ELSEVIER

Operative Techniques in
Orthopaedics

Augmented Reality in Spine Surgery Narrative Review: Seeing is Believing

Antoinette J. Charles,* Emily Luo,* Alissa Arango,* Dana Rowe,* C. Rory Goodwin,† and Melissa M. Erickson‡

In recent years, augmented reality (AR) has emerged as a promising technology in spine surgery. Its benefits are numerous, including enhanced surgical accuracy, improved anatomic approximation, and uninterrupted visualization. It has proven particularly valuable in spinal fusion, allowing for meticulous planning of screw trajectories and precise alignment of screws, plates, and implants, resulting in low complication rates. Additionally, AR reduces radiation exposure by minimizing the need for intraoperative fluoroscopy. The technology has also been utilized for surgical education and training, enabling real-time feedback through telementoring. However, challenges exist. Discomfort and wearability issues are reported with current AR models, and the need for 3D image rendering prolongs procedure time. Accuracy is compromised in patients with larger body habitus, necessitating improvements in calibration to individual anatomies. Cost is another significant challenge as it requires advanced imaging capabilities in operating rooms, along with expenses for AR hardware, software, training, and personnel. Ongoing research is necessary to evaluate the sustained benefits and potential complications of AR in spine surgery. While AR demonstrates advantages in terms of patient outcomes and surgical accuracy, continued optimization is essential to enhance accessibility and success in spine surgery and orthopaedic surgery as a whole.
Oper Tech Orthop 33:101068

KEYWORDS accuracy, augmented reality, pedicle screw, surgical navigation, virtual reality

Introduction

Spine surgery is a complex and highly specialized field that requires precise and accurate execution to achieve optimal clinical outcomes. The conventional technique of spine surgery has involved the free-hand (FH) surgical technique, which requires use of anatomical landmarks to identify the entry point and trajectory for pedicle screw placement.[1] More advanced techniques have introduced intraoperative image-guided navigation that have improved accuracy.[2] However, there are still limitations in image-guided navigation with the lack of real-time guidance during the surgical procedure.[3]

In recent years, augmented reality (AR) has emerged as a promising technology in the field of orthopaedics that has the potential to revolutionize the way spine surgery is performed. AR provides multiple benefits during spine surgery, including being used to overlay preoperative imaging data onto the patient's anatomy, providing surgeons with a more detailed understanding of the underlying pathology, and eliminating the need to interrupt visualization of the patient while operating.[4,5] The primary types of AR technology used in spine surgery have included AR surgical navigation, microscope-mediated heads-up display, and AR head-mounted displays.[6]

While there have been several reviews investigating the literature on the utility and accuracy of AR in spine surgery particularly in regard to spine instrumentation and pedicle screw placement, these studies have been primarily focused on the

*Duke University School of Medicine, Durham, NC.
†Department of Neurosurgery, Duke University, Durham, NC.
‡Department of Orthopaedic Surgery, Duke University, Durham, NC.
Declaration of Interest Statement: The authors report no conflicts of interest.
Address reprint requests to Melissa M. Erickson, Department of Orthopaedic Surgery, Duke University, Durham, NC. E-mail: melissa.erickson@duke.edu

https://doi.org/10.1016/j.oto.2023.101068
1048-6666/

utility, intraoperative technology, accuracy, workflow, and teaching of AR technology.[6-10] Few reviews have explored patient outcomes in depth or analyzed factors including the challenges associated with using AR technology.

The objective of this narrative review is to provide an updated summary on the different types of studies of AR technologies in spine surgery, assess the clinical outcomes and technical outcomes of AR technology, and to understand the application of AR in spine surgery.

Methods

Study Design

In this study, a narrative review approach was chosen to explore the use of AR in the context of spinal surgery. This design allows for qualitative analysis and interpretation of the findings, enabling an understanding of the current state of knowledge in the field.

Search Strategy and Selection Criteria

The search strategy involved an extensive literature search conducted by a qualified medical librarian. The librarian developed the search strategy, which was implemented using the MEDLINE database. The search encompassed the period from January 1st, 2000, to the present (May 8th, 2023), and duplicate references were eliminated. The search terms focused on spinal surgery (eg, spinal fusion, spine, spines, spinal, vertebrae, vertebral, back, surgery, operation, reoperation, fusion, fixation) and AR (eg, AR, imaging, 3-dimensional, augmented, mixed, 3D, imaging). To refine the results, unwanted publications such as editorials, letters, comments, and systematic reviews were excluded. The search strategy involved the use of MeSH terms and relevant keywords (full search strategy: Supplemental Table A). To screen the titles and abstracts, predetermined inclusion, and exclusion criteria were applied based on the population, intervention, comparison, and outcome (PICO) framework (Table 1).

Study Selection

The study selection process involved a 3-step screening procedure. The results from the database search were managed using Zotero, a reference management software that aided in identifying potential duplicate studies for removal. Three reviewers (A.J.C., E.L., A.A.) independently screened the titles, and 2 reviewers (A.J.C., E.L.) assessed the abstracts based on the inclusion criteria. Full texts were evaluated for eligibility, and any remaining duplicates were eliminated. In cases of disagreement during the full-text selection, an independent reviewer (A.A.) was consulted to resolve the discrepancies.

Data Collection

Data extraction encompassed study characteristics, clinical outcomes, technical outcomes, and applicability outcomes. The following details were recorded for study characteristics: study author, year, journal, study design, study duration, sample size, type of spine surgery (eg, degenerative, deformity, tumor, trauma, or infection), anatomic approach to spine surgery (eg, cervical, thoracic, lumbar, sacral),

Table 1 Inclusion and Exclusion Criteria

	Key Concepts	Inclusion Criteria	Exclusion Criteria
Population or problem of interest	Adult and children patients undergoing spine surgery	Adult and children patients spine surgery for any pathology	Non-English language studies
Interventions or exposure of interest	Augmented reality technology	The use of augmented reality technology during any stage of the spine surgery procedure	The use of any other technology other than augmented reality during spine surgery
Comparison	Standard techniques without the use of AR	Standard techniques without the use of AR	
Outcome	Clinical outcomes: mortality (any time point), intraoperative or postoperative morbidities, length of stay, readmission rates, reoperation rates, health related quality of life, functional outcomes (general) Technique outcomes: safety, accuracy, efficiency (eg, length of surgery)	Studies report on any of the listed outcomes	Studies that do not report on any of the listed outcomes or do not have any quantitative data.
Study types	Randomized controlled trials, case-series, cohort studies (retrospective, prospective, ambispective)	Human studies	Systematic and narrative reviews articles, case reports, abstracts without a published full text article, letters, editorials

percentage of male participants, mean or median age, and type of AR technology employed (Table 2). Clinical outcomes reported in the review included mortality, adverse events/complications, length of stay, readmission, and reoperation/revision (Table 3). Technical outcomes encompassed safety, accuracy, efficiency, and radiation dose/exposure (Table 4). Applicability outcomes considered included cost, surgeon satisfaction, education and training, and identified challenges (Table 5).

Results

Literature Search and Selection

Our initial database search returned 3211 articles. Two duplicate studies were removed. After title screening, 3104 studies were excluded and 105 studies underwent abstract screening. Seventy-two abstracts were excluded and 33 full-texts were assessed for eligibility. After evaluating for inclusion criteria, 16 studies were included for the final narrative review. Figure 1 summarizes the selection process.

Study and Cohort Characteristics

The 16 eligible studies were described qualitatively as part of the narrative review (Table 1). The 16 studies included 8 prospective cohort studies, 3 cross sectional studies, 2 retrospective cohort studies, 1 prospective randomized control trial, 1 case series, and 1 retrospective case series. Two of these studies involved human cadavers. One study was focused on resident and attending surgeon performance. Study duration ranged from 2 to 52 months with a mean duration of 12.6 months.

The total sample size of reported studies included in the study was 466 patients, 10 cadavers, 10 resident surgeons, and 4 attending surgeons. For reported studies, there were 206 male patients (47.5%) and 228 female patients (52.5%). The study participant age ranged from 16 to 96 years. Indications for spinal surgery included degenerative disease (n = 202, 51.4%), spinal deformity (n = 88, 22.4%), tumor/metastases/spinal lesion (n = 56, 14.2%), infection (n = 4, 1.0%), and other (n = 43, 10.9%) which included pseudoarthrosis, instability, osteoporosis, post-laminectomy syndrome, spinal stenosis, and other. Anatomic approaches included cervical (n = 32 cases, 16.2%), cervicothoracic (n = 1 case, 0.5%), thoracic (n = 41 cases, 20.8%), thoracolumbar (n = 6 cases, 3.0%), and lumbar (n = 117 cases, 59.4%). Of the 16 studies, 8 (50%) used an AR head mount or lens system, 5 (31.3%) used an AR navigation guidance system, and 3 (18.8%) used a microscope based AR system.

Clinical Outcomes

The clinical outcomes that were examined can be found in Table 2. Out of the 16 studies included, 8 reported on clinical outcomes. Furthermore, 2 examined mortality, 7 examined adverse events/complications, 2 examined length of hospital stay, and 2 examined reoperation/revision surgery. Of the 2 studies analyzing mortality, 1 patient died due to cardiorespiratory failure and 1 patient died due to metastatic disease. Adverse events and complications were minimal, with 5 of the 7 studies reporting no adverse events or complications. No intraoperative complications were reported. Two studies reported postoperative adverse events totaling 4 patients that included deep vein thrombosis, pneumonia, issues with wound healing/postoperative bleeding, pleural effusion, and pulmonary embolism. Two studies reported on length of stay, ranging from 4.1 to 5.5 days. One study found that the AR surgery group had a significantly shorter length of stay compared to the control. In regards to reoperation/revision, 1 study reported 0% reoperation and another study had 1 patient requiring reoperation for a deformity case.

Technical Outcomes

Table 3 summarizes the technical outcomes that were examined. The technical outcomes that were analyzed included accuracy (n = 13 studies), efficiency of surgery (n = 8 studies), and radiation exposure/dose (n = 6 studies). In regard to accuracy, 5 studies reported on accuracy of screw placement with means ranging from 94.1% to 100%. Three studies examined registration error with means ranging from 0.84 mm to 1 mm. Three studies showed no difference in accuracy compared to the control group. Overall, AR was able to improve intraoperative accuracy. In terms of efficiency of surgery, nearly all studies found that AR was less efficient, with more time required for marking, trocar placement, screw placement, and overall procedure time. One study found no difference between the AR and control group. In regard to radiation exposure and dosing, 3 studies reported significantly lower radiation doses compared to the control group. Two studies reported a patient effective dose for exposure ranging from 0.29 mSv to 15.8 mSv.

Applicability Outcomes

Applicability outcomes are summarized in Table 5. Outcomes that were evaluated included cost (n = 1 study), surgeon satisfaction (n = 6 studies), education and training (n = 2 studies), and identified challenges (n = 4 studies). One study reported that the cost of AR technology ranged from $4000 to $30,000 per year to purchase the head-mounted device and to use the AR software. Six studies analyzed surgeon satisfaction. Overall, surgeons enjoyed utilizing the AR technology although there was mixed feedback regarding wearability and comfort. Two studies reported mechanical discomfort with wearing the headset as well as sensory overload and visual discomfort, although 1 study reported positively on wearability and comfort. Two studies noted that it was helpful to be able to turn the display on/off or to use an abstract visualization at times in order to decrease the amount of distracting information present. One study notes that AR was helpful in visualization of structures. Two studies reported on the utility of AR for education and training and found that the technology was valuable as a teaching

Table 2 Study Demographics

Study Author	Year	Journal	Study Design	Study Duration	Sample Size	Type of Spine Surgery	Anatomic Approach of Spine Surgery	% Male (Total Number)	Mean or Median Age (Years)	Type of AR Technology
Aoyama	2022	Spine Surgery and Related Research	Prospective cohort study	8 mo	49	NR	Cervical: 20 Thoracic: 1 Lumbar: 28	61% (n = 30)	68.1	Head mounted display projecting hologram
Auloge	2020	European Spine Journal	Randomized control trial	4 mo	20	Degenerative: 16 Tumor: 2 Trauma: 2	Thoracic: 1 Lumbar: 19	35% (n = 7)	78.0 +/- 10.1	AR/AI-guidance of trocar placement
Bhatt	2022	Global Spine Journal	Prospective cohort study	10 mo	32	Deformity: 6 Degenerative: 26	NR	40.6% (n = 13)	50.9 +/- 15.0	Head mounted AR device
Butler	2023	The Spine Journal	Prospective cohort study	21 mo	165	Deformity: 3 Degenerative: 156 Tumor: 6	Thoracic: number not specified Lumbar: number not specified	50% (n = 83)	59.74	Wireless headset with integrated AR display, xvision system (Augmedics Inc., Arlington Heights, IL, USA)
Carl	2019	European Spine Journal	Prospective cohort study	2 mo	10	Tumor: 9 Infection: 1	Cervical: 2 Thoracic: 6 Lumbar: 2	50% (n = 5)	NR	Microscope based AR
Carl	2020	Global Spine Journal	Prospective cohort study	9 mo	41	Tumor: 20 Intradural lesion: 7 Degenerative: 11 Infections: 2 Deformities: 2	Cervical: 10 Cervicothoracic: 1 Thoracic: 16 Lumbar: 15	44% (n = 18)	57.3	Operating microscope head-ups displays
Cofano	2021	Frontiers in Surgery	Case series	7 mo	12	Degenerative: 12	Lumbar: 12	NR	NR	AR goggles (the Epson BT-300 and BT-350) Head-mounted display (HMD) technology Software: TeamViewer Pilot
Edstrom	2020	Spine	Retrospective cohort study	NR	44	Deformity: 44	NR	43% (n = 19)	Navigation group: 28.3 Control group: 27.8	AR surgical navigation
Edstrom	2020	Spine	Prospective cohort study	10 mo	20	NR	NR	NR	18.5	Integrated AR surgical navigation system in a robotic C-arm
Elmi-Terander	2018	Spine	Prospective cohort study	10 mo	20	Degenerative: 1 Deformity: 19	Thoracic: number not specified Lumbar: number not specified	45% (n = 9)	30.5	Augmented Reality Navigation System in a 3D cone-beam CT scan
Fritz	2014	Cardiovascular and Interventional Radiology	Cross-sectional study	NA	5	NR	Thoracic: 5 Lumbar: 20	80% (n = 4)	73	AR image overlay navigation system 3D Slicer Visualization software

Table 2 (*Continued*)

Study Author	Year	Journal	Study Design	Study Duration	Sample Size	Type of Spine Surgery	Anatomic Approach of Spine Surgery	% Male (Total Number)	Mean or Median Age (Years)	Type of AR Technology
Liu	2022	Journal of Neurosurgery Spine	Retrospective cohort study	6 mo	28	Tumor: 3 Degenerative: 12 Deformity: 12 Trauma: 1	Thoracic: number not specified Lumbar: number not specified	39% (n = 11)	62.5 (IQR 13.8)	AR Head Mount Device (xvision; Augmedics)
Molina	2021	Journal of Neurosurgery Spine	Cross-sectional study	NA	5	NR	Thoracic: number not specified Lumbar: number not specified	NR	NR	AR Head Mount Device (xvision; Augmedics)
Pojskić	2021	Brain Sciences	Prospective cohort study	52 mo	16	Tumor: 4 Trauma: 3 Degenerative:7 Infection: 1 Other: 1	Thoracic: 10 Thorcolumbar: 2 Lumbar: 4	37.5% (n = 6)	59	Heads-up display (Kinevo900)
Wolf	2023	International Journal of Computer Assisted Radiology and Surgery	Cross-sectional study	NR	14	NR	Lumbar: 14	NR	NR	AR HoloLens
Yahanda	2021	Neurosurgical Focus	Case series	NR	9	Degenerative: 3 Deformity: 2 Infection: 1 Tumor: 4	Thoracic: 2 Thorcolumbar: 4 Lumbar: 3	66.6% (n = 5)	71.9	AR head-mounted display

Table 3 Clinical Outcomes

Study Author	Clinical Outcomes Examined	Mortality	Adverse Events/ Complications	Length of Stay	Readmission	Reoperation/ Revision
Aoyama 2022	NR	NR	NR	NR	NR	NR
Auloge 2020	Complications	NR	No complications in the cohort	NR	NR	NR
Bhatt 2022	Complications, revision surgery, length of stay	NR	There were no reported surgical complications (n = 0, 0%). There were 3 reported postoperative adverse event: deep vein thrombosis (n = 1, 3.1%) and pneumonia (n = 2, 6.3%)	The average length of stay was 4.1 +/− 1.6 days.	NR	There were no reported reoperations in this cohort.
Butler 2023	NR	NR	NR	NR	NR	NR
Carl 2019	NR	NR	NR	NR	NR	NR
Carl 2020	Reoperation	NR	NR	NR	NR	One patient (n = 1, 2.3%) had a reoperation for a deformity case
Cofano 2021	Complications	NR	No complications were linked to the use of AR, such as malfunction of neuromonitoring, neuronavigation system, or infections	NR	NR	NR
Edstrom 2020	LOS, complications	NR	For the AR surgical navigation group, the blood loss (mL) was on average 670 mL while it was on average 1306 mL for the control group. Blood loss was significantly lower for the ARSN group ($P < 0.01$).	The LOS for the AR surgical navigation group was on average 5.5 days compared to 8.2 days for the control group. It was significantly lower in the ARSN group ($P < 0.01$).	NR	NR
Edstrom 2020	NR	NR	NR	NR	NR	NR
Elmi-Terander 2018	Adverse events	NR	No device-related adverse events occurred in the cohort	NR	NR	NR
Fritz 2014	NR	NR	NR	NR	NR	NR
Liu 2022	NR	NR	NR	NR	NR	NR
Molina 2021	NR	NR	NR	NR	NR	NR
Pojskić 2021	Mortality, adverse events/ complications	One patient died due to cardiorespiratory failure	One patient had several postoperative complications: wound healing deficit, postoperative bleeding, pleural effusion, and pulmonary embolism	NR	NR	NR
Wolf 2023	NR	NR	NR	NR	NR	NR
Yahanda 2021	Mortality, adverse events/ complications	One patient died due to metastatic cancer	No postoperative complications	NR	NR	NR

Table 4 Technical Outcomes

Study Author	Technical Outcomes Examined	Safety	Accuracy	Efficiency	Radiation Dose/Exposure
Aoyama 2022	Accuracy, efficiency	NR	The misidentification rates by palpation with a head-mounted display (HMD) were 0% (0/20) for cervical, 100% (1/1) for thoracic, and 21.4% (6/28) for lumbar. Without the HMD, the misidentification rates were 5% (1/20) for cervical, 100% (1/1) for thoracic, and 39.3% (11/28) for lumbar. When the HMD was not used, the level misidentification occurred within 2 vertebral bodies. However, when the HMD was used, the level misidentification reduced to within 1 vertebral body.	Marking with the head-mounted display HMD takes approximately 2 minutes longer compared to normal marking.	NR
Auloge 2020	Accuracy, efficiency, radiation exposure/dose	NR	The AI/AR accuracy in the sagittal plane was 1.68 +/− 0.25 mm (skin entry point) and 1.02 +/− 0.26 mm (trocar tip), while in the coronal plane, it was 1.88 +/− 0.28 mm (skin entry point) and 0.86 +/− 0.17 mm (trocar tip). There was no significant difference compared to the control group ($P > 0.05$).	The AI/AR time for trocar deployment was significantly longer at 642 +/− 210 seconds compared to the control group at 336 +/− 60 seconds ($P = 0.001$).	The AR/AI dose-area product was significantly lower at 182.6 +/− 106.7 mGy cm2 compared to the control group at 367.8 +/− 184.7 mGy cm2 ($P = 0.025$). The AR/AI fluoroscopy time was significantly lower at 5.2 +/− 2.6 seconds compared to the control group at 10.4 +/− 4.1 seconds ($P = 0.005$).
Bhatt 2022	Accuracy, radiation exposure/dose	NR	Out of the AR placed screws, 97.1% were considered clinically accurate, with 91.8% classified as Grade A and 5.3% classified as Grade B.	NR	In AR navigation with 3D imaging, the radiation dose was measured at 576.8 +/− 368.8 mGycm, with an average fluoroscopy time of 25.7 +/− 29.8 seconds. Among the 19 patients (70.4%), the mean radiation dose was 0.3 +/− 0.4 mGym2.
Butler 2023	Efficiency	NR	NR	The average time for screw placement was 3 minutes and 54 seconds per screw (median: 4 minutes and 8 seconds per screw, range: 1 minute and 10 seconds to 6 minutes and 30 seconds per screw). There were similar surgical times observed between early cases and later cases with more experience, as indicated by the mean time per screw. In the first 20 cases, the mean time per screw was 4 minutes and 1 second, while in the final 20 cases, it was 3 minutes and 52 seconds ($P = 0.48$).	NR
Carl 2019	Accuracy, efficiency, radiation exposure/dose	NR	The mean registration error was approximately 1 mm.	The entire process of intraoperative registration imaging added approximately 5 minutes to the procedure.	The low-dose iCT protocol reduced the effective radiation dose by approximately 70% compared to the standard spinal helical scan: cervical (0.35-0.98 mSv), thoracic (2.16-6.92 mSv), and lumbar (3.55-4.20 mSv).

Table 4 (*Continued*)

Study Author	Technical Outcomes Examined	Safety	Accuracy	Efficiency	Radiation Dose/Exposure
Carl 2020	Accuracy, efficiency, radiation exposure/ dose	NR	Landmark checks help demonstrate high overall registration accuracy. Repeated landmark checks showed no positional shifting during surgery. Target Registration Error (TRE) ranged from 0.45 to 1.29 mm (mean + SD: 0.87 + 0.28 mm). Low registration error resulted in reliable AR representation with close matching of visualized objects and reality.	NR	The effective dose for exposure was 0.29 + 0.17 mSv for cervical, 3.40 + 2.38 mSv for thoracic, and 3.05 + 0.89 mSv for lumbar regions. For 8 patients, radiation exposure was reduced by defining the scan range on the draping with a marker pen.
Cofano 2021	Efficiency	NR	NR	In 3 cases, AR goggles allowed the surgeon to have access to the CBT surgical planning of patients to help with screw placement.	NR
Edstrom 2020	Accuracy, efficiency	NR	The deformity correction was not significantly different between the ARSN and FH groups. The mean deformity correction for the ARSN group was 59.3% with an SD of 16.6% versus the FH group with a mean of 60.1% and SD of 17.8%.	The total procedure time (min) was on average of 431 min ± 98 versus an average of 417 ± 145 in ARSN and FH groups. There was no significant statistical difference between the ARSN or control group.	NR
Edstrom 2020	Radiation exposure/ dose	NR	NR	NR	The patient's effective dose was 15.8 ± 1.8 mSv. The OR staff exposure per procedure was 0.21 ± 0.06 uSv, and CT contributed to 83.8% of the total staff exposure dose. The median amount of spinal levels treated was 8.
Elmi-Terander 2018	Accuracy, efficiency	NR	The ARSN accuracy for screw placement was 94.1%. No screws were severely misplaced.	The average screw placement time was 5.2 minutes.	NR
Fritz 2014	Accuracy, efficiency	NR	Six (range 3-9) MRI control steps were required for needle placement. The target error of the final needle tip position was 6.1 +/− 1.9mm (range 0.3-8.7; CV = 11.2 +/− 7.9%; range 6.7-14.8%).	The median length of time for 1 vertebroplasty level was 16 min (range 11-21).	NR
Liu 2022	Accuracy, efficiency	NR	The screw placement accuracy was 98.5% in the thoracic region, 97.8% in the lumbar/S1 region, and 98.0% overall, as measured by the Gertzbein-Robbins grade of A or B.	NR	NR
Molina 2021	Accuracy	NR	The total implant insertion accuracy was 99.1% (n = 112). The thoracic implant accuracy was 98.2% (n = 56). The lumbosacral implant accuracy was 100% (n = 56). The pedicle screw insertion accuracy was 98.9% (n = 92). The thoracic pedicle screw insertion accuracy was 97.9% (n = 46).	NR	NR

Table 4 (*Continued*)

Study Author	Technical Outcomes Examined	Safety	Accuracy	Efficiency	Radiation Dose/Exposure
			The lumbosacral pedicle screw insertion accuracy was 100% (n = 46). Only 1 of 93 pedicle screws misplaced. No jamshidi needle misplaced.		
Pojskić 2021	Accuracy, radiation exposure/dose	NR	Use of AR with CT resulted in high accuracy with a target registration error of 0.84 mm ± 0.10 mm.	NR	The effective radiation dose for the registration of CT scans 6.16 ± 3.91 mSv
Wolf 2023	Accuracy	NR	For all measurements, 73% fell within the target deviation of 2 degrees, while 93% fell within the trajectory deviation of 3 degrees. There was no significant difference between participant groups.	NR	NR
Yahanda 2021	Accuracy	NR	The accuracy for the AR guided percutaneous screws was 100% for all 9 cases.	NR	NR

tool and enabled increased participation. Four studies identified challenges associated with AR technology use. Three studies reported difficulty using the technology due to large body habitus with 2 studies aborting AR assistance. One study required significantly increased time in 3D image rendering.

Discussion

The findings of this narrative review offer valuable insights into the application of AR technology in various facets of spine surgery. The included studies illustrate the potential benefits and feasibility of utilizing AR in spine surgical procedures, highlighting its impact on patient outcomes and surgeon performance.

Benefits of Using AR Technology

AR-guided procedures have attracted substantial interest in spine surgery primarily due to their remarkable capacity to enhance accuracy and reduce misidentification errors.[11] Notably, the integration of AR technology in percutaneous pedicle screw placement has demonstrated significant advancements by augmenting the surgeon's understanding of the 3-dimensional (3D) anatomy of patients.[12,13] This advancement is particularly advantageous for patients presenting complex surgical anatomy, where the visualization provided by AR can offer valuable insights. The real-time guidance provided by AR during surgical procedures allows surgeons to make informed decisions and perform actions with increased precision, leading to a notable reduction in surgical duration.[13]

AR technology has demonstrated remarkable effectiveness in treating diverse spinal conditions, including deformities, tumors, degeneration, and infection. Within the realm of fixation techniques, such as pedicle fixation, cortical fixation, and pelvic fixation[4] AR has emerged as an indispensable asset, facilitating unprecedented advancements. By enabling meticulous planning of screw trajectories and promoting the precise alignment of screws, plates, and implants, AR ensures enhanced stability, as supported by previous studies.[1,2,14-17] This may lead to improved long-term constructs and reduced need for revision surgery. The integration of AR into spinal surgery has resulted in a reduction in the risks of complications for patients. Clinical outcomes, such as decreased length of hospital stays and blood loss, exemplify the potential benefits of this innovative technology.[15]

The review findings provide valuable insights into the effective mitigation of radiation exposure through AR technology. The implementation of low-dose protocols and the utilization of registration scanning techniques are crucial strategies for reducing occupational doses among health professionals while optimizing the effective dose of exposure for patients.[15,18] Additionally, by decreasing their reliance on fluoroscopy, surgeons can significantly reduce overall radiation exposure during procedures.[19] This reduction effectively

Table 5 Applicability Outcomes

Study Author	Applicability Outcomes Examined	Cost	Surgeon Satisfaction	Education and Training	Identified Challenges
Aoyama 2022	Cost, identified challenges	$4000-$30,000 USD/year to purchase HMD and to use Holoeyes MD software	NR	NR	The time required to create the 3D image data using HMD was about 30 minutes
Auloge 2020	Identified challenges	NR	NR	NR	Accurately compensating for the substantial displacement caused by trocar handling and wide movements of corpulent patients with thick subcutaneous tissue
Bhatt 2022	NR	NR	NR	NR	NR
Butler 2023	NR	NR	NR	NR	NR
Carl 2019	Surgeon satisfaction, education and training	NR	Heads-up display in the operating microscope can be turned on/off to prevent too much info from being distracted in the surgical field. a microscope video display superimposed with AR along with various representations of image data helped surgeons to maintain orientation even when microscope AR was switched off. Display helped assisting staff to precisely follow procedure.	Microscope AR was a valuable tool for education.	NR
Carl 2020	NR	NR	NR	NR	NR
Cofano 2021	Surgeon satisfaction, education and training	NR	Surgeons reported positive feedback for ergonomy, wearability, and comfort during the procedure.	For telementoring, 3 cases involved sharing surgical procedures through videoconferences, while 7 cases included a surgeon remotely assisting specialized technicians in positioning neuromonitoring electrodes on patients' skin. In the context of teaching, 2 cases allowed for the participation of 4 first-year residents and 2 medical students in a procedure utilizing augmented reality (AR) technology.	NR
Edstrom 2020	NR	NR	NR	NR	NR
Edstrom 2020	NR	NR	NR	NR	NR
Elmi-Terander 2018	Identified challenges	NR	NR	NR	One patient with a body mass index of 37 could not be treated by ARSN since proper isocentering of the spine could not be achieved resulting in cropped 3D visualization and there was limited space between the detector and the patient for navigation.

Table 5 (*Continued*)

Study Author	Applicability Outcomes Examined	Cost	Surgeon Satisfaction	Education and Training	Identified Challenges
Fritz 2014	NR	NR	NR	NR	NR
Liu 2022	Surgeon satisfaction, identified challenges	NR	Mechanical discomfort with wearing the headset, visual discomfort, and visual obstruction of the surgical field. First-time users may experience sensory overload due to mixed reality images.	NR	Two cases in which the use of AR assistance was aborted due to large body habitus. For 1 patient, the use of AR was aborted because the intraoperative scan was unable to be transferred to the console and thus instrumentation placement was converted to a freehand technique.
Molina 2021	Surgeon satisfaction, identified challenges	NR	Potential user experience drawbacks mechanical discomfort, visual discomfort, and visual obstruction.	NR	NR
Pojskić 2021	NR	NR	AR helped with visualizing the tumor outline, pedicle screws, herniated discs, and surrounding structures.	NR	NR
Wolf 2023	Surgeon satisfaction	NR	The best ratings for ease of use and cognitive load were obtained with an abstract visualization displayed peripherally around the entry point and with a 3D anatomic visualization.	NR	NR
Yahanda 2021	NR	NR	NR	NR	NR

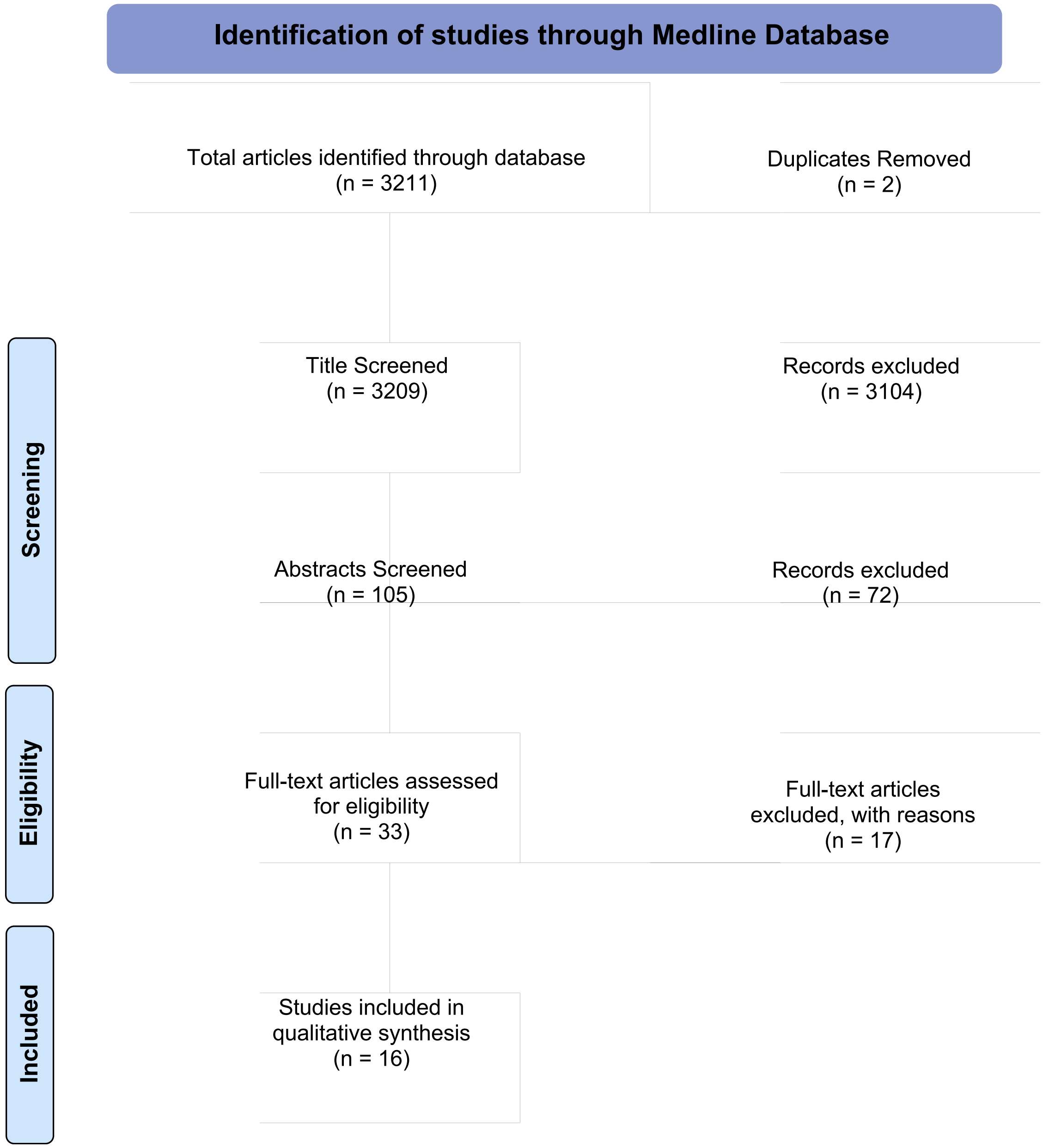

Figure 1 Flow diagram depicting the study selection process. (Color version of figure is available online.)

lowers radiation exposure for both the surgical team and the patient.

Telementoring and education have emerged as additional areas where AR technology has demonstrated significant value. In telementoring, it enables real-time feedback, thereby enhancing the guidance and support provided to surgeons remotely. Through AR-based visualization, mentors can observe surgical procedures and provide precise instructions, leading to improved task performance.[13] The design of trajectories plays a crucial role in influencing visual attention and optimizing the user experience, ensuring that critical anatomical structures are accurately identified and navigated.[20] By leveraging AR technology, surgeons can benefit from enhanced workflow efficiency, as the intuitive and interactive nature of AR interfaces streamlines the surgical process and reduces the potential for errors.[12,14] These advancements in telementoring and education, driven by AR technology, have the potential to revolutionize surgical training and foster continuous professional development in the healthcare field.

Challenges of AR Technology

The implementation of AR technology in spine surgery presents several challenges. One important aspect is the potential discomfort experienced by surgeons when wearing the headset, which can impact their concentration.[1] Additionally, concerns arise regarding visual discomfort and obstruction of the surgical field caused by the AR display.[21] It is crucial to optimize the design and ergonomics of AR systems to minimize any negative impact on surgical performance and patient safety. Another downside is the potential for sensory overload.[1] The integration of additional visual information and stimuli can overwhelm the surgeon's cognitive load and attention.

AR technology may pose challenges when applied to patients with a large body habitus.[1,2] The accurate registration and tracking of anatomical landmarks become more intricate, potentially compromising the accuracy of the system. Overcoming this barrier requires adapting the technology to accommodate variations in patient anatomy and exploring alternative registration methods. By addressing this specific challenge, the application of AR technology in patients with diverse body habitus can be optimized, ensuring accurate and reliable outcomes in spine surgery.

Cost is a pivotal factor to consider when implementing AR technology. The expenses associated with acquiring and maintaining AR systems, which include hardware, software, training, and personnel, can be substantial.[11,21,22] Additionally, the establishment and upkeep of hybrid operating rooms equipped with advanced imaging capabilities, necessary for seamless AR integration, can result in additional costs that may hinder widespread adoption. It is essential to conduct comprehensive cost-effectiveness analyses and explore suitable reimbursement models to assess the economic viability and long-term sustainability of AR technology in the context of spine surgery. Through these assessments, healthcare providers and administrators can make well-informed decisions regarding the integration of AR technology, ensuring its efficient utilization while effectively managing healthcare costs.

Gaps in the Literature

Despite the promising findings, there are still several gaps in the current literature that require attention. Firstly, there is a need for standardized outcome measures and specific reporting guidelines tailored to AR-assisted spine surgery. Consistency in outcome assessment will enable better comparisons across studies and facilitate meta-analyses, allowing for a comprehensive evaluation of the overall effectiveness of AR technology. Additionally, the current literature lacks long-term follow-up studies on patients who undergo AR-guided procedures. Assessing the durability and long-term clinical outcomes will provide valuable insights into the sustained benefits and potential complications associated with AR technology.

Furthermore, larger-scale, multicenter studies are needed to validate the findings observed in smaller cohort studies. Collaborative efforts among institutions and researchers can contribute to a more robust evidence base and enhance the generalizability of the findings. Additionally, there is a dearth of research on the cost-effectiveness and economic impact of implementing AR technology in spine surgery. Future studies should explore the financial implications, resource utilization, and potential cost savings associated with the integration of AR technology.

Lastly, it is essential to further investigate the usability and ergonomic aspects of AR systems. This involves addressing any potential limitations or challenges related to AR hardware, software interfaces, and user experience. Employing user-centered design approaches that incorporate feedback from surgeons and operating room staff can help refine AR systems to optimize their practicality, comfort, and efficiency.

Addressing these gaps in the literature will contribute to a more comprehensive understanding of the benefits, limitations, and optimal implementation strategies for AR technology in spine surgery. By filling these knowledge gaps, we can further enhance patient outcomes, refine surgical techniques, and maximize the potential of AR technology in this field.

Limitations

Several limitations should be considered when interpreting the findings of this narrative review. Firstly, the limited number of studies included may restrict the generalizability of the conclusions. Although efforts were made to include a diverse range of studies, the selection process and specific inclusion criteria may have introduced bias. Furthermore, relying solely on the MEDLINE database may have resulted in the omission of relevant studies published in other databases or using different terminology. The exclusion of certain publication types, such as editorials, letters, comments, and systematic reviews, may have also restricted the breadth of evidence considered. Another limitation is the potential for publication bias, as studies with positive results are more likely to be published, while those with negative or inconclusive findings may be underrepresented, thus affecting the overall interpretation of the effectiveness and outcomes associated with AR technology. Additionally, the majority of the included studies had small sample sizes, which may limit the statistical power and generalizability of their findings.

Conclusions

Overall, the landscape of AR in spine surgery is rapidly evolving, with promising advancements that have the potential to enhance surgical precision, improve patient outcomes, and transform surgical education. Continued research, development, and collaboration between surgeons, engineers, and technology companies are essential to unlock the full potential of AR in orthopaedic surgery. The literature assessed in this narrative review provides a snapshot of the current landscape of AR within spine surgery.

AR provides surgeons the opportunity to achieve better anatomic approximation and increased precision in a wide array of surgical applications. As AR has developed, the indications for its application have broadened. Its ability to provide better patient outcomes and expand the possibilities of minimally invasive procedures is reason enough for continued investment by all parties involved. AR opens the door to possibilities such as remote support during cases which not only streamlines workflow but leads to fewer surgical errors. Overall, both surgeons and patients benefit from the use of AR enhancement.

Still, as the traditional operating room continues to accommodate this evolving technology, AR remains challenging to use and implement. Limited training, difficulty, and cost burden are just a few of the many hurdles AR has to overcome. The design of AR programs must be simplified for both comfort and potential customization for the user and patient. "Normal" anatomy does not exist and as a result, the continued value of this technology will lie in its applicability to every patient's body composition.

Most of all, AR advancements and implementation are costly. As the overall efficiency of orthopaedic procedures is negatively impacted by AR, institutional leaders, and healthcare administration will be challenged in evaluating its potential implementation. Sadly, provider satisfaction and improved patient outcomes will likely not be enough. Therefore, the progression of AR will rely on its continued optimization for users, patients, and healthcare systems. To do so, robust evidence on its use and development must be collected in a standardized way. Once this is established, more extensive multicentered studies on this technology should be pursued. Together, these considerations provide a multifaceted approach to improving the overall accessibility of AR which is critical to its eventual success and further implementation in spine surgery.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.oto.2023.101068.

References

1. Liu A, Jin Y, Cottrill E, et al: Clinical accuracy and initial experience with augmented reality-assisted pedicle screw placement: The first 205 screws. J Neurosurg Spine 36:1-7, 2021. https://doi.org/10.3171/2021.2.SPINE202097
2. Elmi-Terander A, Burström G, Nachabé R, et al: Augmented reality navigation with intraoperative 3D imaging vs fluoroscopy-assisted free-hand surgery for spine fixation surgery: A matched-control study comparing accuracy. Sci Rep 10(1):707, 2020. https://doi.org/10.1038/s41598-020-57693-5
3. Ewurum CH, Guo Y, Pagnha S, et al: Surgical navigation in orthopedics: Workflow and system review. In: Zheng G, Tian W, Zhuang X (eds): Intelligent Orthopaedics. Advances in Experimental Medicine and Biology, Singapore: Springer, 1093:. https://doi.org/10.1007/978-981-13-1396-7_4,
4. Bhatt FR, Orosz LD, Tewari A, et al: Augmented reality-assisted spine surgery: An early experience demonstrating safety and accuracy with 218 screws. Global Spine J 2022. https://doi.org/10.1177/21925682211069321
5. Verhey JT, Haglin JM, Verhey EM, et al: Virtual, augmented, and mixed reality applications in orthopedic surgery. Int J Med Robotics Comput Assist Surg 16:e2067, 2020. https://doi.org/10.1002/rcs.2067
6. Hersh A, Mahapatra S, Weber-Levine C, et al: Augmented reality in spine surgery: A narrative review. HSS J 17(3):351-358, 2021. https://doi.org/10.1177/15563316211028595
7. McCloskey K, Turlip R, Ahmad HS, et al: Virtual and augmented reality in spine surgery: A systematic review. World Neurosurg 173:96-107, 2023. https://doi.org/10.1016/j.wneu.2023.02.068
8. Burström G, Persson O, Edström E, et al: Augmented reality navigation in spine surgery: A systematic review. Acta Neurochir (Wien) 163 (3):843-852, 2021. https://doi.org/10.1007/s00701-021-04708-3
9. Móga K, Hölgyesi Á, Zrubka Z, et al: Augmented or mixed reality enhanced head-mounted display navigation for in vivo spine surgery: A systematic review of clinical outcomes. J Clin Med 12(11):3788, 2023. https://doi.org/10.3390/jcm12113788
10. Jung Y, Muddaluru V, Gandhi P, et al: The development and applications of augmented and virtual reality technology in spine surgery training: A systematic review. Can J Neurol Sci: 1-10, 2023.. https://doi.org/10.1017/cjn.2023.46
11. Aoyama R, Anazawa U, Hotta H, et al: Augmented reality device for preoperative marking of spine surgery can improve the accuracy of level identification. Spine Surg Relat Res 6(3):303-309, 2021. https://doi.org/10.22603/ssrr.2021-0168
12. Carl B, Bopp M, Saß B, et al: Implementation of augmented reality support in spine surgery. Eur Spine J 28(7):1697-1711, 2019. https://doi.org/10.1007/s00586-019-05969-4
13. Cofano F, Di Perna G, Bozzaro M, et al: Augmented reality in medical practice: From spine surgery to remote assistance. Front Surg 8:657901. https://doi.org/10.3389/fsurg.2021.657901, 2021
14. Butler AJ, Colman MW, Lynch J, et al: Augmented reality in minimally invasive spine surgery: Early efficiency and complications of percutaneous pedicle screw instrumentation. Spine J 23(1):27-33, 2023. https://doi.org/10.1016/j.spinee.2022.09.008
15. Edström E, Burström G, Omar A, et al: Augmented reality surgical navigation in spine surgery to minimize staff radiation exposure. Spine (Phila Pa 1976) 45(1):E45-E53, 2020. https://doi.org/10.1097/BRS.0000000000003197
16. Molina CA, Phillips FM, Colman MW, et al: A cadaveric precision and accuracy analysis of augmented reality-mediated percutaneous pedicle implant insertion. J Neurosurg Spine 34(2):316-324, 2020. https://doi.org/10.3171/2020.6.SPINE20370
17. Yahanda AT, Moore E, Ray WZ, et al: First in-human report of the clinical accuracy of thoracolumbar percutaneous pedicle screw placement using augmented reality guidance. Neurosurg Focus 51(2):E10, 2021. https://doi.org/10.3171/2021.5.FOCUS21217
18. Carl B, Bopp M, Saß B, et al: Spine surgery supported by augmented reality. Global Spine J 10(suppl 2):41S-55S, 2020. https://doi.org/10.1177/2192568219868217
19. Auloge P, Cazzato RL, Ramamurthy N, et al: Augmented reality and artificial intelligence-based navigation during percutaneous vertebroplasty: A pilot randomised clinical trial. Eur Spine J 29(7):1580-1589, 2020. https://doi.org/10.1007/s00586-019-06054-6
20. Wolf J, Luchmann D, Lohmeyer Q, et al: How different augmented reality visualizations for drilling affect trajectory deviation, visual attention, and user experience. Int J Comput Assist Radiol Surg 2023. https://doi.org/10.1007/s11548-022-02819-5
21. Dennler C, Bauer DE, Scheibler AG, et al: Augmented reality in the operating room: A clinical feasibility study. BMC Musculoskelet Disord 22(1):451, 2021. https://doi.org/10.1186/s12891-021-04339-w
22. Khor WS, Baker B, Amin K, et al: Augmented and virtual reality in surgery-the digital surgical environment: Applications, limitations and legal pitfalls. Ann Transl Med 4(23):454, 2016. https://doi.org/10.21037/atm.2016.12.23