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Efficacy and safety of direct C1 screw fixation for Jefferson fractures: a systematic review and meta-analysis

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Systematic Review

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Abstract

Purpose

Direct C1 screw fixation (DSF) has emerged as a motion-preserving alternative to C1–C2 fusion for unstable Jefferson fractures, but consolidated evidence regarding its safety and efficacy remains limited. This systematic review and meta-analysis evaluated perioperative parameters, complications, radiological outcomes, and long-term clinical results after DSF.

Methods

A systematic PubMed search was performed according to PRISMA guidelines and registered in PROSPERO (CRD42024531104). English-language studies published between January 2006 and March 2026 reporting at least five patients aged > 15 years treated with DSF and providing fusion rates and/or implant-related complications were included. Pooled estimates were calculated for operative time, blood loss, lateral mass displacement (LMD), fusion, reoperation, pain, and disability outcomes.

Results

Nineteen studies including 302 patients were analyzed. The pooled operative time was 103.6 min (95% CI 92.2–114.9), and pooled blood loss was 109 mL (95% CI 96.5–121.9). LMD decreased significantly from 7.9 mm (95% CI 6.2–9.6) preoperatively to 3.0 mm (95% CI 1.9–4.1) postoperatively. The pooled C1 fusion rate was 92.9% (95% CI 88.1–95.9), and the pooled reoperation rate with C1–C2 fusion was 5.9% (95% CI 3.7–9.4). Final follow-up VAS and NDI scores were 1.2 and 8.5, respectively. Screw trajectory and screw type did not significantly affect operative time, blood loss, or LMD correction.

Conclusion

Direct C1 screw fixation appears to be a safe and effective motion-preserving option for unstable Jefferson fractures, providing reliable fracture reduction, high fusion rates, and favorable clinical outcomes. TAL injury may not preclude the use of this technique in appropriately selected patients. Further comparative studies are required to clarify patient selection, technical nuances, and long-term advantages over C1–C2 fusion.

INTRODUCTION

Unstable C1 fractures represent a relatively uncommon injury pattern and are diagnosed in approximately 5–15% of patients with cervical spine fractures [1]. Although the majority of C1 fractures can be managed conservatively, surgical treatment is generally considered justified in cases involving transverse atlant ligament (TAL) disruption or combined C1–C2 injuries.

For many years, C1–C2 fusion was considered the standard surgical option; however, direct C1 screw-rod fixation (DSF) has gained increasing popularity over the past decade. The technique consists of placing screws into the lateral masses of the atlas and subsequently connecting them transversely with a rod. It was first introduced by Ruf et al. using an anterior transoral approach [2] and was subsequently modified using posterior screw fixation techniques. Despite more than two decades of clinical experience with this procedure, publications reporting patient series exceeding 5–6 cases have only begun to emerge in recent years.

To date, only one systematic review specifically addressing DSF has been published [3]. In that review, the authors compared anterior and posterior DSF techniques and concluded that both approaches provide satisfactory clinical efficacy. Nevertheless, no detailed analysis of surgical nuances or pooled assessment of short- and long-term treatment outcomes

was performed. The absence of robust consolidated evidence regarding the efficacy and safety of DSF prompted the present meta-analysis.

Objectives

The primary aim of this systematic review and meta-analysis was to evaluate the incidence of complications as well as the short- and long-term outcomes associated with DSF.

METHODS

Study design and search strategy

The study protocol was reviewed and approved by the institutional review board. The study was registered in the PROSPERO database (No. CRD42024531104). A systematic review of the PubMed database was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [4].

The following search strategy was used for the MEDLINE database: (("C1"[tiab] OR atlas[tiab] OR atlantal[tiab]) AND ("lateral mass screw"[tiab] OR "C1 screw"[tiab] OR "C1 fixation"[tiab] OR "C1 ring"[tiab] OR "ring fixation"[tiab] OR "internal fixation"[tiab] OR "monosegmental"[tiab] OR "motion preserving"[tiab] OR "motion-preserving"[tiab] OR "function preserving"[tiab] OR "function-preserving"[tiab])).

The inclusion criteria were as follows:

1. articles published between January 1, 2006, and March 1, 2026;
2. availability of the full-text English version of the article;
3. patient series including at least five cases;
4. patient age >15 years;
5. reporting of fusion rates and/or implant-related complications.

Articles not meeting these criteria were excluded from the analysis. The study selection process is illustrated in Fig. 1.

Data collection

Data extracted from the included studies were entered into a dedicated Excel spreadsheet (Microsoft Excel for Mac, Microsoft Corp., Redmond, WA, USA). If specific data were not available in a given publication, the corresponding fields were marked as n/a (not available).

The basic dataset included publication year, number of patients, age, sex, and diagnosis. The primary dataset included the type of C1 screw trajectory, screw head design (monoaxial or polyaxial), pre- and postoperative lateral mass displacement (LMD), postoperative atlantodental interval (ADI), mean operative time and corresponding standard deviation (SD), mean intraoperative blood loss and SD, occurrence of vertebral artery (VA) injury, screw malposition toward the VA, other types of screw malposition, implant failure, radiological outcomes (solid fusion, stable fibrous union, or nonunion), as well as pain severity assessed using the visual analog scale (VAS) and the Neck Disability Index (NDI).

Statistical analysis

Statistical analysis was performed using Statistica software (version 12 for PC; StatSoft, Tulsa, OK, USA). Non-parametric statistical methods were applied for pairwise comparisons. Differences between groups were assessed using the Kruskal–Wallis (K–W) or Mann–Whitney (M–W) tests, as appropriate. Statistical significance was interpreted based on p-values representing the probability of deviation from the null hypothesis under the assumption of no intergroup differences. A p-value <0.05 was considered statistically significant.

Meta-analysis was conducted using Comprehensive Meta-Analysis software (version 2.2.064; Biostat, Englewood, NJ, USA). Statistical heterogeneity among studies was assessed using the I^2 statistic and Cochran's Q test. An I^2 value <50% was considered indicative of low heterogeneity, 50–75% of moderate heterogeneity, and >75% of high heterogeneity. A fixed-effects model was applied in the absence of significant heterogeneity; otherwise, a random-effects model according to DerSimonian and Laird was used. Publication bias was assessed using Begg's test. In the absence of publication bias, the results were presented as forest plots. If publication bias was identified, adjustment was performed using the trim-and-fill method, and the results were presented as funnel plots.

For comparisons of continuous variables reported as means and standard deviations, the standardized mean difference (SMD) was calculated. Results were presented with 95% confidence intervals (95% CI). Differences were considered statistically significant when the entire confidence interval was either above or below zero.

RESULTS

Patient demographics

The initial search identified 874 abstracts. After applying predefined filters (patient age, article language, study subject, and publication date), 302 records were screened, and 180 full-text articles were assessed for eligibility (Fig. 1). Ultimately, 19 studies met the inclusion criteria and were included in the meta-analysis [5-23].

A total of 302 patients were included, of whom 198 (65.6%) were male and 104 (34.4%) were female. The median value of the mean patient age across all studies was 47 years. The predominant mechanisms of injury were falls from height (44.7%) and motor vehicle accidents (41.2%).

The interval between trauma and surgical intervention was reported in 14 studies comprising 211 patients. Among these, 90% underwent surgery during the acute or subacute post-traumatic period, whereas 10% were treated for chronic fractures. Injury to the TAL was identified in most patients (n = 216, 69.7%). Neurological status was intact in 97.4% of cases at presentation.

Surgical Technique

Most authors preferred intraoperative immobilization using a Mayfield head clamp or skeletal traction. Only one study [23] reported the use of a halo vest in a subset of patients.

Two principal screw insertion techniques were used: direct placement into the lateral mass (LM) of the atlas with mobilization of the corresponding nerve root, and fully pedicular screw fixation (PSF) or a notching technique involving partial resection of the inferior border of the C1 posterior arch (Fig. 2). Implant trajectory was described in 17 studies (Table 1). The LM trajectory was used in 112 patients across seven studies [5,7,10,12,16,18,19]. PSF or the notching technique was used in 85 patients across five studies [9,14,15,20,21]. In another five studies, including 73 patients, both LM and notching/PSF techniques were applied [6,8,13,17,23].

Three main types of implant constructs were identified: standard polyaxial screws with rods, monoaxial screws with rods, and custom-designed constructs based on C-shaped plates and dedicated screws. Several studies included two patient cohorts treated with different implant types; therefore, 21 patient groups from 19 studies were included in the analysis. The most used constructs were those based on polyaxial screws, reported in 14 groups comprising 197 patients [5-7,10,12,14,16-23]. Monoaxial screws alone were used in 60 patients across four groups [9,11,20,21]. In one study including eight patients [8], both screw types were used, but without separate reporting. Two authors used custom-designed constructs [13,15] (Table 1).

Table 1 Diagnostic features and surgical treatment characteristics in the included studies

Study	No of patients	TAL injury, n	Preoperative LMD	OpT, min.	BL, ml.	Screw trajectory	Screw type	Length of stay, days
He et al., 2014	22	22	-	86 (68-122)	120 (90-400)	LM	polyaxial	9
Hu et al., 2014	12	5	7.5 (5-13)	70.5 (60-90)	150 (100-300)	PSF or LM	polyaxial	-
Shatsky et al., 2016	12	11	7.1±2.2	-	-	LM	polyaxial	-
Gelinas-Phaneuf et al., 2018	8	0	-	-	-	notching or LM	monoaxial and polyaxial	-
Zhang et al., 2018	9	8	7.0±2.2	126.7±51.2	105.6±91.3	notching	monoaxial	-
Rajasekaran et al., 2020	5	-	14.6±1.3	77±13.9	84.4±8.04	LM	polyaxial	-
Gao et al., 2021	23	18	7.3±2.1	93.6±28.1	158.5±53.6	-	monoaxial	-
Shin et al., 2022	12	12	-	111.92±7.14	125.0±78.3	LM	polyaxial	3.2±1.0
Yan et al., 2022	27	27	7.4±2.6	75.6±11.3	85.6±11.6	PSF or LM	self-designed	4.5±0.6
Bao et al., 2023	14	-	-	82.1±8.8	84.3±16.8	PSF	polyaxial	-
Yang et al., 2023	10	8	7.1±1.9	108.7±20.1	98.0±41.3	notching	self-designed	-
Basankin et al., 2024	15	15	10.4 [8.9-11.4]	90.0 [77.5-102.5]	200 [100-250]	LM	polyaxial	5 [5-7]
Cai et al., 2024	18	18	5.5±3.3	110.6±18.5	103.3±25.4	PSF or LM	polyaxial	8.1±1.6
Goldberg et al., 2024	38	11	5.5±2.5	94±17	-	LM	polyaxial	18.2±7.6
Arena et al., 2025	8	8	-	-	-	LM	polyaxial	-
Beucler et al., 2025	9	8	11.1±3.6	108.7±45.3	233.3±106.1	LM	polyaxial	4.7±1.4
Hong et al., 2025, monoaxial screws	7	7	3.95 [3.49-5.96]	110 [102.5-115.0]	-	PSF or notching	monoaxial	-
Hong et al., 2025, polyaxial screws	12	12	5.28 [4.60-6.10]	130 [121.3-152.5]	-	PSF or notching	polyaxial	-
Niu et al., 2025, Group A	12	12	7.69	83.92±12.64	96.2±16.8	PSF or notching	polyaxial	8.1±1.3

Niu et al., 2025, Group B	21	21	7.43	109.76±15.42	132.3±25.8	PSF or notching	monoaxial	12.9±2.6
Lvov et al., 2026	8	4	6.9±2.6	181.4±20.8	125.0±71.5	LM, notching, PSF	polyaxial	17.7±9.7

BL – blood loss; LMD – lateral mass distance; OpT – operation time; PSF – pedicle screw fixation; TAL – transverse ligament of atlas.

Analysis of Intraoperative Parameters and Hospital Stay

The pooled operative time was 103.6 min (95% CI, 92.2–114.9) (I^2 = 96.8%; Q test, p = 0; Begg's test, p = 0.272). The pooled intraoperative blood loss was 109 mL (95% CI, 96.5–121.9) (I^2 = 91.3%; Q test, p = 0; Begg's test, p = 0.099). Comparison of mean operative time and blood loss according to screw trajectory showed no significant differences (K–W test, p = 0.529 and p = 0.553, respectively). Screw type, either monoaxial or polyaxial, likewise had no significant effect on mean operative time or blood loss (M–W test, p = 0.328 and p = 0.442, respectively).

The pooled preoperative LMD was 7.9 mm (95% CI, 6.2–9.6) (I^2 = 95.1%; Q test, p = 0; Begg's test, p = 0.655). Postoperatively, pooled LMD decreased to 3.0 mm (95% CI, 1.9–4.1) (I^2 = 95.3%; Q test, p = 0; Begg's test, p = 0.322). This reduction was statistically significant (SMD = 2.3 [95% CI, 1.3–3.3]) (Fig. 3). Neither screw trajectory nor screw type had a significant effect on mean LMD correction (K–W test, p = 0.650; M–W test, p = 0.524).

The pooled length of hospital stay was 8.1 days (95% CI, 6.1–10.0) (I^2 = 98.1%; Q test, p = 0; Begg's test, p = 0.176).

Complications and Long-term Outcomes

Screw malposition was reported in 14 patients. In five cases, malposition resulted in VA injury, whereas in nine cases the screws were misplaced toward the VA or the spinal canal. Nevertheless, all cases of screw malposition were asymptomatic and were not associated with neurological deficit or substantial blood loss. Other implant-related complications were rare and included superficial or deep wound infection, C0–C1 arthrosis, transient or persistent greater occipital nerve neuralgia, chronic bursitis, and C1–C2 instability (Table 2). Notably, screw reinsertion was required in only five patients. One patient with deep wound infection underwent surgical revision and wound debridement, and three cases of C1–C2 instability required subsequent fusion. Thus, after adjustment for publication bias (Fig. 4), the pooled rate of reoperation with C1-C2 fusion after DSF was 5.9% (95% CI, 3.7–9.4) (I^2 = 0%; Q test, p = 1.000; Begg's test, p = 0.003).

The median value of the mean follow-up duration was 21.5 months. The pooled fusion rate across all studies at final follow-up was 92.9% (95% CI, 88.1–95.9) (Fig. 5). Subgroup analysis according to screw type yielded the following results: in the monoaxial screw group, the pooled fusion rate was 97.1% (95% CI, 87.0–99.4) (I^2 = 0%; Q test, p = 0.887; Begg's test, p = 0.117), whereas in the polyaxial screw group, it was 91.7% (95% CI, 85.4–95.4) (I^2 = 0%; Q test, p = 0.826; Begg's test, p = 0.360). The pooled postoperative ADI was 2.5 mm (95% CI, 1.9–3.2) (I^2 = 95.1%; Q test, p = 0; Begg's test, p = 0.322).

At final follow-up, the pooled VAS score was 1.2 (95% CI, 0.8–1.5) (I^2 = 87.7%; Q test, p = 0; Begg's test, p = 0.542), and the pooled NDI was 8.5 (95% CI, 4.0–13.1) (I^2 = 98.1%; Q test, p = 0; Begg's test, p = 0.453).

Surgical treatment outcomes in the included studies

Study	Mean follow-up, months	LMD post-surgery	ADI post-surgery	VAS	NDI	Fusion rate, %	Implant-related complications	Revision procedures
He et al., 2014	22.5	-	-	1.9±1.1	-	100	None	None
Hu et al., 2014	22	3.0 (1-6)	2.4 (2-3)	1.8±2.1	-	100	Screw malposition – 2	None
Shatsky et al., 2016	17.3	2.4±1.3	-	0.7±1.6	-	100	C0-C1 arthrosis – 1 Screw malposition - 1	Screw reinsertion - 1
Gelinas-Phaneuf et al., 2018	12.6	-	-	0.9±1.5	-	-	VA injury – 1 Screw loosening - 1	None
Zhang et al., 2018	17.4	0	3.2±2	1.0±0.9	-	100	Temporary OcN neuralgia – 1 Persistent OcN neuralgia – 1 Screw malposition - 1	None
Rajasekaran et al., 2020	40.8	5.2±1.6	1.8±0.2	-	1.6±1.7	100	None	None
Gao et al., 2021	15.3	0.7±0.5	-	1.5±1.1	-	100	Superficial wound infection - 2	None
Shin et al., 2022	12-24	-	3.3±1.2	0.9±1.0	8.1±5.7	91.7	C1-C2 instability – 1	C1-C2 fusion - 1
Yan et al., 2022	60	1.8±1.1	3.5±0.7	0.7±0.4	13.1±2.5	100	Screw malposition - 1	None
Bao et al., 2023	21	-	-	1.9±0.8	12.1±4.3	100	None	None
Yang et al., 2023	16.7	-	2.3±0.8	0.6±0.7	-	100	None	None
Basankin et al., 2024	12.5	2.2 [1.8-2.6]	-	1 [0-1]	-	100	None	None
Cai et al., 2024	19.4	1.9±3.0	-	0.3±0.5	2.2±2.4	83.3	Screw malposition – 2 C1-C2 instability - 1	Screw reinsertion – 2 C1-C2 fusion - 1
Goldberg et al., 2024	-	4.2±2.6	1.5±1	-	-	-	VA injury – 4 Screw malposition - 1	Screw reinsertion - 1
Arena et al., 2025	32.2	-	3.2±1.2	-	-	100	None	None

Beucler et al., 2025	15.7	6.8±3.3	-	1.3±1.2	17.6±8.9	77.8	Deep wound infection – 1 Screw malposition - 1	Screw reinsertion – 1 Wound debridement - 1
Hong et al., 2025, monoaxial screws	24	2.2 [1.1-3.3]	1.6 [1.5-2.4]	2 [1-2]	7.0 [4.4-9.0]	-	None	None
Hong et al., 2025, polyaxial screws	62	2.3 [1.8-3.5]	2.3 [1.6-2.6]	1.5 [1-2]	7.5 [5.6-10.0]	-	C1-C2 instability - 1	C1-C2 fusion - 1
Niu et al., 2025, Group A	≥36	3.2	3.1	1.3	12.2	100	None	None
Niu et al., 2025, Group B	≥36	1.9	3.3	1.85	14.7	100	Temporary OcN neuralgia – 6 C0-C1 pain – 4 Chronic bursitis - 3	None
Lvov et al., 2026	39.7	2.6±2.7	1.9±0.9	2.2±1.0	6.8±2.7	100	None	None

ADI – atlanto-dental interval; LMD – lateral mass distance; NDI – neck disability index; OcN – greater occipital nerve; VAS – visual analogue scale of pain.

DISCUSSION

One of the key issues in evaluating DSF is whether this technique is comparable with C1–C2 fusion in terms of treatment outcomes. In a randomized clinical trial, Yan et al. [13] demonstrated that DSF was superior to C1–C2 fusion regarding operative time, blood loss, and long-term clinical and radiological outcomes. A similar tendency can be observed when pooled estimates for the Goel–Harms technique (GHT) [24] are compared with the DSF outcomes obtained in the present meta-analysis. The pooled operative time and blood loss reported for GHT were 144 min (95% CI, 132.4–155.6) and 264.2 mL (95% CI, 230.8–297.7), respectively [24], which were approximately twice as high as those observed for DSF: 103.6 min (95% CI, 92.2–114.9) and 109 mL (95% CI, 96.5–121.9), respectively. The pooled nonunion rate for GHT was 4.2% (95% CI, 3.3–5.3), whereas only one case of nonunion requiring revision surgery was reported after DSF [12].

At the same time, these findings raise the question of whether C1–C2 fusion is necessary in all patients with C1 fractures. Despite its apparently less rigid nature, DSF is biomechanically justified even in the presence of TAL injury [25]. In horizontal transligamentous C1-C2 dislocation, disruption involves not only the TAL but also the joint capsules, alar ligaments, and atlantoaxial membranes. Such injuries are highly unstable, and C1–C2 fusion remains the only reasonable surgical option. In Jefferson fractures, however, atlantoaxial displacement occurs predominantly in the vertical plane. The C1 lateral masses are displaced laterally, causing tension and subsequent rupture of the TAL, while the remaining alar ligaments generally remain intact. As demonstrated by Puttlitz et al. [26], even complete TAL disruption may still be compatible with sufficient craniocervical stability provided that the alar ligaments, membranes, and other stabilizing structures remain preserved. These biomechanical considerations explain why treatment of C1 fractures should primarily aim to reduce and maintain the position of the C1 lateral masses and prevent their recurrent displacement.

In the present study, TAL injury was reported in approximately 70% of patients; nevertheless, the pooled revision rate due to C1–C2 instability was only 5.9%. Patients treated with DSF demonstrated a statistically significant reduction in LMD, and the pooled final postoperative ADI was 2.5 mm, indicating preserved stability of the atlantoaxial complex at the follow-up. These findings support the efficacy of DSF even in the presence of TAL injury and suggest that TAL disruption may have a less decisive role in Jefferson fractures than traditionally assumed.

Another point of interest was the influence of technical nuances on surgical outcomes. To date, three main techniques for C1 screw placement have been described: direct LM screw insertion, PSF, and the notching technique with partial resection of the inferior portion of the C1 posterior arch. The latter two techniques are generally assumed to be associated with lower blood loss because of a reduced risk of injury to the venous plexus, as well as a lower risk of nerve root irritation. However, in the present study, no significant difference in mean blood loss was observed between these techniques. Moreover, transient or persistent occipital neuralgia was a sporadic complication and was reported specifically in patients treated using the notching technique [9, 21]. Therefore, our analysis did not demonstrate any clear advantage of one screw placement technique over another.

The type of screw used for DSF was another relevant technical consideration. To date, two retrospective studies [20, 21] have suggested that monoaxial screws may provide superior fracture reduction, particularly with respect to the anterior arch diastasis; however, neither study directly compared final fusion outcomes between monoaxial and polyaxial screw constructs. Furthermore, one of these studies [21] emphasized the greater technical difficulty of monoaxial screw placement and reported a higher number of complications in this group. In the present analysis, no significant differences were identified between monoaxial and polyaxial screw groups in terms of mean operative time or intraoperative blood loss. The pooled fusion rate was higher in the subgroup of studies using monoaxial screws. However, the 95% confidence intervals largely overlapped, and this advantage may be explained by the smaller number of studies and patients included in the monoaxial fixation subgroup compared with the polyaxial screw subgroup.

Regarding complications, we did not calculate a pooled rate of VA injury. Four of the five reported cases occurred in a single study that included 38 patients. For the GHT, the pooled VA injury rate has been reported as 2.8% (95% CI, 2.2–3.5) [24]. Given the smaller number of screws used in DSF, the expected rate of VA injury might theoretically be even lower; therefore, the 10% rate reported by Goldberg et al. appears relatively high in this context. Unfortunately, the authors did not discuss the occurrence of VA injury in detail, which precluded a reliable pooled estimate in our analysis.

Long-term clinical outcomes after DSF also remained favorable. The pooled VAS and NDI scores corresponded to minimal residual pain and almost no restriction in quality of life. With respect to cervical range of motion, DSF may have an intuitive advantage over C1–C2 fusion because it preserves atlantoaxial mobility. However, we were unable to identify pooled estimates with 95% CI for NDI after C1–C2 fusion in the available literature. In the study by Yan et al. [13], the difference in NDI between DSF and C1-C2 fusion at final follow-up was statistically significant; however, the absolute mean difference was only 2.8, which is unlikely to exceed the minimal clinically important difference. In individual studies, long-term postoperative NDI after GHT has been reported as 6.7 ± 5.8 [27], which is broadly comparable with the results observed after DSF. In other words, the available evidence does not allow us to conclude that preservation of C1–C2 motion has a clinically meaningful impact on long-term quality of life. This question should be addressed in high-quality studies specifically designed to evaluate the relationship between postoperative range of motion after DSF or GHT and patient-reported quality of life using validated clinical scales, including the NDI, SF-36 etc.

Study Limitations

The main limitation of this study is the small sample size of the included studies. The rarity of this pathology and the highly specialized nature of the DSF technique make it difficult to assemble large patient cohorts and, consequently, to obtain more precise pooled estimates. Nevertheless, the present findings may help surgeons better understand the efficacy and safety of DSF and may also provide evidence-based information for patient counselling and informed surgical decision-making.

CONCLUSION

DSF represents a safe surgical option for the treatment of unstable C1 fractures and allows effective correction of vertical atlantoaxial dislocation. TAL injury identified on MRI should not be considered a contraindication to this technique. Revision surgery with subsequent C1–C2 fusion may be required in only 5.9% of patients after DSF.

Compared with C1–C2 fusion, DSF may substantially reduce intraoperative blood loss and operative time while providing favorable clinical outcomes. The pooled C1 fusion rate after DSF was 92.9%. The use of monoaxial screws may increase the likelihood of fusion by enabling more effective reduction of C1 anterior arch diastasis. In the present study, the choice of screw trajectory, including PSF, notching, or C1 LM techniques, had no significant effect on postoperative complications.

Further high-quality studies involving larger patient cohorts are required to refine the technical aspects of DSF and to determine its long-term clinical impact compared with C1–C2 fusion.

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Figures

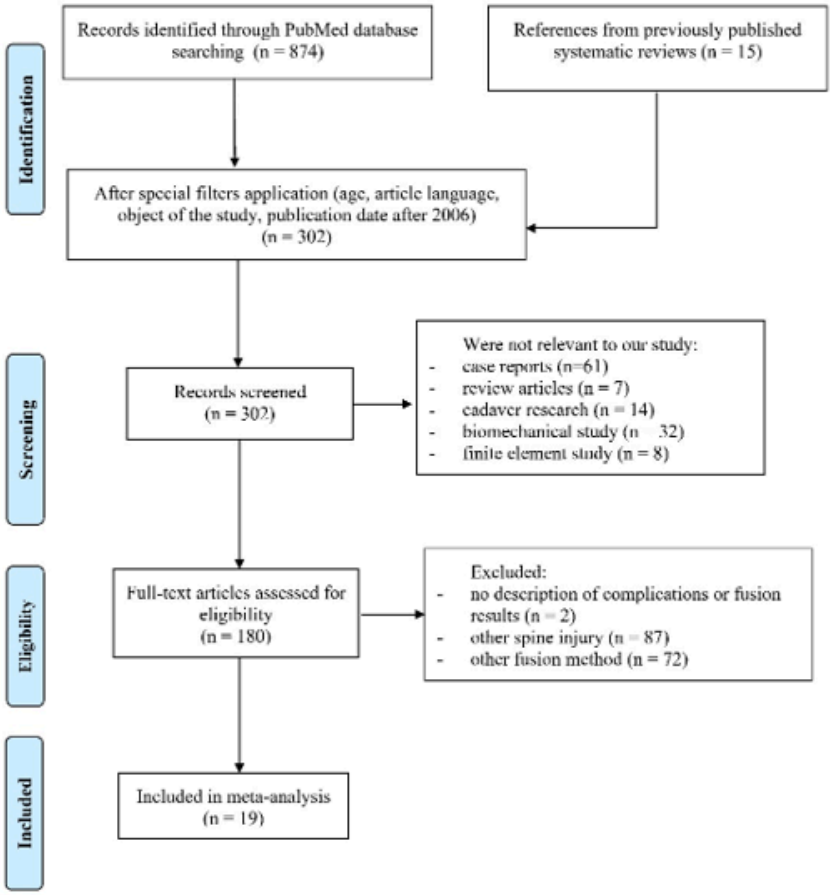


Figure 1

PRISMA Flowchart for Study Selection

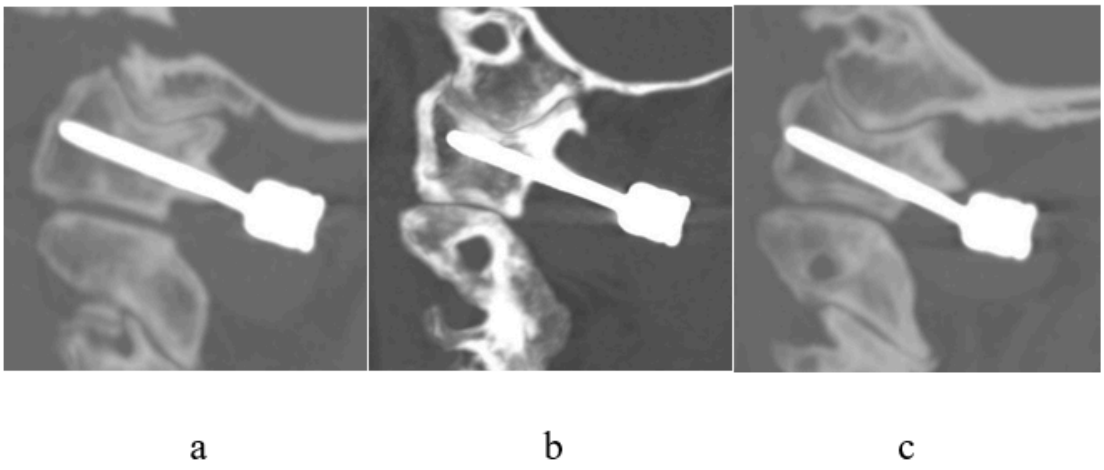


Figure 2

Screw insertion trajectories into the lateral mass of the atlas. a - transpedicular trajectory; b - notching technique; c — lateral mass screw insertion.

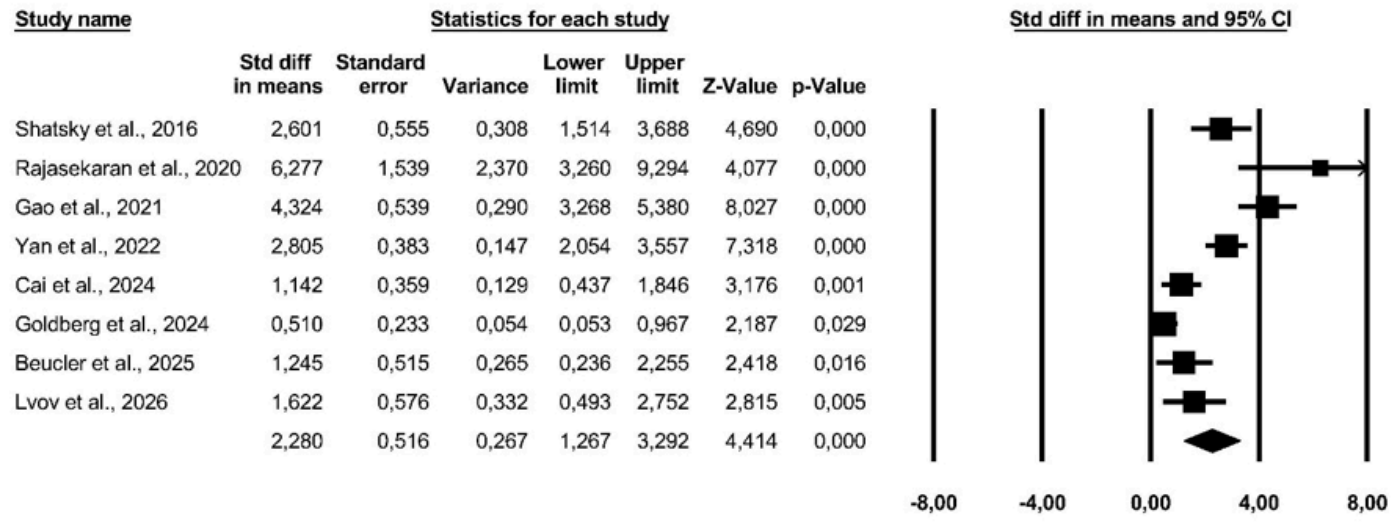


Figure 3

Forest plot showing SMD for the LMD change. I^2 = 90.3%; Q test, p = 0; Begg's test, p = 0.138

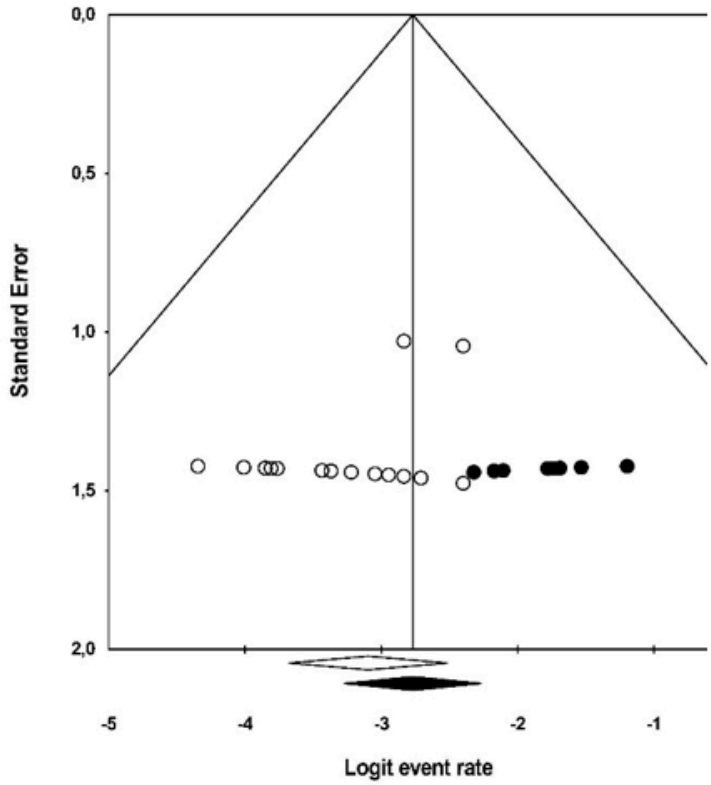


Figure 4

Funnel plot demonstrating adjustment for publication bias using the trim-and-fill method for the pooled rate of C1–C2 fusion after DSF. White markers indicate published studies; black markers indicate imputed studies

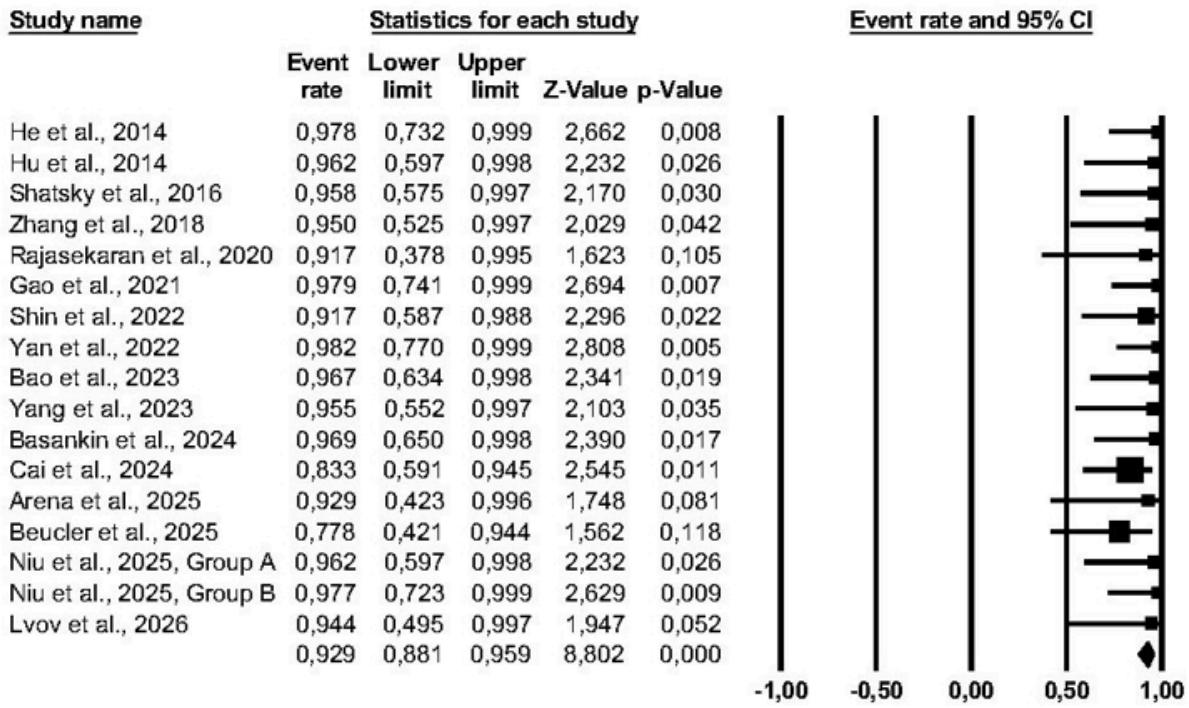


Figure 5

Forest plot demonstrates pooled fusion rate at final follow-up. I^2 = 0%; Q test, p = 0.880; Begg's test, p = 0.06