REVIEW ARTICLE

Clinical Evaluation of Surgery for Single-Segment Lumbar Spinal Stenosis: A Systematic Review and Bayesian Network Meta-Analysis

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To compare the efficacy and safety of different surgical procedures for patients with single-segment lumbar spinal stenosis (LSS), Bayesian network meta-analysis (NMA) was conducted in this study. Randomized controlled trials (RCTs) which reported 2 years' results after surgery were searched from PubMed, Embase, and Cochrane Register of Controlled Trials up to February 2021. Eligible RCTs that contained at least two of the following surgical procedures, bilateral decompression *via* the unilateral approach (BDUL), decompression with conventional laminectomy (CL), decompression with fusion (DF), endoscopic decompression (ED), interspinous process devices only (IPDs), decompression with interlaminar stabilization (DILS), decompression with lumbar spinal process-splitting laminectomy (LSPSL), and minimally invasive tubular decompression (MTD), would be included after screening based on the inclusion and exclusion criteria. The primary outcome was Oswestry Disability Index (ODI). Twenty eligible RCTs were included, with a total of 2201 patients enrolled. The NMA showed that the following surgical procedures ranked first (surface under the cumulative ranking) when compared with CL and DF: DILS for ODI (SUCRA 87.8%); LSPSL for back pain (95%); and MTD for leg pain (95.6%). MTD ranked among the top three surgical procedures for most outcomes. The quality of the synthesized evidence was low according to the Grading of Recommendations Assessment, Development, and Evaluation criteria. DILS, LSPSL, MTD, IPDs, and ED are the most effective procedures for patients with single-segment LSS. Because of combining efficacy and safety, MTD may be the most promising routine surgical option for treating single-segment LSS.

Key words: bayesian network meta-analysis; lumbar spinal stenosis; randomized controlled trials; surgical procedures

Introduction

Lumbar spinal stenosis (LSS) is caused by the changes of the disc, ligamentum flavum, and facet joints, in which the space of the lumbar spinal canal is narrowed.[1] Neurogenic claudication, pain in the back and legs, and limb weakness may occur after changes in the lumbar spinal canal.[2,3] A study on LSS in the Framingham Cohort showed that the LSS prevalence rate was 47.2% in people between the ages of 60 and 90 years.[4] LSS is the main cause of spinal surgery in people over the age of 65 years.[5] In America, more than 30,000 patients with LSS underwent surgery, and the total hospital spending amounted to $1.65 billion.[6] For patients with radiological evidence of LSS and corresponding clinical symptoms (including lumbago, leg pain, and neurogenic claudication), surgical treatment is recommended to improve symptoms for those in whom non-surgical treatment (including physical therapy, drug therapy, among others) for 6 months has failed.[7]

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Currently, decompression with conventional laminectomy (CL) and decompression with fusion (DF) remain the most commonly used surgical methods for the treatment of LSS in clinical practice.[8] In 2016, Ghogawala *et al.*[9] and Forsth *et al.*[10] reported findings from prospective randomized controlled trials (RCTs) of therapeutic differences between CL and DF. Ghogawala *et al.*[9] observed that patients who underwent DF performed better in the postoperative SF-36 physical-component summary score and reoperation than those who underwent CL. However, there was no significant difference in the clinical results between DF and CL in the study by Forsth *et al.*[10] The best choice of surgical procedure for LSS remains under debate in the literature. With the development of minimally invasive spine surgery, less invasive surgical procedures have been proposed in recent years, such as bilateral decompression *via* the unilateral approach (BDUL), interspinous process devices only (IPDs), decompression with interlaminar stabilization (DILS), endoscopic decompression (ED), minimally invasive tubular decompression (MTD), and decompression with lumbar spinal process-splitting laminectomy (LSPSL), among others.[11–17] Several RCTs[9–16,18–30] and pairwise meta-analyses[8,31–37] were conducted to compare the LSS surgical procedures, although no procedures were significantly superior. Therefore, the surgical procedures for LSS that are chosen by the surgeon vary.[38] A previous pairwise meta-analysis was only able to make partial comparisons and analysis of LSS surgical procedures. One limitation of this method was that the researchers were unable to determine the extent to which each component of the included intervention influenced the overall treatment outcomes. This limitation was overcome by network meta-analysis (NMA). The NMA is conducted by synthesizing data from direct and indirect comparisons among various studies to construct an analytical network and compare the merits and shortcomings of multiple interventions.[39]

We sought to evaluate and rank the effectiveness and safety of different LSS surgical procedures through systematic review and NMA and provide a reference for the selection of LSS treatment.

Methods

The study strictly followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses for Network Meta-Analyses (PRISMA-NMA)[40] for NMA. A Bayesian NMA was performed in this study. The study protocol was registered in the Prospective Register of Systematic Reviews (PROSPERO CRD42020154945). Based on the retrieval of online electronic databases, RCTs were collected and analyzed using NMA. Therefore, this study did not require ethical approval.

Patient and Public Involvement

This study did not directly involve patients or the public.

Search Strategy

We retrieved relevant articles from the PubMed, Embase, and Cochrane Central Register of Controlled Trials databases from inception to February 2021 without language limitation. The search strategy was composed of keywords and MeSH terms, including "spinal stenosis," "spinal disease," "lumbar spinal stenosis," "canal stenosis," "neurogenic claudication," "laminotomy," "unilateral laminectomy," "decompression," "decompression with fusion," "minimally invasive," "endoscopic," and "randomised controlled trial" (Table S1). The reference lists of the previously published pairwise meta-analyses were also checked for relevant articles.

According to the search strategy, two investigators (ZL and XX) searched the online electronic databases and verified the retrieved results independently to ensure that the results were detailed and exact. Any discrepancy in the retrieved results was resolved after an additional search of the databases based on the strategy and reassessment. If consensus could not be reached, a third investigator (CC) would adjudicate the discrepant result.

Inclusion and Exclusion Criteria

Studies that met the following criteria were included: (i) patients with LSS who had indications for surgery; (ii) the presence of at least two of the following interventions: BDUL, CL, DF, ED, IPDs, DILS, LSPSL, and MTD; (iii) at least one of the following outcome measures of interest: the Oswestry Disability Index (ODI), and visual analog scale (VAS), 36-Item Short Form Survey (SF-36), operation time, duration of hospital stay, reoperation, complications, and blood loss; and (iv) RCTs.

Studies that did not meet the inclusion criteria were excluded. Other exclusion criteria were as follows: (i) patients with multi-segment LSS; (ii) grade II degenerative spondylolisthesis and LSS (according to the Meyerding Grading System for classifying spondylolisthesis[41]); (iii) patients with LSS with spinal instability (preoperative hyperextension and hyperflexion radiograph showed that the angle between the upper and lower endplates was greater than 10° or the migration distance between vertebral bodies was greater than 3 mm[9]); (iv) reoperation or secondary surgery; and (v) the follow-up time was less than 24 months.

Data Extraction

Author information, year of publication, RCT study design (both arms or more), number of patients, baseline characteristics of the patients (age, sex), interventions, and outcomes of the included RCTs were extracted into a spreadsheet. The primary outcome was ODI, which was used to evaluate the postoperative function status of the patients.[42] A lower ODI score was considered superior. The secondary outcomes were VAS,[43] SF-36,[44] operation time, duration of hospital stay, blood loss, complications, and requirement for reoperation.

Data collection was performed independently by two investigators (ZL and XX). Any disagreement was dealt with by consulting. In instances in which the data were not clear or were incomplete, the authors were directly contacted to acquire the missing data.

Assessment of Risk of Bias and Quality of Evidence

The risk of bias for the included studies was assessed using the Cochrane Risk of Bias Tool.[45] The 13 domains of bias included random sequence generation, allocation concealment, blinding of participants, blinding of personnel and care providers, blinding of outcome assessment, incomplete outcome data, intention-to-treat analysis, selective reporting, group similarity at baseline, co-interventions, compliance, timing of outcome assessment, and other biases. Bias in each domain was classified as low, high, or unclear (if the study did not report the relevant information) risk. Usually, surgeons familiarize themselves with the patient's condition in advance and then select the requisite surgical procedure. Therefore, blinding of personnel and care providers was regarded as a high-risk domain. If six domains or more in a study were assessed as low risk, the overall migration risk in the study was low. The Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach[46,47] was used to evaluate the quality level of this NMA. The results of direct comparison, indirect comparison, and NMA were evaluated for evidence quality, which was classified into high, medium, low, and very low levels, respectively.

Data Synthesis and Statistical Analyses

The safety and efficacy of the different surgical procedures were compared using an NMA that analyzed all direct and indirect results. R-software (GeMTC, version 4.0.2), based on a Bayesian framework using a Markov Chain Monte Carlo approach, was used to analyze the outcomes. A fixed-effects consistency model was used. Noninformative uniform and normal prior distributions[48] and three different sets of initial values to fit the model were applied. Dichotomous variables were analyzed using the odds ratio (OR), and continuous variables were analyzed using the mean difference (MD). Fifty thousand iterations were generated with 20,000 burn-ins and a thinning interval of 1 for continuous variables. A total of 100,000 sample iterations were generated with 50,000 burn-ins and a thinning interval of 1 for dichotomous variables. The Brooks–Gelman–Rubin method was used to assess the convergence.[49]

Under the analysis of NMA based on the Bayesian framework, the surface under the cumulative ranking (SUCRA) was calculated to classify the overall ranking of surgical procedures. A surgical procedure is predicted to be the best when SUCRA equals 1 and is predicted to be the worst when SUCRA equals 0.[50]

Transitivity and consistency are two key assumptions of NMA.[51] Transitivity was evaluated using descriptive statistics for study and population baselines, such as age and sex.[52] Meta-regression was conducted to test the outcomes (ODI, VAS) to explore heterogeneity source and transitivity. The following methods were used for consistency assessment[53]: (i) comparing deviance information criteria (DIC) between the consistency model and inconsistency model; the similarity or smaller value of DIC in the consistent model compared with that in the inconsistent model indicated superior consistency[54]; (ii) direct and indirect results were compared by node splitting. If there was no significant difference between the direct and indirect results ($P > 0.05$), the inconsistencies were considered to be low; (iii) the results of the pairwise meta-analysis and NMA were compared to observe the consistency of the direct and indirect comparisons. Sensitivity analysis was conducted by comparing the differences in DIC generated under the random-effects model and the fixed-effects model. Instances in which the results were similar indicated that the NMA results were relatively robust. If the results showed considerable differences, the random-effects model was used instead of the fixed-effects model.

Direct comparisons between different surgical procedures were performed using traditional pairwise meta-analysis. Dichotomous variables were analyzed using the OR, and continuous variables were analyzed using the MD and 95% confidence intervals (CIs). I square (I^2) was used to test the heterogeneity of the statistical results. Instances in which the I^2 value was greater than 50% indicated greater heterogeneity among the data, and the random-effects model was used. Each result is represented as a forest map. Sensitivity analyses were performed to assess the robustness of the results by comparing fixed- or random-effects models. Paired meta-meta-analysis was performed using Review Manager (version 5.3).

Results

Systematic Review and Characteristics

A total of 141 studies were identified from the initial title and abstract screening. After removing duplicates, 20 eligible RCTs[9,10,12–16,18–30] were included (Figure 1), with a total of 2201 patients enrolled who received eight surgical procedures including BDUL, CL, DF, ED, IPDs, DILS, LSPSL, and MTD. Unknown decompression (UD)[18–20,22,24] was noted when the procedure was uncertain or involved multiple options (BDUL, CL, and so forth). The follow-up time of the primary outcome (ODI) was 24 months. The follow-up times for the secondary outcomes ranged from intraoperation to 24 months for some outcomes that could be observed in the short term during and after surgery. The main characteristics of all studies are reported in Table 1. The network plot is shown in Figure 2. According to the Cochrane Risk of Bias Tool, 85% of the studies showed a low risk of overall bias. Figure 3 shows the detailed risk of bias assessments. The GRADE analysis indicated that the quality of evidence was relatively low for all outcomes (Table S4).

Network Meta-Analysis in Surgical Interventions for LSS

Primary Outcomes

ODI was the primary outcome of this study, which was used to assess the body function of the patients. There were seven

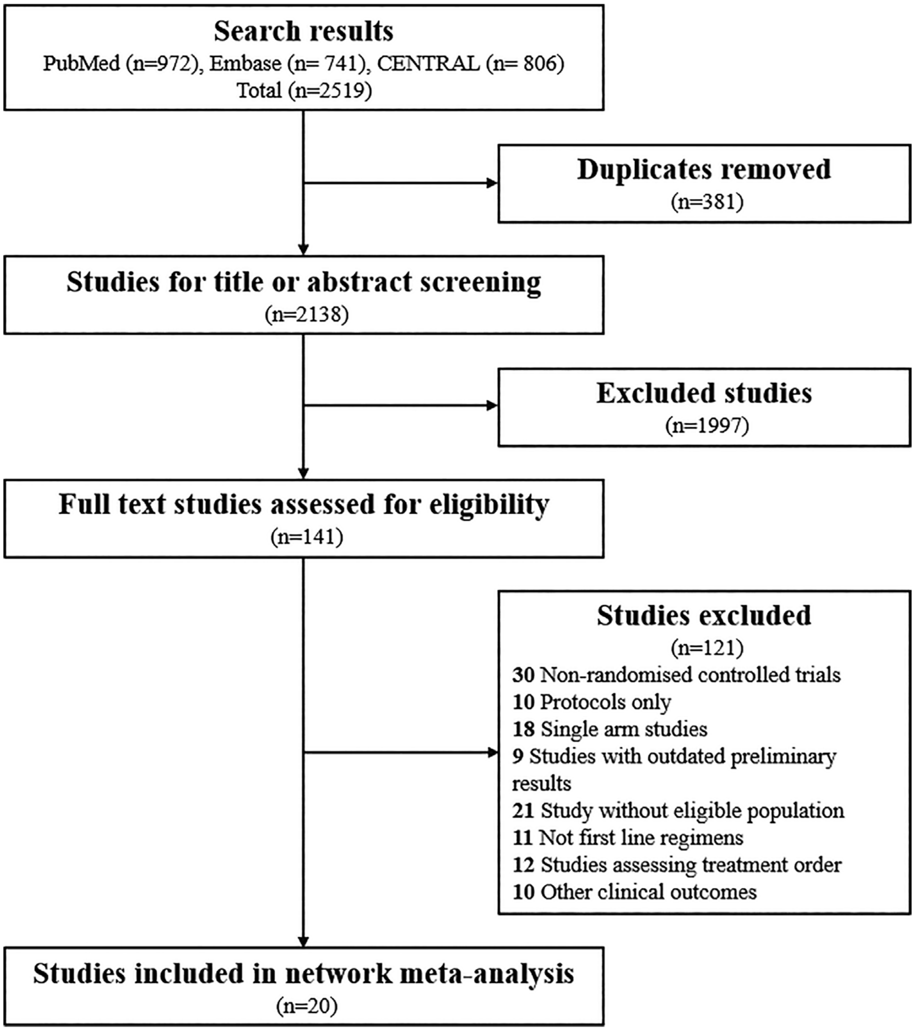

Fig. 1 Study selection.

studies[9,10,12,14,18,20,21] that used ODI as the outcome measure, with seven surgical procedures and 792 patients. In these seven studies, the DILS procedure was significantly superior than BDUL (MD −9.86, CI −17.26 to −2.46), CL (−9.33, −15.50 to −3.16), IPDs (−17.70, −22.59 to −12.78), and UD (−21.81, −26.57 to −17.03). Statistical significance was not observed for the comparison between DILS with MTD (−1.48, −12.98 to 10.08) and BDUL with DF (−4.68, −10.02 to 0.68) (Table 2).

Secondary Outcomes

VAS back pain scores were used as outcome measures in six RCTs[10,14,16,19,22,30] with seven surgical procedures performed in 810 patients. VAS leg pain scores were used as outcome measures in six RCTs[10,14,16,19,21,30] with seven surgical procedures performed in 764 patients. Regarding VAS back pain scores, LSPSL showed significant benefits over CL (−16.00, −19.19 to −12.82), IPDs (−24.00, −38.50 to −9.63), and UD (−24.34, −39.93 to −8.84), while no significant differences were observed in comparison with DILS (−8.64, −23.49 to 6.21) and DF (−12.03, −24.91 to 0.81). With respect to the VAS leg pain scores, MTD was significantly superior to CL (−16.96, −27.94 to −6.06), DF (−17.95, −34.76 to −1.22), LSPSL (−12.97, −24.03 to −1.95), and UD (−16.86, −33.01 to −0.75). There was no significant difference between MTD and DILS (−14.45, −32.95 to 4.00) or IPDs (−11.98, −26.05 to 2.13) (Tables 3 and 4).

Regarding blood loss, a total of 12 RCTs[9,10,14,16,18,19,23–28] were included, involving eight surgical procedures and 1333 patients. Those who underwent DF had significantly more blood loss than that for any of the other surgical procedures including BDUL (296.6, 152.8 to 464.33), CL (319.95, 194.05 to 482.95), DILS (251.74, 85.73 to 418.4), ED (499.08, 279.82 to 765.67), IPDs (421.35, 161.29 to 681.13), LSPSL (321.83, 159.3 to 526.88), and UD (238.37, 72.15 to 408.59) (Table S5).

Considering operation time, 18 RCTs[9,10,12,14–16,18–20,22–30] were included involving all surgical procedures performed in 1849 patients. The operation time of IPDs was significantly

TABLE 1 Baseline characteristics of studies included in the network meta-analysis of patients with lumbar spinal stenosis

Study ID	Study design	Surgical procedures	Sample size	Gender(M/F)	Age(y)[a]	Follow-up (months)	Outcomes
Davis2013	RCT	DILS	215	–[b]	62.1 (9.2)	24	ODI, VAS, ZCQ, operative time, blood loss, duration of hospital stay
		DF	107	–	64.1 (9.0)	24	
Försth2016	RCT	CL	120	27/85	67 (7)	24	ODI, VAS, ZCQ, operative time, blood loss, reoperation, duration of hospital stay, complications
		DF	113	50/70	68 (7)	24	
Ghogawala2016	RCT	CL	35	8/27	66.5 (8.0)	24	ODI, ZCQ, SF-36, operative time, blood loss, reoperation, duration of hospital stay, complications
		DF	31	5/26	66.7 (7.2)	24	
Hamawandi2019	RCT	BDUL	50	16/34	56.60 (7.79)	12	ODI, VAS, operative time, blood loss
		DF	50	19/31	55.20 (8.28)	12	
Hu2019	RCT	CL	60	29/31	66.90 (3.61)	12	VAS, JOA, operative time, blood loss, duration of hospital stay, complications
		ED	60	25/35	65.01 (4.23)	12	
Inose2018	RCT	UD	29	17/12	63.4 (8.6)	12	VAS, JOA, operative time, blood loss, duration of hospital stay, complications, reoperation
		DF	31	11/20	61.2 (6.7)	12	
Kang2019	RCT	ED	32	18/14	65.1 (8.6)	6	operative time, blood loss, duration of hospital stay, complications, reoperation
		MTD	30	14/16	67.2 (8.5)	6	
Ko2019	RCT	BDUL	25	8/17	68.08 (10.716)	24	ODI, SF-36, operative time, blood loss, duration of hospital stay
		CL	25	10/15	66.24 (8.110)	24	
komp2015	RCT	BDUL	71	–	–	24	operative time, blood loss, reoperation, complications
		ED	64	–	–	24	
Liu2013	RCT	CL	29	18/11	61.1 (3.1)	24	VAS, JOA, operative time, blood loss, reoperation, complications
		LSPSL	27	15/12	59.4 (4.7)	24	
Lønne2015	RCT	DILS	40	17/23	67 (8.8)	24	ODI, ZCQ, operative time, blood loss, reoperation, complications, duration of hospital stay
		UD	41	23/18	67 (8.7)	24	
Meyer2018	RCT	UD	81	–	65	24	VAS, SF-36, ZCQ, operative time, blood loss, reoperation, complications
		IPDs	82	–	65	24	
Mobbs2014	RCT	CL	40	20/20	65.8 (14.3)	24	ODI, VAS, blood loss, reoperation, duration of hospital stay, complications
		MTD	39	6/33	72.7(10.4)	24	
Moojen2015	RCT	CL	79	42/37	64	24	ZCQ, VAS, operative time, blood loss, duration of hospital stay, reoperation, complications
		IPDs	80	31/49	66	24	
Park2019	RCT	BDUL	32	18/14	67.1	0.5	operative time, duration of hospital stay, reoperation, complications
		ED	32	13/19	66.2	0.5	
Rajasekaran2013	RCT	CL	23	14/9	54.48(8.21)	12	operative time, blood loss, duration of hospital stay
		LSPSL	28	16/12	57.25(11.23)	12	
Schmidt2018	RCT	UD	115	57/57	68(8.6)	24	ODI, operative time, blood loss, reoperation
		DILS	110	47/63	68(8.8)	24	
Strömqvist2013	RCT	UD	50	26/24	71	12	VAS, ZCQ, operative time, blood loss, reoperation, complications
		IPDs	50	30/20	67	12	
Watanabe2011	RCT	CL	16	8/8	71 (8)	12	JOA, operative time, blood loss
		LSPSL	18	10/8	69 (10)	12	
Yagi2009	RCT	ED	20	8/12	73.3 (range63–79)	12	VAS, JOA, operative time, blood loss, hospital day,
		CL	21	6/21	70.8 (range 66–73)	12	

[a] Age is indicated by mean (standard deviation) or just mean if no standard deviation.; [b] "- "means no relevant data from original articles.; Abbreviations: BDUL, bilateral decompression *via* the unilateral approach; CL, decompression with conventional laminectomy; DF, decompression with fusion; DILS, decompression with interlaminar stabilization; ED, endoscopic decompression; IPDs, interspinous process devices only; LSPSL, decompression with lumbar spinal process-splitting laminectomy; MTD, minimally invasive tubular decompression; UD, unknown decompression; ODI, the Oswestry Disability Index; VAS, visual analog scale.

shorter than that for BDUL (−49.51, −69.46 to −8.47), CL (−18.88, −23.47 to −12.79), DF (−106.93, −131.43 to −70.49), DILS (−38.86, −55.26 to −16.94), LSPSL (−24.73, −33.22 to −15.71), MTD (−20.46, −29.30 to −12.88), and UD (−36.00, −36.04 to −35.96). Compared with ED (−2.25, −9.65 to 3.00), BDUL was not significantly superior. On the other hand, the DF procedure had a significantly longer operative time than that for any other surgical procedure (Table S6).

Regarding the duration of hospital stay, a total of 13 RCTs[9,10,12,14,15,20,21,23,24,26,28–30] were included, and all surgical procedures were performed in 1344 patients. Significant differences were observed when ED was compared with BDUL (−0.8, −1.33 to −0.25), CL (−3.72, −4.19 to −3.25), DF (−5.50, −6.13 to −4.87), DILS (−4.21, −4.93 to −3.49), IPDs (−3.60, −4.19 to −3.02), LSPSL (−3.82, −4.55 to −3.08), MTD (−2.28, −2.57 to −1.98), and UD (−4.22, −5.27 to −3.17) (Table S7).

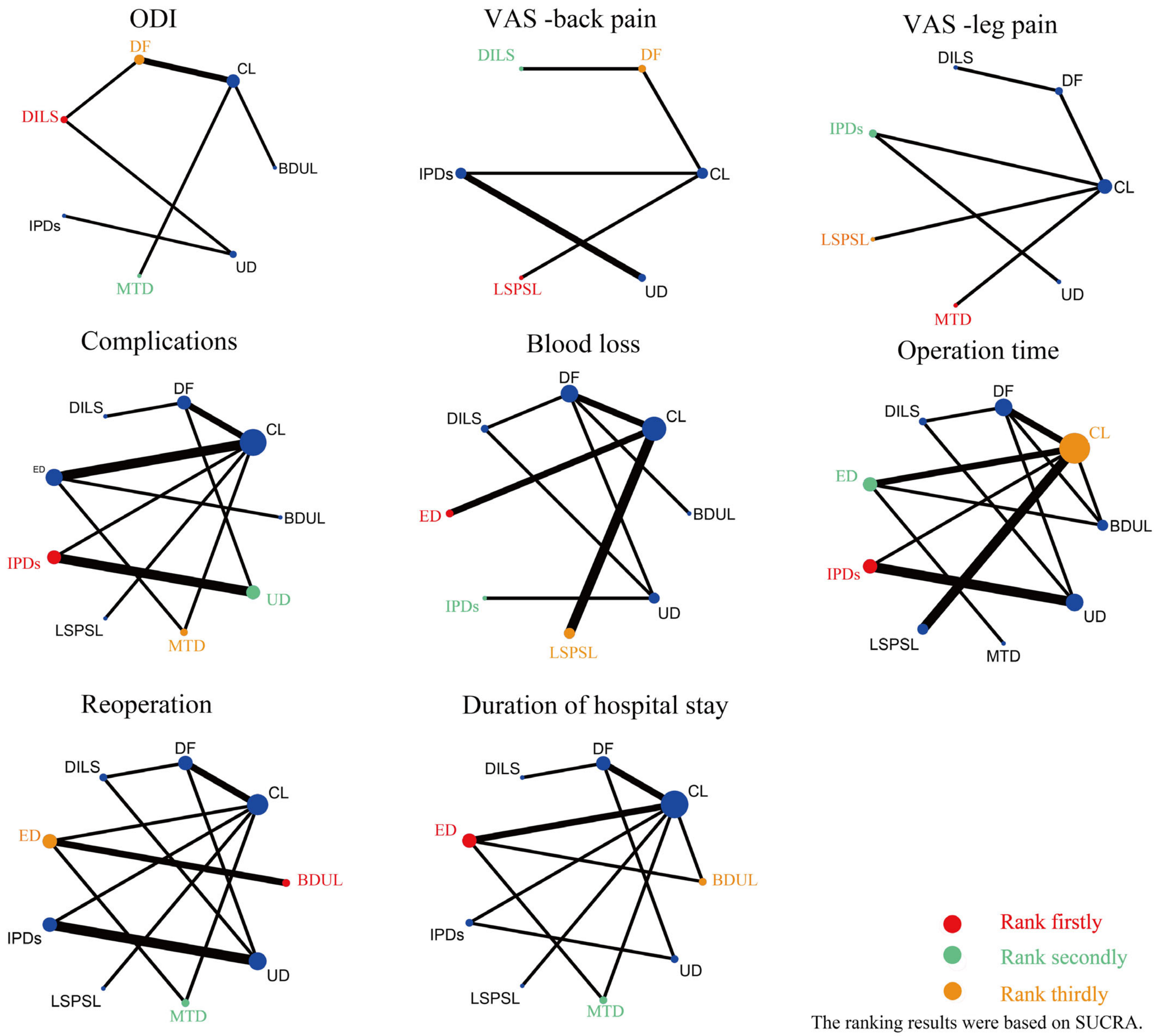

Fig. 2 The network plot of all outcomes. Network meta-analysis maps of studies examining the efficacy of surgical procedures in patients with lumbar spinal stenosis on Oswestry Disability Index (ODI), visual analog scale (VAS) back or leg pain, complications, blood loss, operation time, reoperation and duration of hospital stay. The size of the nodes relates to the number of participants in that surgical procedure type and the thickness of lines between surgical procedures relates to the number of studies for that comparison.

Considering the complications of the surgical procedure, a total of 15 RCTs[9,10,13–16,19–24,26,29,30] were included, which included all surgical procedures and 1622 patients. Patients who underwent UD had a significantly reduced number of complications when compared with BDUL (OR 0.14, CI 0.02 to 0.99), CL (0.23, 0.02 to 0.99), DF (0.16, 0.05 to 0.48), and DILS (0.14, 0.04 to 0.44). Complications associated with IPDs were not significantly greater than those for UD (1.11, 0.38 to 3.31) (Table S8).

Regarding reoperation, a total of 15 RCTs[9,10,13–16,18–22,24,26,29,30] were included, including all surgical procedures, and a total of 1660 patients. Except for the absence of significant differences compared with

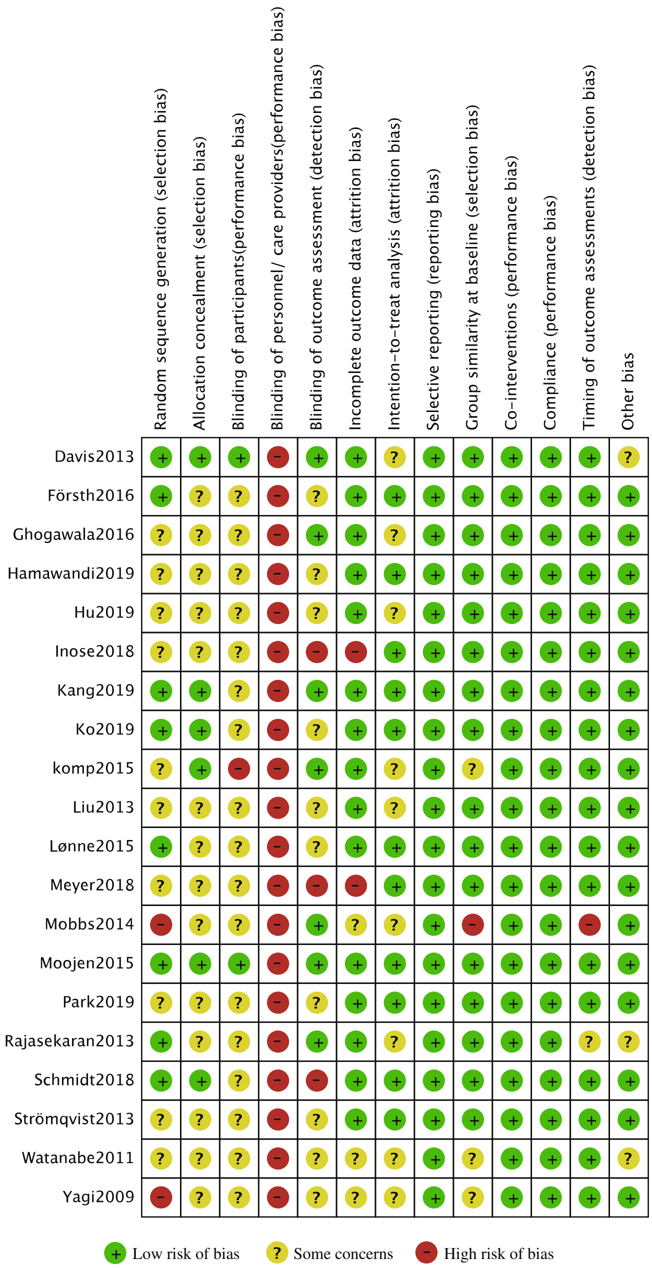

Fig. 3 Risk of bias summary: Reviewers' judgments about each risk of bias item per included study.

LSPSL (1.14, 0.04 to 13.27), the requirement of reoperations was significantly higher for IPDs than for other surgical procedures (Table 5).

Surface under the Cumulative Ranking and Rank Probability

Figure 4 and Table 6 show the SUCRA for the different outcomes. The DILS procedure was most likely to rank first in the ODI score (87.8%). The LSPSL procedure showed the highest rates of back pain relief and ranked highest among

TABLE 2 Pooled estimates of the network meta-analysis for ODI

BDUL	−0.52 (−4.67, 3.62)	−5.18 (−10.32, −0.05)	−9.86 (−17.26, −2.46)	7.85 (−1.03, 16.77)	−8.39 (−18.99, 2.21)	11.96 (3.16, 20.8)
0.52 (−3.62, 4.67)	CL	**−4.65 (−7.65, −1.64)**	**−9.33 (−15.5, −3.16)**	**8.38 (0.49, 16.24)**	−7.86 (−17.6, 1.89)	**12.48 (4.67, 20.24)**
5.18 (0.05, 10.32)	**4.65 (1.64, 7.65)**	DF	−4.68 (−10.02, 0.68)	**13.04 (5.73, 20.25)**	−3.21 (−13.46, 6.99)	**17.14 (9.94, 24.27)**
9.86(2.46, 17.26)	**9.33(3.16, 15.5)**	4.68(−0.68, 10.02)	DILS	**17.7(12.78, 22.59)**	1.48(−10.08, 12.98)	**21.81(17.03, 26.57)**
−7.85 (−16.77, 1.03)	**−8.38 (−16.24, −0.49)**	**−13.04 (−20.25, −5.73)**	**−17.7 (−22.59, −12.78)**	IPDs	**−16.21 (−28.77, −3.69)**	**4.1 (2.96, 5.25)**
8.39 (−2.21, 18.99)	7.86 (−1.89, 17.6)	3.21 (−6.99, 13.46)	−1.48 (−12.98, 10.08)	**16.21 (3.69, 28.77)**	MTD	**20.32 (7.87, 32.82)**
−11.96 (−20.8, −3.16)	**−12.48 (−20.24, −4.67)**	**−17.14 (−24.27, −9.94)**	**−21.81 (−26.57, −17.03)**	**−4.1 (−5.25, −2.96)**	**−20.32 (−32.82, −7.87)**	UD

Data are expressed as MD (95% confidence intervals (CIs)); Abbreviations: BDUL, bilateral decompression *via* the unilateral approach; CL, conventional laminectomy; DF, decompression with fusion; DILS, decompression with interlaminar stabilization; IPDs, interspinous process devices; MTD, minimally invasive tubular decompression; UD, unknown decompression; ODI, the Oswestry Disability Index. The bold values mean the differences between one surgical procedure and another one were significant.

TABLE 3 Pooled estimates of the network meta-analysis for VAS back pain

CL	−3.96 (−16.39, 8.48)	−7.35 (−21.81, 7.14)	8.01 (−6.03, 22.14)	−16 (−19.19, −12.82)	8.34 (−6.8, 23.57)
3.96 (−8.48, 16.39)	DF	−3.39 (−10.8, 3.95)	11.98 (−6.77, 30.71)	−12.03 (−24.91, 0.81)	12.31 (−7.23, 31.91)
7.35 (−7.14, 21.81)	3.39 (−3.95, 10.8)	DILS	15.38 (−4.79, 35.61)	−8.64 (−23.49, 6.21)	15.69 (−5.24, 36.75)
−8.01 (−22.14, 6.03)	−11.98 (−30.71, 6.77)	−15.38 (−35.61, 4.79)	IPDs	**−24 (−38.5, −9.63)**	0.34 (−5.46, 6.12)
16 (12.82, 19.19)	12.03 (−0.81, 24.91)	8.64 (−6.21, 23.49)	**24 (9.63, 38.5)**	LSPSL	**24.34 (8.84, 39.93)**
−8.34 (−23.57, 6.8)	−12.31 (−31.91, 7.23)	−15.69 (−36.75, 5.24)	−0.34 (−6.12, 5.46)	**−24.34 (−39.93, −8.84)**	UD

Data are expressed as MD (95% confidence intervals (CIs)); Abbreviations: CL, decompression with conventional laminectomy; DF, decompression with fusion; DILS, decompression with interlaminar stabilization; ED, endoscopic decompression; IPDs, interspinous process devices only; LSPSL, decompression with lumbar spinal process-splitting laminectomy; MTD, minimally invasive tubular decompression; UD, unknown decompression; VAS, visual analog scale. The bold values mean the differences between one surgical procedure and another one were significant.

the surgical procedures (95%). The MTD procedure was most likely to rank first for leg pain relief (95.6%). The IPDs procedure had the highest probability of having the shortest operating time (99.1%). The blood loss in the ED procedure was the least among all procedures (98.1%). The ED procedure also had the shortest duration of hospital stay (94%). Both IPDs and UD procedures had the lowest incidences of complications (79.2%). Reoperation was least likely to occur when performing BDUL (77%).

Consistency Test and Heterogeneity Analysis

The convergence of outcomes is shown in Figure S1. The DIC of the consistency model was most similar to, or better than, that of the inconsistency model (Table S2). Inconsistency assessed with node-splitting analysis was not significant for reoperation, blood loss, and operation time. Local differences were observed in the duration of hospital stay and complications (Table S3). The direct and indirect results were consistent when the pairwise meta-analysis was compared with NMA (Table S4).

Pairwise meta-analysis was used to assess heterogeneity by calculating the I^2 index. Most comparisons had low heterogeneity for I^2 values less than 50%. However, I^2 values greater than 50% were observed in some comparisons.

Sensitivity Analysis and Transitivity

The results of this study were robust overall except for blood loss and operation time. With regard to blood loss and operation time, the pooled results (DIC) of the fixed- and random-effects model showed considerable differences; thus, the random-effects model was used (Table S2). Transitivity of this study was accepted because significant differences in basic characteristics were not observed in the included RCTs (Figure S2 and Table S9).

Discussion

Principal Findings

In this systematic review and NMA, we comprehensively summarized the comparative efficacy and safety of several surgical procedures for single-segment LSS, including CL, DF, BDUL, IPDs, DILS, ED, MTD, and LSPSL. The results of the NMA were as follows. With respect to improving the ODI score, the DILS procedure was the most promising surgical option; however, DILS also ranked first in the likelihood of complications and had a high reoperation rate. The LSPSL procedure was the best choice for improving low back pain, and the findings suggest that MTD might be the most effective procedure for improving leg pain symptoms. The IPD procedure is a suitable surgical procedure with a shorter operation time and fewer complications. In terms of reducing blood loss and the duration of hospital stay, the ED procedure was better than any other surgical procedure. Patients who underwent the BDUL procedure had the lowest reoperation incidences 2 years after surgery. In view of combining the efficacy (ODI, VAS) and safety (duration of hospital stay, complications, and reoperation) of surgery, this study's findings indicate that the MTD procedure might be the most promising routine surgical option for most patients with LSS.

The advantages of the DILS procedure in improving ODI in 2 years after surgery may lie in the less-invasive nature of implantation of the coflex device after laminectomy. Thus, direct nerve decompression and motor segment stabilization could be achieved.[14,55] CL without fusion might have a risk of postoperative spinal instability.[56] Because of the rigid structure, patients undergoing the DF procedure may experience postoperative problems such as adjacent segmental degeneration, prosthesis, internal fixation devices, incidence of donor graft site, and hardware pain among others.[57,58] The DILS procedure provides a compromise between the rigidity of fusion and the instability of decompression alone. However, the DILS procedure also had the highest association with postoperative complications. This might be due to the fact that the coflex device was located between two adjacent laminae, leading to a risk of spinous process fracture, which is a unique complication associated with spinal surgery involving the DILS or IPDs procedures. Compared with DILS, the IPD was simply inserted between the spinous processes, thus increasing the volume of the vertebral canal and intervertebral foramina. Despite the short operation time and the low rate of

TABLE 4 Pooled estimates of the network meta-analysis for VAS leg pain

CL	0.96 (−11.66, 13.7)	−2.56 (−17.4, 12.3)	−5 (−13.89, 3.92)	−4 (−5.33, −2.66)	−16.96 (−27.94, −6.06)	−0.11 (−11.98, 11.71)
−0.96 (−13.7, 11.66)	DF	−3.51 (−11.22, 4.23)	−5.99 (−21.51, 9.49)	−4.95 (−17.75, 7.73)	**−17.95 (−34.76, −1.22)**	−1.11 (−18.52, 16.29)
2.56 (−12.3, 17.4)	3.51 (−4.23, 11.22)	DILS	−2.48 (−19.82, 14.77)	−1.44 (−16.38, 13.48)	−14.45 (−32.95, 4)	2.4 (−16.6, 21.38)
5 (−3.92, 13.89)	5.99 (−9.49, 21.51)	2.48 (−14.77, 19.82)	IPDs	1.01 (−8, 10.01)	−11.98 (−26.05, 2.13)	4.89 (−2.89, 12.64)
4 (2.66, 5.33)	4.95 (−7.73, 17.75)	1.44 (−13.48, 16.38)	−1.01 (−10.01, 8)	LSPSL	**−12.97 (−24.03, −1.95)**	3.88 (−8.09, 15.75)
16.96 (6.06, 27.94)	17.95 (1.22, 34.76)	14.45 (−4, 32.95)	11.98 (−2.13, 26.05)	12.97 (1.95, 24.03)	MTD	**16.86 (0.75, 33.01)**
0.11 (−11.71, 11.98)	1.11 (−16.29, 18.52)	−2.4 (−21.38, 16.6)	−4.89 (−12.64, 2.89)	−3.88(−15.75, 8.09)	**−16.86(−33.01, −0.75)**	UD

Data are expressed as MD (95% confidence intervals (CIs)); Abbreviations: CL, decompression with conventional laminectomy; DF, decompression with fusion; DILS, decompression with interlaminar stabilization; IPDs, interspinous process devices only; LSPSL, decompression with lumbar spinal process-splitting laminectomy; MTD, minimally invasive tubular decompression; UD, unknown decompression; VAS, visual analog scale. The bold values mean the differences between one surgical procedure and another one were significant.

TABLE 5 Pooled estimates of the network meta-analysis for reoperation

BDUL	4.5 (0.3, 95.7)	4.29 (0.26, 96.16)	6.42 (0.37, 151.61)	1.51 (0.31, 8.25)	24.24 (1.42, 571.66)	22.82 (0.59, 1967.56)	1.28 (0.06, 25.55)	12.91 (0.75, 306.05)
0.22 (0.01, 3.37)	CL	0.95 (0.51, 1.77)	1.41 (0.61, 3.34)	0.34 (0.03, 3.04)	**5.33 (2.48, 12.24)**	4.67 (0.47, 140.11)	0.29 (0.02, 2.11)	**2.84 (1.23, 6.75)**
0.23 (0.01, 3.81)	1.05 (0.56, 1.97)	DF	1.48 (0.73, 3.16)	0.36 (0.02, 3.48)	**5.63 (2.46, 13.46)**	4.94 (0.45, 154.61)	0.31 (0.02, 2.43)	**2.99 (1.35, 6.92)**
0.16 (0.01, 2.71)	0.71 (0.3, 1.63)	0.67 (0.32, 1.36)	DILS	0.24 (0.02, 2.51)	**3.78 (1.73, 8.39)**	3.31 (0.28, 106.69)	0.2 (0.01, 1.76)	**2.01 (1.12, 3.65)**
0.66 (0.12, 3.24)	2.91 (0.33, 39.49)	2.78 (0.29, 40.17)	4.17 (0.4, 63.97)	ED	**15.72(1.53, 240.06)**	14.77 (0.56, 951.59)	0.85 (0.07, 10.15)	8.35 (0.79, 128.44)
0.04 (0, 0.71)	**0.19 (0.08, 0.4)**	**0.18 (0.07, 0.41)**	**0.26 (0.12, 0.58)**	**0.06 (0, 0.66)**	IPDs	0.88 (0.08, 28.18)	**0.05 (0, 0.46)**	0.53 (0.28, 0.98)
0.04 (0, 1.71)	0.21 (0.01, 2.14)	0.2 (0.01, 2.21)	0.3 (0.01, 3.52)	0.07 (0, 1.78)	1.14 (0.04, 13.27)	LSPSL	0.06 (0, 1.33)	0.61 (0.02, 7.12)
0.78 (0.04, 15.73)	3.43 (0.47, 41.44)	3.27 (0.41, 42.45)	4.9 (0.57, 67.12)	1.18 (0.1, 15.28)	**18.61 (2.19, 251.47)**	17.49 (0.75, 1039.98)	MTD	**9.86 (1.13, 135.22)**
0.08 (0, 1.34)	**0.35 (0.15, 0.81)**	**0.33 (0.14, 0.74)**	**0.5 (0.27, 0.89)**	0.12 (0.01, 1.26)	**1.88 (1.02, 3.54)**	1.65 (0.14, 53.57)	**0.1 (0.01, 0.88)**	UD

Data are expressed as OR (95% confidence intervals (CIs)); Abbreviations: BDUL, bilateral decompression *via* the unilateral approach; CL, decompression with conventional laminectomy; DF, decompression with fusion; DILS, decompression with interlaminar stabilization; ED, endoscopic decompression; IPDs, interspinous process devices only; LSPSL, decompression with lumbar spinal process-splitting laminectomy; MTD, minimally invasive tubular decompression; UD, unknown decompression. The bold values mean the differences between one surgical procedure and another one were significant.

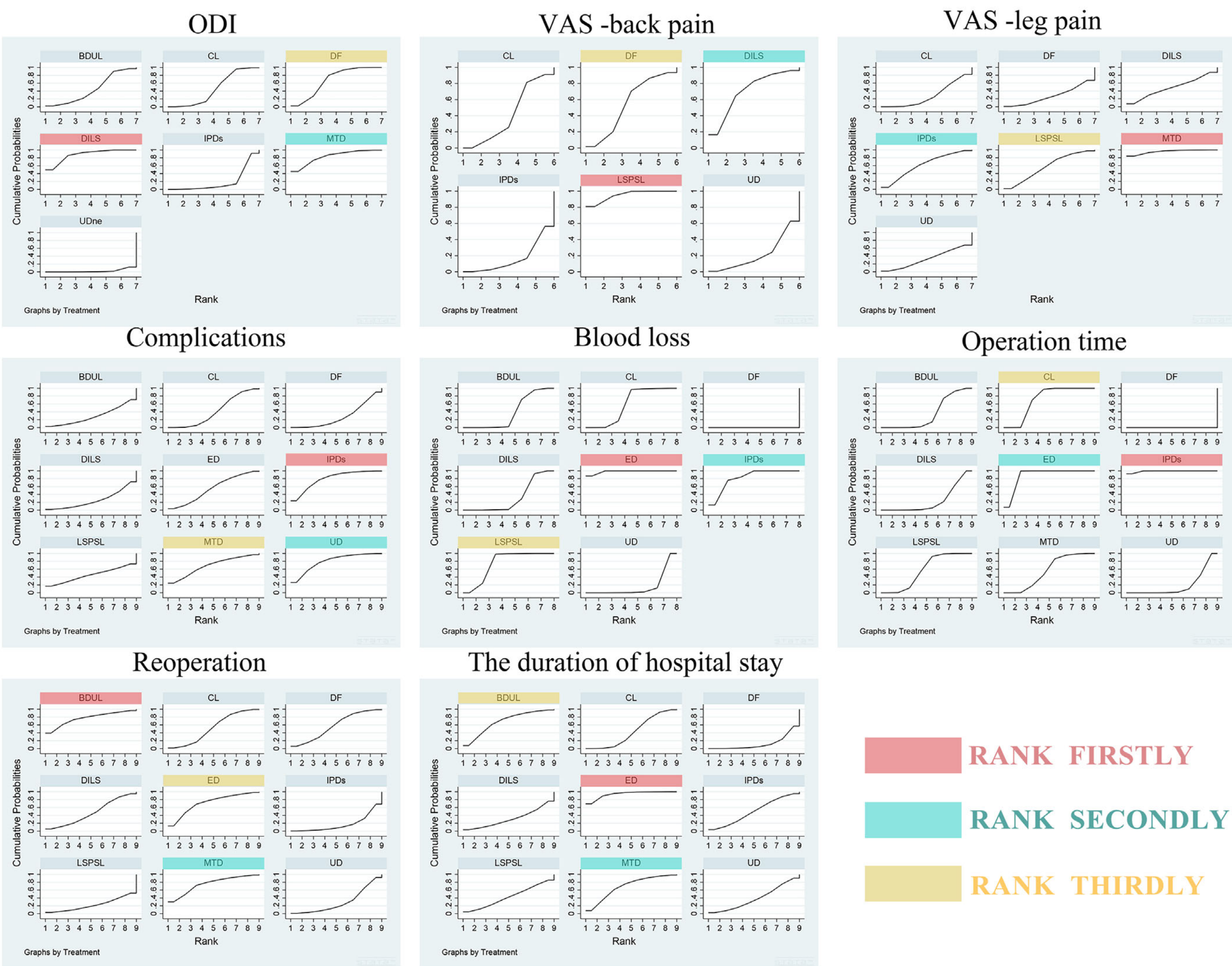

Fig. 4 Surface under the cumulative ranking (SUCRA) for different outcomes. For the outcome measures, we ranked the interventions through the SUCRA. The larger the cumulative area between the curve and the X-axis was, the higher the ranking of the intervention was. A higher ranking for interventions means more effectiveness. The top three interventions are highlighted in red, green, and yellow, respectively.

complications associated with IPDs, patients had the highest incidence of reoperation in 2 years due to the lack of direct spinal canal decompression and nerve decompression.[59] Based on the results of NMA, the ED procedure is the best at reducing blood loss in all surgical procedures because of the small incision of approximately 1 cm that is performed in ED, which is considered to be a minimally invasive spinal surgical procedure, along with the performance of continuous intraoperative saline irrigation, which is helpful to control bleeding.[60]

Some available evidence suggests that the CL is a surgical procedure in which the supraspinous and interspinous ligaments should be removed along the posterior median approach; additionally, the multifidus muscle should be stripped from the spinous process. However, extensive muscle stripping was associated with chronic low back pain.[61,62] Consequently, the advantage of the LSPSL procedure in relieving low back pain might be due to its retention of the muscles connected to the spinous process through the bilateral retraction of the division of the spinous process and ligaments, thus effectively avoiding postoperative muscle atrophy.[63] However, because of the limited number of existing studies, the surgical effect of the MTD procedure was not involved in the outcome comparison of VAS back pain scores. According to the results of NMA, and compared with other surgical procedures, the MTD procedure had obvious advantages in relieving leg pain.

TABLE 6 The SUCRA for the different outcomes

MEASUREMENT	1	2	3	4	5	6	7	8	9
ODI	DILS (87.8)	**MTD (83.2)**	DF (67.2)	CL (45.4)	BDUL (44.4)	IPDs (19.5)	UD (2.5)	/	/
VAS -back pain	LSPSL (95)	DILS (70.3)	DF (54.4)	CL (41.9)	UD (21.5)	IPDs (16.8)	/	/	/
VAS -leg pain	**MTD (95.6)**	IPDs (61.3)	LSPSL (56.9)	DILS (48.1)	UD (32.7)	CL (28.3)	DF (27.1)	/	/
Operation time	IPDs (99.1)	ED (88.4)	CL (70.9)	LSPSL (57.2)	**MTD (55.5)**	BDUL (35.5)	DILS (24)	UD (19.4)	DF (0)
Blood loss	ED (98.1)	IPDs (81.8)	LSPSL (74.4)	CL (58.7)	BDUL (38.6)	DILS (32)	UD (16.3)	DF (0)	/
Duration of hospital stay	ED (94)	**MTD (68.9)**	BDUL (68.3)	IPDs (49.9)	LSPSL (42.9)	CL (42.7)	UD (39.2)	DILS (31.6)	DF (12.5)
Complication	IPDs (79.2)	UD (79.2)	**MTD (68.5)**	ED (54.2)	LSPSL (44.8)	CL (41.7)	BDUL (28.8)	DF (28.3)	DILS (25.2)
Reoperation	BDUL (77)	**MTD (75.3)**	ED (71.6)	DF (57.5)	CL (52.1)	DILS (46.9)	UD (29.7)	LSPSL (22.5)	IPDs (17.4)

BDUL, bilateral decompression *via* the unilateral approach; CL, decompression with conventional laminectomy; DF, decompression with fusion; DILS, decompression with interlaminar stabilization; ED, endoscopic decompression; IPDs, interspinous process devices only; LSPSL, decompression with lumbar spinal process-splitting laminectomy; MTD, minimally invasive tubular decompression; SUCRA, surface under the cumulative ranking; UD, unknown decompression. The bold values mean the differences between one surgical procedure and another one were significant.

In this NMA, we assessed the efficacy and safety of various surgical procedures for LSS. However, the results showed that none of the surgical procedures had an absolute advantage in the evaluation of every NMA. Davis *et al.*[14] introduced the concept of composite clinical success, which refers to the combination of efficacy (degree of symptom relief) and safety (risk of complications, among others) to assess the advantages and disadvantages of various procedures. The SUCRA results are summarized in Table 6. In addition to these results, we observed that the MTD procedure ranked in the top three for improving ODI (83.2, No. 2) and VAS leg pain (95.6, No. 1), duration of hospital stay (68.9, No. 2), reducing complications (68.5, No. 3), and reoperation rate (75.3, No. 2). The reasons why MTD ranked in the top three of multiple outcomes were probably due to the adoption of blunt muscle separation to reduce muscle injury, choosing the paravertebral approach to preserve the supraspinatus and interspinous ligaments, and performing bilateral decompression *via* a unilateral approach.[64,65] This ensured that adequate spinal decompression was performed without damaging the stable structure of the spine. Additionally, most patients with LSS were elderly,[66] in whom preoperative comorbidities are common. Reducing the incidence of surgical trauma and shortening the duration of hospital stay were beneficial in reducing postoperative complications (such as deep vein thrombosis, urinary tract infections, cardiopulmonary problems, and pulmonary embolism, among others). Therefore, MTD may provide the greatest potential to become a routine surgical option for most patients with single-segment LSS. However, the disadvantages of MTD include the long operation time, the steep learning curve, and the higher risk of a dural tear due to the limited operative field.[67,68]

Strengths and Limitations

Our study was the first NMA to compare the efficacy and safety of different surgical procedures for single-segment LSS, strictly following the guidance of the PRISMA-NMA Statement. All included studies were RCTs, 85% of which had a low risk of overall bias. Evidence quality evaluation (GRADE) was also performed in this study. This study was not associated with any organization, which ensured that the results were not biased.

The limitations of this study were as follows: (i) lack of quality-of-life assessment: SF-36 is commonly used to assess the patients' quality of life. In all of the included studies, three studies reported SF-36.[9,12,19] We did not pool the data because of differences found in the data of these studies; (ii) lack of assessment of treatment costs: apart from the efficacy and safety of the surgical procedure, the cost of the whole treatment process is also an important factor that influences the choice of treatment; (iii) lack of comprehensive assessment of efficacy and safety: currently, there is no optimal surgical procedure for single-segment LSS according to the comparison of efficacy and safety. Consequently, it is necessary to consider efficacy and safety simultaneously while selecting an appropriate surgical procedure to treat LSS; (iv) potential publication bias: we did not use funnel plots to assess publication bias and small study effect for the number of trials included in each comparison was small; (v) low quality of evidence: GRADE analysis was performed for every outcome, although the overall level of evidence was low. The effectiveness, safety, and ranking of all outcomes might change when high-quality studies are performed and the techniques are improved.

Conclusion

In this NMA, for single-segment LSS, DILS was the most promising procedure to improve the function status; however, its shortcomings include a higher number of complications. The LSPSL and MTD procedures were the best choices to improve back and leg pain, respectively. Patients with the shortest operation time and the least complications had undergone IPDs. Considering the incidence of reoperation, IPD listed last with SUCRA. With regard to blood loss and the duration of hospital stay, ED performed better than any of the other surgeries. Considering complications, postoperative function status, degrees of pain (back or leg), duration of hospital stay, and reoperation, among others, MTD may have the most potential to become a routine surgical option for most patients with single-segment LSS.

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Conflict of interest

The authors declare no conflicts of interest.

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