



JOURNAL
Of Universal Applied
Research

ISSN (Online): XXX
Vol. 01, Issue 02 (2026)
<https://universalappliedresearch.com/index.php/JUAR/issue/archive>

Image Guidance in Cervical Pedicle Screw Fixation: A Review of the Meta-Analytic Evidence for 3D-Printed Templates and Computer-Assisted Navigation

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Received:- 09/06/2026 Revised:- 09/07/2026 Accepted:- 16/07/2026
Published:- 24/07/2026

Abstract

Cervical pedicle screw fixation provides greater biomechanical stability than lateral mass screw techniques, but the narrow pedicle diameter and proximity to the vertebral artery, nerve roots, and spinal cord make freehand insertion technically demanding and carry a nontrivial risk of vascular or neurologic injury. Two image-guidance strategies have emerged to reduce this risk: patient-specific 3D-printed drill templates and intraoperative computer-assisted navigation (CT- or O-arm-based). This review synthesizes the current body of systematic reviews and meta-analyses on the topic, anchored by a 2026 network meta-analysis in the Journal of Minimally Invasive Spine Surgery & Technique, and contrasts its favorable conclusions with an earlier, larger, and more skeptical 2024 meta-analysis that found no significant accuracy benefit for navigation over freehand technique. Across the literature, image guidance is associated with higher screw-placement accuracy in most individual series, with the strongest evidence at the atlantoaxial (C1–C2) level; however, pooled estimates vary considerably depending on which studies and accuracy thresholds are used, and no study has directly compared 3D-printed templates against computer-assisted navigation. The evidence base overall remains small, retrospective, and institutionally clustered, and long-term clinical outcome data are scarce. Navigation-assisted cervical pedicle screw fixation should therefore be regarded as a promising, increasingly well-supported adjunct rather than a proven, universally superior standard of care.

Keywords: cervical pedicle screw; 3D-printed drill template; computer-assisted navigation; O-arm; freehand technique; atlantoaxial fixation; meta-analysis

1. Introduction

Posterior cervical fixation was historically achieved through in-situ fusion and wiring constructs, both of which carried a meaningful risk of failed bony union. The introduction of transpedicular screw fixation in the 1990s gave surgeons a biomechanically stronger construct, with markedly better resistance to pull-out forces than the lateral mass screw alternative. That advantage comes at a cost: the average cervical pedicle is only a few millimeters wide — often narrower than the screws used to instrument it — and sits immediately adjacent to the vertebral artery, exiting nerve roots, and spinal cord. A misdirected trajectory can cause vascular injury, radiculopathy, or a permanent neurologic deficit.

Traditional freehand insertion under fluoroscopic guidance depends heavily on surgeon experience, exposes the operating team to repeated radiation, and carries a long learning curve. These limitations have motivated the development of image-guided alternatives, broadly divided into two families of technology: patient-specific 3D-printed drill templates and intraoperative computer-assisted navigation. This review synthesizes the recent systematic review and meta-analytic literature comparing these approaches with each other and with conventional freehand technique.

2. Two Competing Navigation Strategies

2.1 Patient-Specific 3D-Printed Drill Templates

These templates are manufactured from a preoperative CT scan of the patient's cervical spine. A digital model is used to design a custom-molded guide with pre-drilled channels that fits precisely onto posterior bony landmarks — typically the lamina, spinous process, or lateral mass — at the intended screw level. Once seated intraoperatively, the guide mechanically fixes the entry point and trajectory without requiring real-time tracking equipment.

2.2 Intraoperative Computer-Assisted Navigation

CT-based or O-arm-based navigation instead registers the patient's anatomy to a three-dimensional dataset in real time. A preoperative or intraoperative CT scan builds a model of the spine, anatomical landmarks are registered to the navigation system after surgical exposure, and the surgeon receives continuous visual feedback of instrument position relative to the planned trajectory throughout screw insertion, rather than relying on a single fixed mechanical guide.

Both approaches aim to reduce reliance on freehand judgment and repeated fluoroscopic exposure, but they differ substantially in workflow, upfront planning time, capital equipment requirements, and — as the literature below shows — reported accuracy.

3. The 2026 Network Meta-Analysis: Design and Findings

A systematic review and network meta-analysis published in January 2026 by Sarasombath, Liawrungrueang, Kotheeranurak, and Chitragran compared both image-guidance technologies against conventional freehand fixation. The authors followed PRISMA methodology, pre-registered their protocol with PROSPERO, and searched PubMed for studies published between 2019 and 2024. Of an initial pool of 130 records, eight studies met inclusion criteria: five evaluated 3D-printed templates (all from China, ranging from 23 to 71 patients), and three evaluated computer-assisted navigation systems (from Germany and Japan, ranging from 11 to 157 patients). Most included studies concentrated on the atlantoaxial (C1–C2) region, reflecting both where freehand placement is riskiest and where image guidance is felt to add the most value.

Pooled results were notably favorable to navigation. Individual 3D-printed template studies reported accuracy as high as 95.7–95.8%, compared with roughly 77–87% in matched freehand comparison groups, alongside reductions in operative time (in some studies 30–60 minutes), intraoperative blood loss, and fluoroscopic radiation exposure. Computer-assisted navigation studies showed a similar pattern: one German series reported 92.8% accuracy with intraoperative CT navigation versus 67% with fluoroscopy alone, while a Japanese O-arm series reported 96.2% versus 87.5% accuracy, albeit with longer operative time in the navigated group. A separate German series comparing intraoperative CT navigation with fluoroscopy at both C1 and C2 favored navigation at both levels.

When all eight studies were pooled, navigation-assisted techniques — combining templates and computer navigation — were associated with roughly a fourfold increase in the odds of accurate screw placement relative to freehand technique, a difference the authors described as statistically significant with only moderate heterogeneity. A network meta-analysis comparing the two navigation strategies directly against freehand placement found that 3D-printed templates achieved a statistically significant accuracy improvement, while computer-assisted navigation showed a smaller improvement that did not reach statistical significance — a finding the authors attributed to the smaller number of available navigation studies and higher heterogeneity in that subgroup, rather than a true difference in underlying technology. Because no included study directly compared 3D-printed templates with computer-assisted navigation, the review could only situate both technologies relative to freehand technique; it could not determine whether one image-guidance approach is genuinely superior to the other.

4. Summary of Reported Accuracy Across Studies

Table 1 summarizes headline accuracy figures reported across the reviews discussed in this article. Direct numerical comparison across rows should be made cautiously, since studies differ in patient population, screw level, and — critically — in how "accuracy" itself is defined.

Table 1. Reported accuracy figures by guidance technology across the reviewed literature.

Study / Series	Guidance Technology	Reported Accuracy	Freehand Comparator
Chinese series (n=5 studies, 3D-printed templates)	Patient-specific 3D-printed drill guide	95.7–95.8%	77–87%
German series (CT navigation)	Intraoperative CT navigation	92.8%	67% (fluoroscopy)
Japanese series (O-arm)	O-arm navigation	96.2%	87.5%
Mahmoud et al., 2021 (9 studies, 1,427 screws)	Pooled: freehand / navigation / templates	91.4% (nav.) / 96.7% (templates)	80.6%
Global Spine Journal, 2024 (18 studies, 4,697 screws)	Computer-assisted navigation (pooled)	94% (≤ 2 mm breach)	96% (non-navigated)
O-arm institutional series (>1,000 screws, all levels)	O-arm intraoperative 3D navigation	93% (cervical)	—

5. A More Skeptical Prior Meta-Analysis

The favorable picture painted by the 2026 review sits in some tension with an earlier, larger meta-analysis (Global Spine Journal, 2024) that pooled 4,697 cervical pedicle screws across 18 studies specifically evaluating computer-assisted navigation. That analysis found essentially no difference between navigated and non-navigated screws on several accuracy measures: pooled rates of screws with only a minor (≤ 2 mm) pedicle breach were statistically similar between groups (94% navigated versus 96% non-navigated), as were rates of screws placed entirely within the pedicle (76% versus 82%), intraoperative repositioning rates, and postoperative revision rates. The authors concluded that navigation alone did not demonstrably improve cervical pedicle screw accuracy and suggested that future research should instead focus on learning-curve effects, postoperative complication profiles, and how case complexity influences outcomes — a notably more cautious stance than the 2026 network meta-analysis.

5.1 Reconciling the Two Reviews

Reconciling these two bodies of evidence is informative rather than simply contradictory. Several factors likely explain the divergence:

- Different inclusion windows and comparator groups: the 2024 review pooled a larger, more heterogeneous set of navigation studies extending further back in time, while the 2026 review restricted itself to 2019–2024 publications and included the newer 3D-printed template literature, which reported some of the field's highest accuracy figures.
- Different accuracy thresholds: studies vary in how they define an "accurate" screw — no cortical breach at all versus a breach under 2 mm considered clinically insignificant — and pooling studies with different thresholds can produce meaningfully different headline numbers.
- Publication and institutional clustering: the 2026 review's own authors noted that three of the five 3D-printed template studies came from a single research group, concentrating the pooled effect in one center's results rather than reflecting broad, independent replication — a pattern that can inflate apparent benefit.
- Small individual study sizes: many included studies in both reviews involved fewer than 50–80 patients at a single institution, limiting how confidently any pooled estimate generalizes to other surgeons, patient populations, or institutions.

6. Complementary Evidence

Other systematic reviews add further texture. An earlier review restricted to nine studies and 1,427 screws found fluoroscopic freehand technique achieved 80.6% accuracy, compared with 91.4% for navigation and 96.7% for 3D-printed templates — directionally consistent with the 2026 network meta-analysis in ranking templates above navigation above freehand, though again without a controlled head-to-head comparison between the two image-guidance methods.

A large single-institution series using O-arm-based intraoperative 3D scanning across cervical, thoracic, and lumbar levels reported an overall cervical pedicle screw accuracy of 93%, with most breaches classified as low-grade, reinforcing that navigation performance in real-world, all-comer practice tends to sit somewhat below the figures reported in smaller, efficacy-focused trials. Outside the cervical spine, a 2024 meta-analysis of navigated thoracolumbar pedicle screw fixation similarly concluded that navigation improved both accuracy and clinical outcomes relative to conventional technique, suggesting that the broader trend toward benefit from navigation is not confined to the cervical region, even if cervical-specific evidence remains more contested.

7. Interpreting the Evidence: What Can Be Said With Confidence

Pulling the available reviews together, several conclusions appear reasonably well supported:

- Freehand technique remains the riskiest comparator across essentially every study design, and both major forms of navigation are consistently associated with numerically higher accuracy figures in individual trials, even where pooled statistical significance is inconsistent.
- The C1–C2 (atlantoaxial) region is where the case for navigation is strongest, reflecting both the anatomical difficulty of this level and the concentration of available published evidence there; extrapolation to the lower cervical spine (C3–C7) rests on comparatively less data.
- 3D-printed templates appear to offer secondary benefits beyond accuracy — shorter operative time, reduced blood loss, and fewer fluoroscopic exposures were reported fairly consistently across the template literature, an advantage not as uniformly demonstrated for computer-assisted navigation, where one study even reported a longer operative time in the navigated group.
- The apparent conflict between the 2024 and 2026 meta-analyses is best read as a reflection of evidence immaturity rather than genuine contradiction. Both reviews draw on small, heterogeneous, mostly retrospective, single-institution datasets, and neither claims Level I evidence. The 2026 review's own authors acknowledged that a single-database search strategy, limited long-term follow-up, and institutional clustering of results all constrain how far their favorable conclusions can be generalized.
- No trial has directly compared 3D-printed templates against computer-assisted navigation. Every existing comparison uses freehand technique as the common denominator, so any claim that one navigation strategy is superior to the other remains an indirect, network-meta-analytic inference rather than a head-to-head trial result.

8. Limitations of the Current Literature

Across essentially all the reviews discussed here, several recurring limitations temper how strongly the findings should be interpreted. Most included studies are retrospective, single-center, and modestly sized, which limits statistical power and generalizability. Long-term functional and clinical outcome data — as opposed to short-term radiographic accuracy — remain scarce, so it is not yet clear whether small differences in screw accuracy translate into meaningfully different rates of neurologic injury, revision surgery, or patient-reported outcomes over years of follow-up. Search strategies in several reviews were restricted to a single database, typically PubMed, raising the possibility that relevant non-English or non-indexed studies were missed. Finally, cost-effectiveness — a practical consideration for any technology requiring either 3D-printing infrastructure or intraoperative CT/O-arm equipment — has been addressed in almost none of the available literature.

9. Future Directions

The field would benefit most from a direct, adequately powered comparative trial between 3D-printed templates and computer-assisted navigation, rather than continued indirect comparisons anchored to freehand technique. Multicenter designs would help dilute the institutional clustering that has affected several of the largest single-group effect estimates to date. Standardizing how "accuracy" is defined and measured — ideally converging on a single validated grading system across studies — would make future pooled analyses considerably more interpretable. Finally, incorporating learning-curve data, long-term neurologic and functional outcomes, and formal cost-effectiveness analysis would help clarify whether the accuracy advantages reported for navigation translate into meaningful clinical and economic benefit at scale, rather than remaining a purely radiographic finding.

10. Conclusion

The best current evidence, anchored by a 2026 network meta-analysis of eight studies, supports the use of both 3D-printed navigation templates and intraoperative computer-assisted navigation as effective adjuncts to cervical pedicle screw placement, with templates showing a particularly consistent accuracy advantage alongside reduced operative time and blood loss. This favorable picture should be read alongside an earlier, larger meta-analysis that found no significant accuracy benefit for computer-assisted navigation specifically — a reminder that this remains an actively contested area of the literature rather than a settled question. Both bodies of evidence agree on where the technology is most needed — the technically demanding C1–C2 region — and on where the evidence base is weakest: direct comparisons between navigation strategies, long-term clinical outcomes, and multicenter validation. Until those gaps are filled, navigation-assisted cervical pedicle screw fixation is best regarded as a promising and increasingly well-supported tool rather than a proven, universally superior standard of care.

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