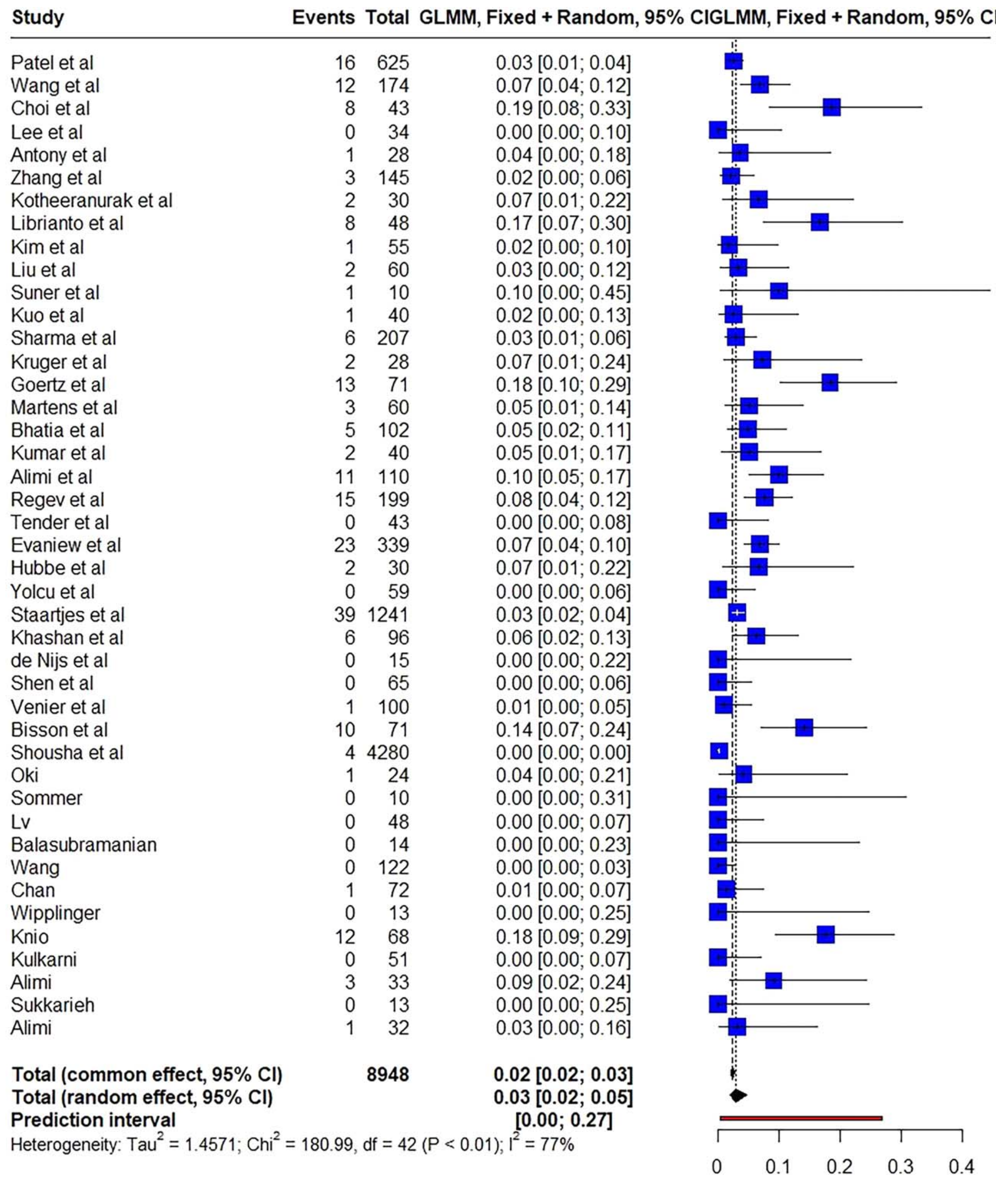

Figure 8. Forest plot for the incidence of surgical revisions in lumbar tubular spine surgery.

rate of 3%, which is notably lower than rates reported in other studies. A single-center study on single-level lumbar discectomy found a 9.5% recurrence rate,[129] while a meta-analysis on percutaneous endoscopic lumbar discectomy (PELD) reported a pooled rate of 3.6%.[130] However, compared with open microdiscectomy, a randomized controlled trial found no significant difference in long-term outcomes between tubular and open microdiscectomy, with reoperation rates of 18% *versus* 13%.[131] Risk factors for reherniation include young age, male sex, smoking, large annular defects, and residual disc fragments.[129,132–134] Prevention focuses on careful patient selection, optimal disc removal techniques, and postoperative activity modification.[129] Reoperation is often necessary when recurrence occurs, with tubular microdiscectomy and microendoscopic discectomy being effective revision strategies.[129] As surgical techniques evolve, further reductions in recurrence risk may be achieved while preserving the benefits of minimally invasive approaches.

Surgical Revisions

The pooled rate of surgical revisions following lumbar tubular surgeries was 2%. Literature data suggest lower revision rates in MISS compared with open surgery, with MIS fusion showing a 4.1% revision rate *versus* 5.6% for open fusion ($P = 0.032$) and minimally invasive decompression (MIL) demonstrating a 5.8% revision rate *versus* 16.3% in open laminectomy (OL).[135,136] Secondary fusion rates were also significantly lower in MISS (3.3%)

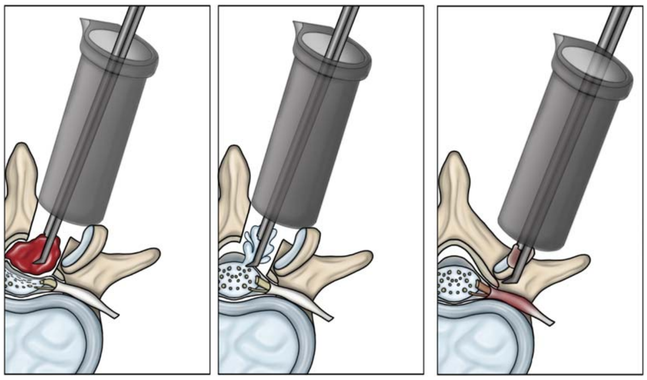

Figure 9. Illustration depicting potential hematoma, dural tear and CSF leak, and nerve injury during tubular minimally invasive lumbar spine surgery.

compared with OL (12.8%), likely due to reduced instability progression (0% *vs.* 72%). Revision surgery in tubular approaches often results from residual stenosis, recurrent disc herniation, or progressive instability, emphasizing the need for careful patient selection and thorough decompression. Preventative strategies include assessing preoperative instability risk, optimizing decompression techniques, and monitoring for spondylolisthesis progression. When revision is required, secondary fusion and re-decompression are common approaches, with MISS techniques offering reduced morbidity compared with open reoperations. As surgical techniques evolve, optimizing decompression while preserving stability remains key to minimizing revision rates.

Limitations

This study has several limitations. First, high heterogeneity ($I^2 = 93\%$) reflects variations in patient populations, techniques, and complication definitions, affecting generalizability despite using a random-effects model. Second, most studies were retrospective with variable quality, introducing potential bias. Third, inconsistent complication reporting in minimally invasive spine surgery may have influenced pooled estimates. Fourth, short follow-up in many studies limits insights into long-term outcomes. Fifth, surgeon experience impacts results due to the steep learning curve of tubular MISS. However, restricting the analysis to the last decade likely includes more experienced surgeons, reducing this concern. Sixth, although the breadth of included studies provided large sample sizes and broad estimates, most complication data were reported in aggregate across diverse lumbar pathologies and without stratification by key patient characteristics such as age, pathology, or comorbidity. As a result, the findings should be interpreted as overall estimates rather than pathology-specific or patient-specific rates. Future studies should prioritize standardized complication reporting stratified by clinically relevant subgroups to improve clinical applicability. Seventh, the certainty of evidence for all pooled estimates was rated very low using the GRADE framework (Supplemental Digital Content 9, http://links.lww.com/BRS/C892).[137] This reflects the retrospective nature of most included studies, high heterogeneity, lack of standardized complication definitions, and imprecision for outcomes with rare events. These limitations restrict the strength of inferences that can be drawn and emphasize the need for prospective studies with standardized, subgroup-stratified complication reporting. Despite these limitations, this study provides a detailed assessment of complication rates and underscores the need for standardized reporting and further research

CONCLUSION

This meta-analysis comprehensively evaluates complication rates in lumbar tubular MISS, revealing generally low rates but significant variability across studies. While dural tears and nerve injuries remain concerns, the overall safety profile supports the continued use of this approach. However, high heterogeneity and inconsistent complication reporting highlight the need for standardized data collection. Future research should focus on long-term outcomes and refine techniques to reduce complications. Despite its limitations, this study offers valuable insights for patient counseling and surgical decision-making, emphasizing the importance of experience and technique optimization in minimizing risks associated with tubular MISS.

➢ Key Points

- ❑ Tubular MISS demonstrates acceptable complication rates: the pooled complication rate for tubular lumbar MISS was 10%, with dural tears (4%) and nerve injuries (1%) being most frequent.
- ❑ Rates comparable to other MISS techniques: complication rates were similar to those reported in uniportal and biportal endoscopic approaches, supporting the safety of tubular techniques.
- ❑ High heterogeneity reflects practice variation: differences in patient populations, surgical technique, and reporting standards contributed to substantial heterogeneity, limiting direct comparisons.
- ❑ Need for standardized reporting and long-term data: findings highlight the importance of consistent complication definitions and multicenter studies to better assess long-term outcomes and refine risk stratification.

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