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REVIEW

The impact of augmented reality on radiation exposure during spine surgery: a systematic review

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Abstract

Background: Augmented reality (AR) has rapidly emerged as an important navigational technology in spine surgery, with growing interest in its potential to reduce dependence on fluoroscopy and mitigate radiation exposure for both patients and operating room staff. Methods: This systematic review examined current evidence on radiation-related outcomes of AR-assisted spine procedures. A PRISMA-guided search of PubMed, Embase, and Scopus identified twelve eligible studies, including randomized trials, prospective and retrospective clinical cohorts, and cadaveric or synthetic-model investigations. Results: Across the included studies, AR was consistently associated with reduced fluoroscopy use, with several studies demonstrating statistically significant reductions in exposure time compared with conventional fluoroscopy. Two clinical studies directly measured occupational radiation and reported substantially lower staff doses when AR-based navigation and optimized shielding strategies were employed. Patient radiation exposure was similarly decreased in most studies, particularly when AR was integrated with low-dose cone-beam CT protocols. Operative time findings were mixed, reflecting early learning curves and variability in AR systems, but accuracy remained high across platforms. Conclusion: Current evidence suggests that AR may reduce intraoperative radiation exposure without compromising workflow or surgical precision, available studies are limited by small sample sizes, heterogenous methodologies, and a paucity of direct staff-dosimetry data. Larger, high-quality multicenter studies are needed to clarify the magnitude of AR's radiation-sparing benefits and to define its role in modern spine surgery.

Keywords Augmented Reality · Spine Surgery · Radiation Exposure · Surgical Navigation · Fluoroscopy

Introduction

Spine surgery relies heavily on intraoperative fluoroscopy [33], which has been crucial to ensure accurate instrumentation and safe navigation, especially with the increased utilization of minimally invasive spine surgery (MIS) techniques. Spinal procedures routinely require surgeons to place devices in close proximity to structures of the central nervous system (CNS) and vascular structures [21]. Dangerous complications which might arise in case of misplacement include arterial injuries, spinal dura mater injury, implant breakage, surgical failure, and even late infection [36], but are mitigated by the use of fluoroscopy. However, the use of this technology comes at a cost: radiation exposure to both patients and operating room staff [8], with excessive exposure significantly increasing the risk of long-term effects [2] such as malignancies, cataracts, heart disease, and other conditions [33]. Conventional protective measures, including lead aprons, thyroid shields, and

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physical barriers, as well as more modern technologies, such as image-guided navigation, decrease but do not completely eliminate radiation exposure [20, 30]. Augmented reality (AR) emerges as a more promising navigation technology, superimposing imaging data on a surgeon's view in real-time [35]. Its increasing adoption in neurosurgery [14] and specifically spine surgery [16] aligns with the technological advancements in the field, to address common challenges surgeons face, such as those associated with traditional visualization techniques and the reliance on radiation-based imaging [16]. Current evidence shows superior workflow and comparable accuracy when comparing AR to conventional navigation or to free-hand techniques [7], but points to the limited number of studies exploring the decreased use of radiation. This systematic review specifically synthesizes evidence regarding the impact of AR on staff and patient radiation exposure during spine surgery. Prior reviews that broadly evaluated AR navigation performance and accuracy treated radiation exposure as a secondary outcome, while the present review was designed with radiation-related endpoints as the primary analytical focus. We differentiate between direct dosimetric measurements, surrogate measures, and workflow-dependent effects associated with navigation-based imaging. The methodological and quantitative angle presented represents an important addition to the current literature around the implementation of AR in spine surgery.

A focused evaluation of this outcome is necessary to clarify the potential occupational safety benefits of AR, guide clinical adoption, and inform future research.

Materials and methods

Study design

A systematic review of the literature was conducted for this article following the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [24].

PICO framework

- Population: Surgical staff and patients involved in intraoperative care during spine surgery.
- Intervention: The use of AR systems during intraoperative navigation or guidance.
- Comparator (not always applicable): Conventional surgical techniques, including freehand approaches or fluoroscopy-based navigation without AR assistance.
- Outcome: Measured radiation exposure to staff or patients.

Eligibility criteria

Inclusion criteria were: (i) randomized controlled trials (RCTs), prospective or retrospective cohort studies, case-control studies, and case series with >5 participants; (ii) studies published in English; (iii) studies clearly documenting the use of AR during spine surgery; and (iv) studies quantifying radiation exposure either directly or indirectly (e.g., fluoroscopy time as a proxy).

Exclusion criteria included: (i) case reports and case series with <5 participants; (ii) editorials, letters, reviews, meta-analyses, or conference abstracts without full text; (iii) studies not involving spine surgery; (iv) studies not utilizing AR as part of the surgical workflow; (v) studies focusing solely on patient outcomes without reporting radiation exposure; and (vi) animal studies.

A stratified narrative synthesis was planned due to anticipated heterogeneity. Studies were categorized a priori into clinical comparative studies, clinical non-comparative studies, and experimental/ cadaveric model investigations. The latter were interpreted separately as proof-of-concept evidence and were not used to infer real-world occupational or patient radiation exposure.

Search strategy

Articles were systematically reviewed from the MEDLINE (PubMed), Embase, and Scopus databases. One author (J.E.C.) conducted the initial assessment of the electronic search results and promptly excluded duplicate records.

The remaining articles were then screened by two independent authors (J.E.C., L.D.R) based on the title, abstract, and publication type. Subsequently, a full-text screening was independently performed by two authors (J.E.C. and F.P.), followed by an extraction of relevant data (F.P., D.C.). Any conflicts or discrepancies were resolved by consensus and consultance with senior colleagues (V.G.E., G.C.).

The electronic search was performed on PubMed, Embase, and Scopus using relevant keywords, phrases, and medical subject headings (MeSH) terms. The search strategy applied and translated for Pubmed, Embase, and Scopus was:

("augmented reality"[Title/Abstract] OR "mixed reality"[Title/Abstract] OR "virtual reality"[Title/Abstract] OR AR[Title/Abstract] OR MR[Title/Abstract] OR "head-mounted display"[Title/Abstract] OR HMD[Title/Abstract] OR "holographic display"[Title/Abstract] OR "navigation system"[Title/Abstract])

AND

("spine surgery"[Title/Abstract] OR "spinal surgery"[Title/Abstract] OR "vertebral surgery"[Title/

Abstract] OR “spine procedure“[Title/Abstract] OR “spinal instrumentation“[Title/Abstract])

AND

(“radiation exposure“[Title/Abstract] OR “occupational radiation“[Title/Abstract] OR “radiation dose“[Title/Abstract] OR “radiation protection“[Title/Abstract] OR “radiation safety“[Title/Abstract] OR “fluoroscopy“[Title/Abstract] OR “scatter radiation“[Title/Abstract] OR “dosimeter“[Title/Abstract] OR “radiation“[Title/Abstract])

Data from each included study were extracted into a standardized spreadsheet capturing patient demographics, surgical indication and procedure, and relevant outcomes. All data were independently extracted by three authors (L.D.R, F.P., J.E.C), with discrepancies resolved by discussion or senior adjudication (G.C).

Methodological quality evaluation

Methodological evaluation of the included studies was assessed using the Cochrane RoB 2 tool for comparative studies [31], and the Joanna Briggs Institute (JBI) checklist for non-comparative studies [28]. The individual results for the included articles (Fig. 1) are summarised in Fig. 2; Table 1. Concerning cadaveric and synthetic model studies, as conventional quality assessment tools could not be applied, they were evaluated as good quality articles based on methodological rigor, fidelity to clinical conditions and the relevance of their outcomes.

Results

Study selection and PRISMA flow chart

A total of 654 articles were identified through the database search, with 132 articles from PubMed, 145 from Embase, and 377 from Scopus. After removing 230 duplicate records, 424 articles remained for screening. Of these, 399 articles were excluded during the initial title and abstract screening process for not meeting the inclusion criteria. 25 reports were sought for retrieval, with 3 reports not retrieved. The remaining 22 reports were assessed for eligibility, and 10 were excluded based on specific exclusion criteria. Ultimately, 12 studies met the inclusion criteria and were included in the final review.

The flow chart for study selection according to PRISMA is presented in Fig. 1.

Methodological quality evaluation

Risk of bias and quality assessment outcomes are summarized in Fig. 2; Table 1, with most studies demonstrating acceptable methodological quality.

Description of included studies

Hiranaka et al. [19] conducted a prospective experimental study using a synthetic lumbar spine model to evaluate smart glasses for percutaneous pedicle screw insertion. While accuracy and insertion times were comparable, fluoroscopy time and radiation exposure were significantly reduced, suggesting improved procedural safety without compromising precision.

Edström et al. [15] performed a prospective observational study of 20 patients undergoing AR-assisted pedicle screw placement. Using a hybrid OR with cone-beam CT, they reported markedly reduced occupational exposure with a learning effect, while patient doses remained within expected ranges.

Auloge et al. [3] prospectively compared AR/AI-guided versus fluoroscopy-assisted vertebroplasty in 20 patients. AR significantly reduced radiation exposure with similar accuracy, although it was associated with longer procedure times and increased resource use.

Bhatt et al. [5] conducted a prospective cohort study of 32 patients undergoing thoracolumbar fusion with AR navigation. High screw accuracy (97%) and low radiation exposure were reported, supporting AR as a safe and precise tool.

Charles et al. [13] retrospectively evaluated 20 patients undergoing minimally invasive transforaminal lumbar interbody fusion (TLIF) with AR navigation. High accuracy (94%) was achieved, with radiation exposure and operative times comparable to conventional navigation.

Carl et al. [9–12] evaluated microscope-based AR systems (Pentero/Pentero900) across multiple spinal indications, including degenerative conditions, intradural tumors, and spinal lesions. Across these studies, AR demonstrated high navigational accuracy, sub-millimeter precision, and consistently reduced patient radiation exposure, with reductions of up to 70% when low-dose intraoperative CT protocols were applied. Radiation exposure remained low particularly in intradural procedures, where imaging is limited to registration. Overall, these findings support the feasibility, safety, and integration of AR-assisted navigation in routine spinal surgery. In intradural or soft tissue–dominant procedures, radiation exposure is typically limited to registration imaging and does not constitute a fluoroscopy-intensive workflow. Accordingly, these studies have limited applicability to radiation-heavy instrumentation procedures.

Matsukawa et al. [25] conducted a pilot randomized study of 20 patients using smart glasses for lumbar fusion. The AR group showed slightly reduced operative and radiation times, with no compromise in safety.

Urakov et al. [32] performed a cadaveric study comparing AR-guided and fluoroscopy-guided screw placement. AR eliminated radiation and reduced operative time but showed lower accuracy due to registration errors.

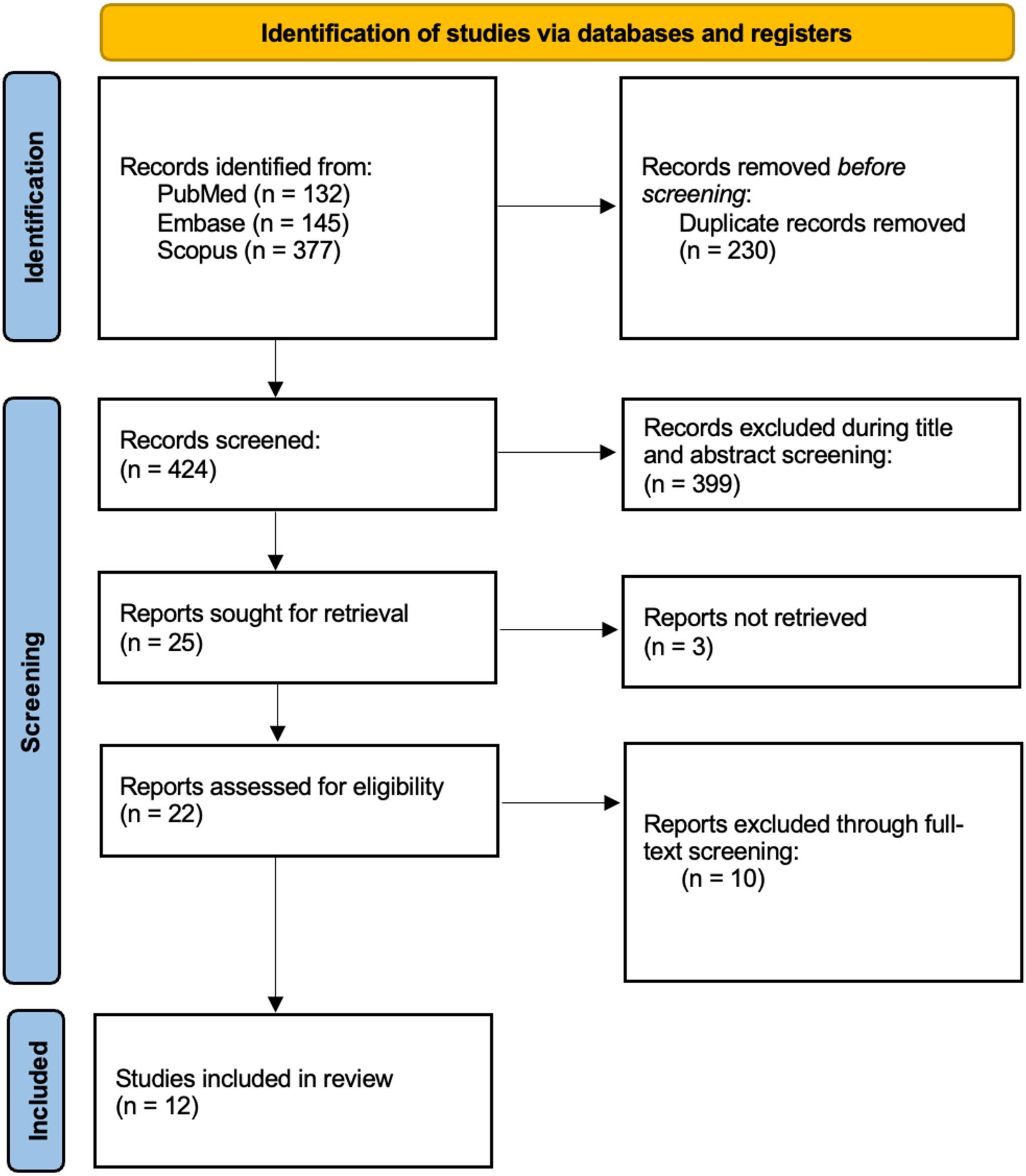
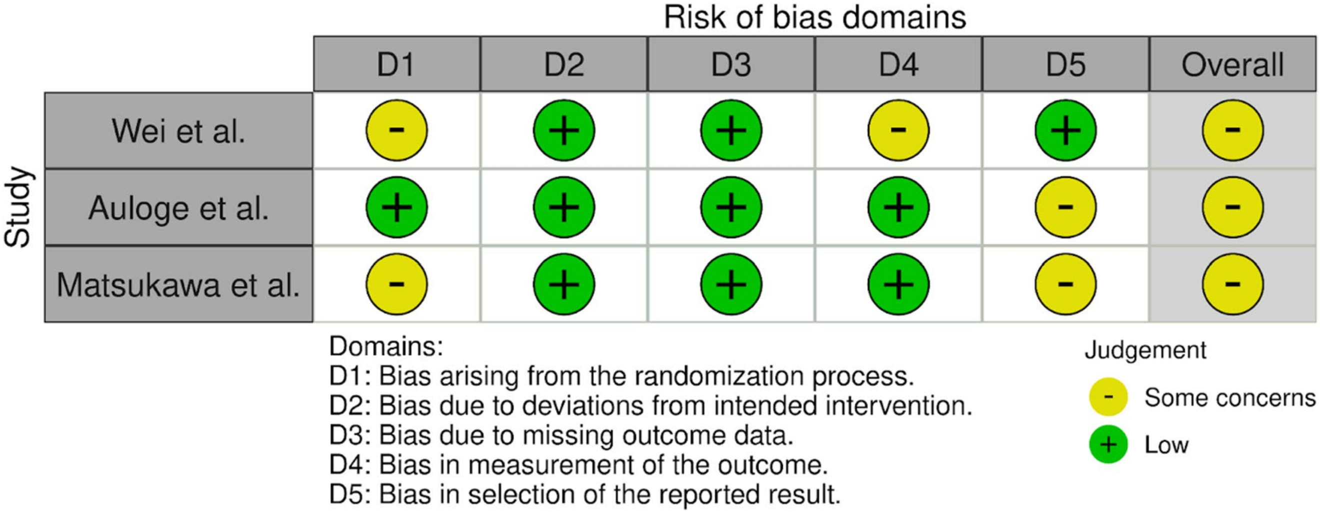


Fig. 1 Flow chart of study search and selection according to preferred reporting items for systematic reviews and meta-analyses (PRISMA)

Wei et al. [34] conducted a randomized study of 40 patients undergoing kyphoplasty. AR significantly reduced operative and fluoroscopy times while maintaining comparable accuracy.

Several clinical studies evaluated AR within 3D navigation workflows driven by cone-beam CT or intraoperative CT. In these settings, radiation exposure is largely



Risk of bias domains

Study	D1	D2	D3	D4	D5	Overall
Wei et al.	-	+	+	-	+	-
Auloge et al.	+	+	+	+	-	-
Matsukawa et al.	-	+	+	+	-	-

Domains:
D1: Bias arising from the randomization process.
D2: Bias due to deviations from intended intervention.
D3: Bias due to missing outcome data.
D4: Bias in measurement of the outcome.
D5: Bias in selection of the reported result.

Judgement
- Some concerns
+ Low

Fig. 2 Cochrane RoB 2 tool for quality evaluation of comparative trials

Table 1 JBI appraisal table for quality evaluation of non-comparative studies

Study	Overall appraisal
Edström et al. 2020	8/10
Carl et al. 2019	8/10
Carl et al. 2019	8/10
Carl et al. 2019	9/10
Carl et al. 2020	8/10
Bhatt et al. 2022	9/10
Charles et al. 2021	8/10

determined by the imaging strategy itself rather than AR visualization per se.

For interpretative clarity, included studies represent three distinct implementation patterns: (1) AR used as a visualization interface within fluoroscopy-based workflows, (2) AR integrated into 3D navigation paradigms such as cone-beam CT or intraoperative CT, and (3) experimental or cadaveric proof-of-concept investigations. These categories are referenced throughout the synthesis to contextualize radiation findings.

Table 2 Includes an overview of the study design of the included studies and their methodology.

Description of outcomes

Staff and patient dose

Staff radiation exposure was reported in two of the included studies, of which one using a synthetic lumbar spine model, thus analyzed separately [19]. Most investigations relied on patient dose metrics or surrogate endpoints such as fluoro time.

Edström et al. [15] using real-time active personal dosimeters (APDs) worn on the chest of all OR staff, calibrated for personal dose equivalent Hp(10). After excluding two procedures due to incomplete operator dose structured reports (ODSR), the average staff exposure per procedure was 0.21 ± 0.06 mSv. Furthermore, radiation protection measures included a 2 mm lead shield wall and a separate shielded remote control for the imaging technologist. To evaluate the effectiveness of such strategies, staff APD measurements were compared with a reference dosimeter attached to the C-arm, which represented a worst-case exposure scenario. Although the study was not comparative, the authors reported that occupational doses were significantly lower than those described in the literature.

Concerning patient radiation exposure, data were reported in nine of the included articles. Edström et al. [15] found an average exposure dose of 15.8 ± 1.8 mSv, with cone-beam CT accounting for 97 ± 1% of the total dose. Interestingly, radiation exposure was significantly correlated with the number of vertebrae treated ($r = 0.59$, $p < 0.05$) and the number of CBCT acquisitions ($r = 0.48$, $p < 0.05$), but not with patient characteristics such as BMI, weight, height, or age. Moreover, the average air kerma and DAP per procedure were 159 ± 16 mGy and 31.3 ± 2.8 Gy·cm², respectively. Additionally, implementation of a low-dose protocol for the final 10 procedures resulted in a 32% reduction in exposure dose and a 52% reduction in DAP per spinal level treated, without compromising image quality.

Auloge et al. [3] reported patient radiation exposure in terms of DAP during trocar deployment. Results showed that DAP was significantly lower in the AR/AI group compared than in the control group (182.6 ± 106.7 vs. 367.8 ± 184.7 mGy·cm²; $p = 0.025$): in particular, radiation dose

Table 2 Overview of the included studies

First author, Year	Country	Study design	Procedure	Imaging modality	AR system
Hiranaka et al. 2024	Japan	Study on human spine model	Percutaneous pedicle screw placement	Intraoperative fluoroscopy	MOVERIO Smart Glasses (SG) model BT-30E
Edström et al. 2020	Sweden	Prospective observational study	Pedicle screw placement	2D fluoroscopy for spinal level identification and iso-centering of the region of interest; 3D cone-beam computed tomography (CBCT) imaging	Hybrid OR using a ceiling-mounted robotic C-arm (Allura Clarity Flex move, Philips Healthcare, Best, the Netherlands), with an integrated navigation system implementing ARSN (Augmented Reality Surgical Navigation)
Matsukawa et al. 2020	Japan	Pilot prospective randomized study	Single-segment posterior lumbar interbody fusion	Intraoperative fluoroscopy	Smart glasses display device picoLinker, Westunitis (monocular see-through head-mounted display)
Carl et al. 2019	Germany	Case series	Surgery for intra- and extradural spinal lesions	Preoperative CT, MRI, PET, intraoperative CT	Microscope-based AR system (Pentero/Pentero900) with integrated heads-up display
Carl et al. 2019	Germany	Prospective case series	Degenerative spine surgeries	Preoperative CT and MRI, intraoperative CT	Microscope-based AR system (Pentero/Pentero900) with integrated heads-up display
Carl et al. 2019	Germany	Prospective study	Intradural spinal tumors resections	preoperative CT and MRI, intraoperative CT	Microscope-based AR system (Pentero/Pentero900) with integrated heads-up display
Carl et al. 2020	Germany	Prospective case-based observational study	NR	Preoperative automatic anatomical mapping and additional manual segmentation, intraoperative CT	Microscope-based AR system (Pentero/Pentero900) with integrated heads-up display
Urakov et al. 2019	USA	Cadaver lab session	Pedicle screw placement	Preoperative CT, postoperative CT scan	OpenSight (Novarad) on Hololens AR glasses (Microsoft, Redmond, Washington, USA)
Wei et al. 2019	China	Prospective randomized study	Percutaneous kyphoplasty	Preoperative plain radiography, CT, MRI, Intraoperative C-arm fluoroscopy	AR glasses HoloLens (Microsoft, USA) with CAD image into computer of MR system (Medivi)
Auloge et al. 2020	France	Prospective parallel randomised open trial	percutaneous vertebroplasty	MRI, CT, fluoroscopy	Four video cameras within the flat-panel detector of a standard C-arm fluoroscopy machine (Allura, release 8.1; Phillips Healthcare, Best, The Netherlands)
Bhatt et al. 2022	USA	Prospective cohort study	Thoracolumbar fusion	Intraoperative 3D imaging, fluoroscopy, intraoperative CT	xvision-Spine (XVS) system (Augmedics, Ltd, Philadelphia, PA)
Charles et al. 2021	France	Retrospective observational study	Percutaneous pedicle screw placement for minimally invasive transforaminal lumbar interbody fusion	Preoperative X-ray and CT, intraoperative fluoroscopy and CT	Hybrid OR (AlluraClarity Flexmove, Philips, the Netherlands) equipped with a video camera at each side of the detector frame for ARSN (Augmented Reality Navigation System)

during the targeting phase was reduced by 50% with AR/AI guidance compared to fluoroscopy alone.

In Bhatt et al. [5], the average 3D imaging radiation dose for screw placement using AR navigation was 576.8 ± 368.8 mGy·cm, and in 19 patients the mean radiation dose was 0.3 ± 0.4 mGy·m².

Charles et al. [13] reported radiation exposure as a secondary outcome, documented across three phases of the procedure: preparation, pedicle screw placement, and cage placement. Specifically, the average patient DAP was 35.9 ± 15.5 Gy·cm², of which 0.9 ± 1.0 Gy·cm² was attributed to fluoroscopy and 35.0 ± 15.0 Gy·cm² to CBCT. Moreover, during CBCT acquisition, all OR staff remained in a separate room to avoid ionizing radiation exposure. The authors also noted that factors such as patient BMI and imaging system parameters for both 2D and 3D modalities influence radiation dose.

Carl et al. [12], by implementing low-dose iCT protocols, achieved radiation exposures of 0.35–0.98 mSv for cervical, 2.16–6.92 mSv for thoracic, and 3.55–4.20 mSv for lumbar surgeries, representing a 70% reduction in effective dose compared with standard spinal helical CT scans. Low-dose iCT protocols have been included in Carl et al. [10], Carl et al. [11] and Carl et al. [9].

Fluoro time

The majority of comparative studies demonstrated a reduction in fluoroscopy time with AR-assisted workflows, though the magnitued and statistical significance varied.

Fluoroscopy time was documented in six of the included articles.

Matsukawa et al. [25] found the radiation exposure time to be lower in the smart glass group (picolinker Smart glasses) compared to the control group, although the difference was not significant (38.6 ± 6.6 vs. 41.8 ± 16.1 s, $p = 0.57$).

In Wei et al. [34], the cumulative time of radiation exposure in the group in which mixed reality technology was used is significantly lower than the one with the employment of traditional fluoroscopy (31.87 ± 9.77 vs. 76.94 ± 8.65 s, $p < 0.05$).

Furthermore, using a system of four video cameras within a flat panel detector of a C-arm machine, Auloge et al. [13] measured the fluoroscopy time for trocar deployment to be nearly half that of the traditional fluoroscopy procedure (5.2 ± 2.6 vs. 10.4 ± 4.1 s, $p = 0.005$).

Among the non-comparative studies, Edström et al. [15] measured an average time of 43 ± 5 seconds for 2D X-ray imaging, specifically used to identify the spinal level and achieve isocentering of the region of interest. Moreover, Bhatt et al. [5], using the xvision-Spine AR system (Augmedics, Ltd, Philadelphia, PA), recorded a mean total fluoroscopy time of 25.7 ± 29.8 s with AR-guided procedures. Similarly, in a retrospective observational study, Charles et al. [13] observed an average fluoroscopy time of 22.5 ± 10.1 s for percutaneous pedicle screw placement in TLIF procedures.

Operative time

Data on operative time were provided in four of the selected studies. In Matsukawa et al. [25] the operative time was found to be lower in the group with the Picolinker Smartglasses with respect to the control one (100.2 ± 10.4 vs. 105.5 ± 14.6 min). Analogously, the mixed reality through the AR HoloLens glasses (Microsoft, USA) used by Wei et al. [34] was found to significantly contribute to the reduction of the mean operative time, if compared to the control group (25.12 ± 5.36 vs. 45.14 ± 3.86 min, $p < 0.05$). This does not reflect the findings of Urakov et al. [32] (36 vs. 40 min), but this study is a cadaveric study and thus analyzed separately.

Finally, the non-comparative study by Charles et al. [13] reported an average operative time of 117 ± 11 min. Specifically, the preparation phase, screw placement phase, and cage placement phase accounted respectively for 3 ± 1% (3 ± 1 min), 36 ± 5% (43 ± 9 min), and 61 ± 5% (71 ± 7 min) of the total procedure. Furthermore, no correlation was observed between the operative time and BMI ($r = 0.23$, $p = 0.3356$), while a negative correlation was found between operative time and procedure number($r = -0.64$, $p = 0.0030$), suggesting a learning curve effect.

Experimental and model-based studies

Two included studies were conducted under non-clinical conditions and are therefore analyzed here. Hiranaka et al. [19], in their evaluation of smart glasses in a synthetic lumbar spine model for percutaneous pedicle screw insertion, found that fluoroscopy time was significantly reduced in the AR group compared with conventional guidance (109.1 ± 43.5 vs. 150.9 ± 38.7 s, $p = 0.003$). They also found that radiation dose was significantly lower in the group using smart AR glasses compared to the control group, both for the overall procedure (1.3 ± 0.6 mGy vs. 1.7 ± 0.5 mGy, $p = 0.023$) and for operator A (1.2 ± 0.4 mGy vs. 1.8 ± 0.5 mGy, $p = 0.013$).

Urakov et al. [32] performed a cadaveric study comparing AR-guided pedicle screw placement using OpenSight (Hololens) with conventional fluoroscopy. They noted that radiation was eliminated in the AR group, but total radiation from preoperative CT was not included in dose calculations, and screw accuracy was lower in the AR group due to registration-related errors.

Table 3 summarizes the results of the included studies.

Discussion

This systematic review evaluated the impact of AR on radiation exposure during spine surgery. Overall, twelve studies investigating outcomes related to radiation exposure, fluoroscopy time, and operative time were included and compared. Two studies specifically assessed staff exposure and found that AR technologies and optimized protective strategies consistently reduced occupational doses compared with conventional workflows or values reported in the literature [15, 19]. Regarding patient radiation exposures, studies generally reported favorable outcomes when AR guidance was used alongside low-dose protocols [3, 5, 9–13, 15, 32]. Of course, dose levels were influenced by procedural factors such as the number of vertebrae treated and cone-beam CT acquisitions [15], showing that radiation exposure can be influenced by multiple procedural factors. Most studies reported a reduction of fluoroscopy time with AR support compared to conventional fluoroscopy: significant decreases were observed in several studies [2, 19, 34], while others found non-significant results [25]. These reduced exposure times were reflected in the non-comparative studies [5, 13, 15]. Finally, operative time gave mixed results: while some studies observed shorter procedures with AR integration [25, 34], others reported comparable or slightly longer times relative to fluoroscopy [32].

As pointed out by Kim et al. [23], the three principles of radiation safety are time, distance, and shielding. Shielding can be achieved with lead aprons or lead shields, and Bohoun et al. [6] showed an almost 90% decrease in radiation measured inside compared to outside the apron. Similarly, previous studies showed a significant decrease in operator radiation dose when standing away from the imaging system [1, 15].

The use of intraoperative cone-beam CT has become popular and shown efficacy, but concern about the intraoperative radiation exposure remains high. Previous literature showed higher radiation exposure with CBCT compared to standard fluoroscopy, and in vitro studies demonstrated decreased radiation to the operator specifically [29, 30]. In spine surgery, prior narrative and systematic reviews report a trend toward lower radiation use when AR is employed. For instance, Burström et al. [7], in a 2021 systematic review considering all aspects of AR navigation in spine surgery, described five studies that assessed radiation exposure, and that generally documented reductions. In similar fashion, McCloskey et al. [26] conducted a systematic review in 2023, and included four studies demonstrating decreased radiation exposures in the AR group compared to the fluoroscopy group.

These observations reflect a plausible rationale: AR minimizes the need for repeated fluoroscopic checks or viewpoint shifting. MIS usually requires more fluoroscopy for visualization, increasing the risk of associated complications [18], and AR may reduce the dependency on “spot-check” X-ray verification. In a 2023 review, Avrumova et al. [4] describe how AR promises can be beneficial in MIS by eliminating repeated monitor shifts away from the field and by embedding navigation cues within the surgeon’s line of sight. It is important to note, however, that exposure levels in fluoroscopy may be affected by many factors, including the surgeon’s experience, the fluoroscopy technician’s aptitude, the extent of spinal fusion, imaging modalities among others [27].

A critical distinction must be made between AR as a visualization interface and the underlying imaging paradigm in which it is implemented. In several included studies, AR was embedded within cone-beam CT or intraoperative CT–based navigation systems, which independently modify radiation exposure patterns compared to conventional 2D fluoroscopy. Therefore, reductions in radiation observed in these contexts cannot be attributed solely to AR visualization. Similarly, when compared with standard CT- or O-arm–based navigation without AR visualization, overall radiation exposure is primarily dictated by the registration imaging protocol, and AR does not inherently alter the number of required CT acquisitions.

Despite its promise, the use of AR in spine surgery faces many limitations, of which we mention hardware or software failure, a demanding learning curve, and high dependence on the accuracy of imaging and registration [22], but studies are showing increasing accuracy and benefits. An additional aspect that remains unexplored is surgeon comfort and ergonomics when using AR systems. Several studies describe learning curve effects, but not many directly evaluate physical strain, visual fatigue, or overall ergonomic impact associated with HMDs or microscope-integrated overlays.

Our study remains limited by factors that warrant consideration. First, the number of studies directly assessing staff radiation exposure was limited. Second, the included studies were heterogeneous in design, which complicates direct comparison and precluded a meta-analysis. Also, sample sizes were generally small and single-center, limiting generalizability, and the diversity of AR platforms ranging from HMDs to microscope-based systems introduces variability in outcomes and hinders standardized evaluation. Publication bias can also not be excluded, since studies with favorable outcomes might have been more likely to be reported.

Table 3 Summary of the results of included studies

First author, year	Sample size, *N*		Flourscopy time		Staff radiation exposure		Patient radiation exposure		Screw accuracy		Operative time	
	AR	Non-AR	AR	Non-AR	AR	Non-AR	AR	Non-AR	AR	Non-AR	AR	Non-AR
Edström et al. 2020	20	NR	109.1 ± 43.5	150.9 ± 38.7	1.3 ± 0.6 mGy	1.7 ± 0.5 mGy	NR	NR	80%	70%	NR	NR
Matsukawa et al. 2020	20	NR	43 ± 5	NR	0.21 ± 0.06 µSv	NR	15.8 ± 1.8 mSv	NR	NR	NR	NR	NR
Carl et al. 2019	10	10	38.6 ± 6.6	41.8 ± 16.1	NR	NR	NR	NR	NR	NR	100.2 ± 10.4	105.5 ± 14.6
Carl et al. 2019	10	NR	NR	NR	NR	NR	Cervical: 0.35–0.98 mSv Thoracic: 2.16–6.92 mSv Lumbar: 3.55–4.20 mSv	NR	TRE in the range of 1 mm	NR	NR	NR
Carl et al. 2019	10	NR	NR	NR	NR	NR	3.38 ± 2.22 mSv	NR	TRE: 1.11 ± 0.42 mm	NR	NR	NR
Carl et al. 2020	10	NR	NR	NR	NR	NR	Cervical: 0.22 ± 0.16 mSv Thoracic: 1.68 ± 0.61 mSv	NR	TRE: 0.72 ± 0.24 mm	NR	NR	NR
Urakov et al. 2019	42	NR	NR	NR	NR	NR	Cervical: 0.29 ± 0.17 mSv Thoracic: 3.40 ± 2.38 mSv Lumbar: 3.05 ± 0.89 mSv	NR	TRE: 0.87 ± 0.28 mm	NR	NR	NR
Wei et al. 2019	NA (19 screws)	NA (19 screws)	0	158.7	NR	NR	0 [mGy·m²]	0.90505 [mGy·m²]	NR	NR	40	36
Auloge et al. 2020	20	20	31.87 ± 9.77	76.94 ± 8.65	NR	NR	NR	NR	NR	NR	25.12 ± 5.36	45.14 ± 3.86
Bhatt et al. 2022	10	10	5.2 ± 2.6	10.4 ± 4.1 s	NR	NR	(DAP during trocar deployment): 182.6 ± 106.7 mGy·cm2	(DAP during trocar deployment): 367.8 ± 184.7 mGy·cm2	NR	NR	NR	NR
Charles et al. 2021	32	0	25.7 ± 29.8 (referred to 27 patients)	NR	NR	NR	576.8 ± 368.8 mGy·cm	NR	98.20%	NR	NR	NR
Charles et al. 2021	20	0	22.5 ± 10.1	NR	NR	NR	35.9 ± 15.5 Gy·cm2	NR	Gertzbein scale: Grade 0: 62%; Grade 1: 13%; Grade 2: 5%	NR	117 ± 11	NR

It becomes evident that in several studies, radiation exposure is primarily determined by the unerlying imaging/navigation strategy rather than AR visualization alone. Therefore, the independent radiation-reducing contribution of AR could not be isolated in many reports.

Future studies should include multicenter randomized trials and prospective cohort studies with staff radiation as a primary outcome, alongside cost-effectiveness analyses. Continued refinement of AR technology, integration with low-dose imaging, and evaluation of learning curve effects will be essential to establish its role in routine spine surgery. The currently ongoing SPInal NAVigation (SPINAV) trial [17] compares AR and conventional surgical navigation to free-hand technique, and will explore among the secondary outcomes radiation exposure.

Conclusion

Current evidence suggests that AR-integrated navigation worflows may reduce reliance on continuous fluoroscopy during selected spine procedures. It could have a role in reducing radiation exposure for both staff and patients during spine surgery, while maintaining accuracy and procedural safety.

Current evidence is limited by small sample sizes, heterogeneous study designs, and few direct assessments of staff dose. Further high-quality, multicenter trials are needed to confirm these findings and define the role of AR as a reliable strategy for occupational radiation safety in spine surgery.

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References

1. Abdullah KG, Bishop FS, Lubelski D et al (2012) Radiation exposure to the spine surgeon in lumbar and thoracolumbar fusions with the use of an intraoperative computed tomographic 3-dimensional imaging system. Spine 37(17):E1074–E1078
2. Anon (1999) Summary of health effects of ionizing radiation. In: Toxicological Profile for Ionizing Radiation. Agency for Toxic Substances and Disease Registry (US). Available at: https://www.ncbi.nlm.nih.gov/books/NBK597567/. Accessed 28 Sept 2025
3. Auloge P, Cazzato RL, Ramamurthy N et al (2020) Augmented reality and artificial intelligence-based navigation during percutaneous vertebroplasty: a pilot randomised clinical trial. Eur Spine J Off Publ Eur Spine Soc Eur Spinal Deform Soc Eur Sect Cerv Spine Res Soc 29(7):1580–1589
4. Avrumova F, Lebl DR (2022) Augmented reality for minimally invasive spinal surgery. Front Surg 9:1086988
5. Bhatt FR, Orosz LD, Tewari A et al (2023) Augmented reality-assisted spine surgery: an early experience demonstrating safety and accuracy with 218 Screws. Glob Spine J 13(7):2047–2052
6. Bohoun CA, Naito K, Yamagata T et al (2019) Safety and accuracy of spinal instrumentation surgery in a hybrid operating room with an intraoperative cone-beam computed tomography. Neurosurg Rev 42(2):417–426
7. Burström G, Persson O, Edström E, Elmi-Terander A (2021) Augmented reality navigation in spine surgery: a systematic review. Acta Neurochir (Wien) 163(3):843–852
8. Butler RB, Kornelis AP (2008) Risks of excessive intraoperative radiation. Semin Spine Surg 20(3):175–180
9. Carl B, Bopp M, Saß B et al (2020) Spine surgery supported by augmented reality. Glob Spine J 10(2 Suppl):41S–55S
10. Carl B, Bopp M, Saß B, Nimsky C (2019) Microscope-based augmented reality in degenerative spine surgery: initial experience. World Neurosurg 128:e541–e551
11. Carl B, Bopp M, Saß B, Pojskic M, Nimsky C (2019) Augmented reality in intradural spinal tumor surgery. Acta Neurochir (Wien) 161(10):2181–2193
12. Carl B, Bopp M, Saß B, Voellger B, Nimsky C (2019) Implementation of augmented reality support in spine surgery. Eur Spine J Off Publ Eur Spine Soc Eur Spinal Deform Soc Eur Sect Cerv Spine Res Soc 28(7):1697–1711
13. Charles YP, Cazzato RL, Nachabe R et al (2021) Minimally invasive transforaminal lumbar interbody fusion using augmented reality surgical navigation for percutaneous pedicle screw placement. Clin Spine Surg 34(7):E415–E424

14. Di Cosmo L, El Choueiri J, Pellicanò F et al (2025) From experimental to essential: the evolving role of augmented reality in neurosurgery (2012–2024). Neurochirurgie 71(4):101672
15. Edström E, Burström G, Omar A et al (2020) Augmented reality surgical navigation in spine surgery to minimize staff radiation exposure. Spine 45(1):E45–E53
16. El Choueiri J (2025) Augmented reality in spinal neurosurgery: a bibliometric analysis of trends and clinical applications. World Neurosurg 200:124204
17. El-Hajj VG, Charalampidis A, Fell D et al (2025) Study protocol: the SPInal NAVigation (SPINAV) trial – comparison of augmented reality surgical navigation, conventional image-guided navigation, and free-hand technique for pedicle screw placement in spinal deformity surgery. BMC Musculoskelet Disord 26(1):543
18. Godzik J, Mastorakos GM, Nayar G, Hunter WD, Tumialán LM (2020) Surgeon and staff radiation exposure in minimally invasive spinal surgery: prospective series using a personal dosimeter. J Neurosurg Spine 32(6):817–823
19. Hiranaka Y, Takeoka Y, Yurube T et al (2024) The utility and feasibility of smart glasses in spine surgery: minimizing radiation exposure during percutaneous pedicle screw insertion. Neurospine 21(2):432–439
20. Hyun S-J (2016) Efficiency of lead aprons in blocking radiation – how protective are they? Heliyon 2(5):e00117
21. Jenkins NW, Parrish JM, Sheha ED, Singh K (2021) Intraoperative risks of radiation exposure for the surgeon and patient. Ann Transl Med 9(1):84
22. Khor WS, Baker B, Amin K et al (2016) Augmented and virtual reality in surgery-the digital surgical environment: applications, limitations and legal pitfalls. Ann Transl Med 4(23):454
23. Kim JH (2018) Three principles for radiation safety: time, distance, and shielding. Korean J Pain 31(3):145–146
24. Liberati A, Altman DG, Tetzlaff J et al (2009) The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. BMJ 339:b2700
25. Matsukawa K, Yato Y (2021) Smart glasses display device for fluoroscopically guided minimally invasive spinal instrumentation surgery: a preliminary study. J Neurosurg Spine 34(1):150–154
26. McCloskey K, Turlip R, Ahmad HS et al (2023) Virtual and augmented reality in spine surgery: a systematic review. World Neurosurg 173:96–107
27. Mulconrey DS (2016) Fluoroscopic radiation exposure in spinal surgery: in vivo evaluation for operating room personnel. Clin Spine Surg 29(7):E331–335
28. Munn Z, Barker TH, Moola S et al (2020) Methodological quality of case series studies: an introduction to the JBI critical appraisal tool. JBI Evid Synth 18(10):2127–2133
29. O'Donnell C, Maertens A, Bompadre V, Wagner TA, Krengel W (2014) Comparative radiation exposure using standard fluoroscopy versus cone-beam computed tomography for posterior instrumented fusion in adolescent idiopathic scoliosis. Spine 39(14):E850–855
30. Smith HE, Welsch MD, Sasso RC, Vaccaro AR (2008) Comparison of radiation exposure in lumbar pedicle screw placement with fluoroscopy vs computer-assisted image guidance with intraoperative three-dimensional imaging. J Spinal Cord Med 31(5):532–537
31. Sterne JAC, Savović J, Page MJ et al (2019) RoB 2: a revised tool for assessing risk of bias in randomised trials. BMJ 366:l4898
32. Urakov TM, Wang MY, Levi AD (2019) Workflow caveats in augmented reality-assisted pedicle instrumentation: cadaver lab. World Neurosurg 126:e1449–e1455
33. Watanabe S, Nakanishi K, Mura M et al (2024) Investigation of radiation exposure of medical staff during lateral fluoroscopy for posterior spinal fusion surgery. J Clin Med 13(21):6442
34. Wei P, Yao Q, Xu Y et al (2019) Percutaneous kyphoplasty assisted with/without mixed reality technology in treatment of OVCF with IVC: a prospective study. J Orthop Surg 14(1):255
35. Wilson BR, Wang TY, O'Toole J (2025) Augmented reality in spine surgery. Neurosurgery 96(3S):S103
36. Zhao Q, Zhang H, Hao D et al (2018) Complications of percutaneous pedicle screw fixation in treating thoracolumbar and lumbar fracture. Med (Baltim) 97(29):e11560