INTRODUCTION

In the 100 years since Roentgen discovered the X-ray in 1895, a “new kind of ray,” medical imaging technology has enabled clinicians to demystify the intact human body, which was previously impossible. The rapid development of imaging technology, which brought about an “industrial revolution” in medicine, was due to the desire of doctors to further improve the accuracy of surgery while reducing related complications.1-3 Over the decades, various radiographic techniques have appeared, including three-dimensional (3D) reconstruction from two-dimensional (2D) images.4,5 By improving surgeons’ ability to convert 2D to 3D images with new imaging technology installed with faster scan speeds and higher resolution image quality, radiation exposure on patients and staff can be reduced.6 Although technology has been developing rapidly over the past few years, we have never stopped innovating, and continue to do so today. Computer-aided surgery has become an integral part of modern surgical procedures, and a series of derivative technologies have emerged as a result of the combined efforts of computer scientists and clinical researchers, including augmented reality-based head-mounted displays (AR-HMD) such as the HoloLens glasses and the augmented reality surgical navigation (ARSN) systems.

AR, virtual reality (VR), and mixed reality nomenclature may initially seem strange and easily confused for one another, as they have similar technical aspects in virtual technology.7-14 VR usually consists of closed computer-generated digital information, and it completely replaces the real world to create an immersive visual experience. Conversely, AR provides an overlapping environment consisting of computer-generated images superimposed upon a real stereotaxic space. Therefore, it provides an awareness of real-world depth perception. As early as in 1968, Ivan Sutherland, who was dubbed “the innovator of computer graphics and AR,” developed the first HMD...

This present systematic review examines spine surgery literature supporting augmented reality (AR) technology and summarizes its current status in spinal surgery technology. Database search strategies were retrieved from PubMed, Web of Science, Cochrane Library, Embase, from the earliest records to April 1, 2021. Our review briefly examines the history of AR, and enumerates different device application workflows in a variety of spinal surgeries. We also sort out the pros and cons of current mainstream AR devices and the latest updates. A total of 45 articles are included in our review. The most prevalent surgical applications included are the augmented reality surgical navigation system and head-mounted display. The most popular application of AR is pedicle screw instrumentation in spine surgery, and the primary responsible surgical levels are thoracic and lumbar. AR guidance systems show high potential value in practical clinical applications for the spine. The overall number of cases in AR-related studies is still rare compared to traditional surgical-assisted techniques. These lack long-term clinical efficacy and robust surgical-related statistical data. Changing healthcare laws as well as the increasing prevalence of spinal surgery are generating critical data that determines the value of AR technology.

Key Words: Augmented reality, neurosurgical procedures, pedicle screws, smart glasses, microscopy, radiation exposure
system (The Sword of Damocles), which converts a plane line into a 3D form. In 1997, Peuchot first reported the use of AR in spinal surgery. His group designed an approach to generating AR, based on the VR tools, for correcting scoliosis through 3D visualization that allows surgeons to observe vertebral body displacement through superimposed 3D transparent imaging. In 2016, Elmi-Terander reported the first spine cadaveric study of pedicle screw placement (PSP) using ARSN; and 2 years later, the same technique was adopted in the first prospective clinical study in a hybrid operating room. In 2018, Micro soft introduced the U.S. Federal Drug Administration (FDA)- approved AR glasses called HoloLens, which adapts sensual and natural interface commands for preoperative surgical planning. Then, in 2019, Molina published a cadaveric proof-of-concept study of an augmented reality heads-up device (AR-HUD) called xVision, allowing surgeons to observe a virtual 3D model of a patient’s specific spine. Moreover, in 2021, the xVision Spine System developed by Augmedics was approved by the U.S. FDA (Fig. 1).

The development of spinal surgery AR techniques has recently introduced new questions and new potential avenues for research on whether this could be combined with other novel techniques, such as navigational or robotic systems, and whether these innovations could bring spinal surgery to the next generation. Although the clinical application of AR guidance in spinal surgery is still in its infancy, some pioneers have already made tremendous inroads with impressive research findings. Here, our team describes the currently available AR-assisted spinal surgery techniques and summarizes the workflows and outcomes.

**METHODOLOGY**

**Search strategy and study selection**

We conducted our systematic review using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. We searched the PubMed, Web of Science, Cochrane Library, and Embase databases from their earliest records through April 1, 2021. We used the search terms “spine” OR “spinal” OR “vertebra” related to “augmented reality” OR “virtual reality” OR “mixed reality.”

Eligibility criteria and selection process

We conducted our literature search to identify original research articles published in peer-reviewed journals. Inclusion criteria were as follows: application of AR-related technologies in spinal surgery on phantom systems, cadavers, or clinical practice, reported in English. It is worth mentioning that, even though HoloLens glasses have been identified as mixed reality technology in the Microsoft official promotions, after reviewing the related article, we believe that its primary function in recent spinal surgeries presents in the form of AR. Therefore, we included the paper describing the application of HoloLens glasses in spinal surgery in our systematic review. Exclusion criteria were AR concept confusion, technology illustration without application results, and non-spine-related surgery.

Data collection process and data extraction

After excluding the duplicate records, two independent researchers (YT and MG) screened the titles and abstracts of the included articles. Then, these two same reviewers independently conducted full-text screening to identify articles based on the study inclusion and exclusion criteria. After a full-text screening review, the included papers were retained, and the data was extracted. Therefore, in this systematic review, we extracted data composed mainly of publication year, model type, application level, primary purpose, important conclusion, work systems, strengths and weaknesses, and new trends in AR.

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**Fig. 1.** Timeline illustrating the development of augmented reality historical pioneers and milestone events.
RESULTS

A total of 1318 records were found after searching the database, and an additional six records were identified through other sources. After deleting duplicates, the articles were screened based on the titles and abstracts. Then, the articles considered to be eligible for this review were included. Next, we screened the full-text papers to exclude those with concept confusion with AR, non-spine-related surgeries, or only technical mechanisms without experimental results. Finally, 45 AR-related articles were included (Fig. 2). Table 1 illustrates the experimental model, application level, primary purpose, important conclusions, and working system in the included AR studies.

According to our search, AR-related articles have been published since 2011 (n=2); and related articles began to increase; and reaching a peak in 2020 (n=18). Starting in 2019, clinical application reports gradually increased, indicating that AR-related spinal surgery-assisted systems have acquired acceptable preclinical and clinical experimental results. This may be directly related to the recent rapid development of hardware and software in the AR field. The most prevalent AR-assisted surgical navigation system included in our systematic review was the ARSN system, which was installed in a hybrid operating room (n=14) and had an HMD (n=17). The Microsoft HoloLens accounted for a large percentage of HMD designs (n=12). Another type of AR-mediated surgery-assisted device was the HUD, which uses operating microscopes as its hardware tool. This technique has already been used in neurosurgery for intracranial surgery for a long time. Moreover, with the recent development of AR technology, spinal surgeons have attempted its use in different spinal surgeries such as injection, vertebroplasty, tumor resection, and rod bending. The most popular surgical application was pedicle screw instrumentation (n=28), and the main responsible surgical level were the lumbar (n=40) and thoracic (n=30) regions. The distinctive workflows utilizing the concept of AR are described below. The pros and cons of the mainstream AR-assisted spinal surgery systems are also discussed.

Pedicle screw placement

PSP requires an accurate skin location and operative trajectory, which differs in every patient with the angle and width of the pedicle. Less experienced surgeons performing PSP usually use repeated intraoperative, anteroposterior, and lateral fluoroscopy for guidance, which increases radiation exposure and prolonging operation time, and also causes an increased rate of postoperative complications. For reducing these occurrences, Ma, et al. combined ultrasound-assisted CT imaging techniques with AR techniques, which utilized integrated photog-
| Authors, yr | Model | Segments | Surgery | Purpose | Important conclusion |
|------------|-------|----------|---------|---------|----------------------|
| Luciano, et al., 2011 | Phantom | Lumbar | Spinal injection | Virtual protactor AR system | The image overlay navigation system was technically accurate. 94% of lesions were sufficient for pathological analysis and diagnosis. |
| Weiss, et al., 2011 | Phantom | Lumbar | Osteo biopsy | AR-assisted navigation system | Without neurological deficits, the deformed vertebrae were successfully resected according to the preplanned resection planes. The spine was restored in near-physiological posture. |
| Abe, et al., 2013 | Phantom | Lumbar | Thoracic | AR-assisted navigation system | VIPAR was successfully used to assist in needle insertion, and there was no pedicle breach or leakage of polymethylmethacrylate in clinical trials. |
| Fritz, et al., 2012 | Phantom | Lumbar | Thoracic | AR-assisted navigation system | All anatomic targets were successfully punctured. The average time for needle path planning and insertion was 5-7 s, respectively. |
| Fritz, et al., 2012 | Phantom | Lumbar | Lumbar | AR-assisted navigation system | 97.5% of AR-guided needle placements were either perfect or acceptable without unsafe needle placements, and the time to final needle placement was substantially faster with AR guidance. |
| Elmi-Terander, et al., 2016 | Phantom | Lumbar | Thoracic | AR-assisted navigation system | Experimental outcomes demonstrated that the proposed navigation system has acceptable targeting accuracy and radiation exposure. |
| Kosterhon, et al., 2017 | Clinical | Thoracic | Lumbar | AR-assisted navigation system | The overall accuracy of PSP was 93% (total: 18), the average procedure time was around 30 seconds, and the error angle was around 0.3°. There was no correlation between navigation time and accuracy. |
| Authors, yr    | Model     | Segments | Surgery         | Purpose                                      | Important conclusion                                                                 | Working system                                                                 |
|---------------|-----------|----------|-----------------|----------------------------------------------|------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Elmi-Terander, et al., 2019 | Clinical | Thoracic Lumbar Sacrum | Pedicle screw instrumentation | AR-assisted navigation system | The overall accuracy of PSP was 94.1% (total: 253). There were no severely misplaced screws and no occurrence of device-related adverse event. | ARSN (Philips Healthcare, Best, the Netherlands) Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT |
| Gibby, et al., 2019 | Phantom | Lumbar | Pedicle screw instrumentation | AR-HMD navigation system | The HMD-AR technology projecting reconstructed 3D and 2D CT images can be accurately superimposed over the lumbar model and used to place pedicle screws. | HMD: Microsoft HoloLens OpenSight AR software (Novarad, American Fork, Utah, USA) |
| Urakov, et al., 2019 | Cadaver  | Thoracic Lumbar Sacrum | Pedicle screw instrumentation | Workflow caveats of Microsoft HoloLens | There were three major medical breaches and four major inferior breaches in the AR group; also, the author separately elaborated the caveats of workflow in AR-assisted PSP. | HMD: Microsoft HoloLens OpenSight AR software (Novarad, American Fork, Utah, USA) |
| Müller, et al., 2020 | Cadaver  | Lumbar | Pedicle screw instrumentation | AR-HMD combined with pose-tracking system | There was no significant difference in accuracy between AR-navigated and pose-tracking systems. | HMD: Microsoft HoloLens Pose-tracking system (fusionTrack500, Switzerland) CASPA (Balgrist CARD AG, Zurich, Switzerland) |
| Burström, et al., 2019 | Cadaveric Animal | Thoracic Lumbar | Pedicle screw instrumentation | ARSN combined with the automatic instrument tracking system | 97.4% screws were correctly placed without breaching the pedicle walls, and there was no difference between Jamshidi needle and high-speed drill in terms of accuracy or surgical time per pedicle. | ARSN (Philips Healthcare, Best, the Netherlands) Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT |
| Liebmann, et al., 2019 | Phantom | Lumbar | Pedicle screw instrumentation | AR-HMD combined with surface digitization system | The specific navigation method achieved registration and tool tracking with real-time visualization without intraoperative imaging. | HMD: Microsoft HoloLens (Microsoft Corporation, Redmond, WA, USA) |
| Auloge, et al., 2020 | Clinical | Thoracic Lumbar | Vertebroplasty | AR combined with an artificial intelligence system | There was no difference between the accuracy of the AR group in the skin entry point and the trocar tip and fluoroscopy group; however, the time for trocar deployment was significantly longer in the AR group. | ARSN (Philips Healthcare, Best, the Netherlands) Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT |
| Carl, et al., 2019 | Clinical | Cervical Thoracic | Tumor resection | Microscope-based AR navigation system | Microscope-based AR provided close matching of visible tumor outline and AR visualization in all cases, the mean percentage of HUD-AR use was 51%, and the switch time of HUD was 2 to 17. | HUD of operating microscopes Pentero and Pentero900 (Zeiss, Oberkochen, Germany) Microscope element software (Brainlab) |
| Carl, et al., 2019 | Clinical | Cervical Thoracic | Tumor resection | Microscope-based AR navigation system | The application of intraoperative CT combined with AR ensured high navigational accuracy (mean error around 1 mm), and low-dose intraoperative CT protocols reduced the 70% effective radiation. | HUD of the operating microscopes Pentero/Pentero900 (Zeiss, Oberkochen, Germany) Anatomical mapping software (Brainlab, Germany) |
| Carl, et al., 2019 | Clinical | Cervical Thoracic | Various | Microscope-based AR navigation system | Identification of bony and artificial landmarks allowed validating registration accuracy, AR facilitated visualization of the target structures reliably in the surgical field, along with their surgical orientation. | The HUD of the operating microscopes Pentero and Pentero 900 (Zeiss, Oberkochen, Germany) Microscope element application (Brainlab) |
| Molina, et al., 2019 | Cadaver  | Thoracic Lumbar | Pedicle screw instrumentation | Comparative accuracy of AR with the conventional method | The accuracy of the AR system was superior to manual computer-navigated PSP, and the user experience analysis yielded "excellent" usability classification. | AR-HMD display (xvision; Augmedics, Chicago, IL, USA) |
Table 1. Studies on AR Navigation in Spine Surgery (Continued)

| Authors, yr | Model | Segments | Surgery | Purpose | Important conclusion | Working system |
|-------------|-------|----------|---------|---------|----------------------|----------------|
| Edström, et al., 2020 | Clinical | Thoracic | Pedicle screw instrumentation | Compare freehand and ARSN system in deformity | The procedure time of ARSN was not prolonged with significantly higher PS density in the construct. Pedicle density is significantly higher in the upper instrumented vertebra in ARSN. | ARSN (Philips Healthcare, Best, the Netherlands). Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT. |
| Elmi-Terander, et al., 2020 | Clinical | Thoracic Lumbar Sacrum | Pedicle screw instrumentation | Comparative accuracy of ARSN with freehand | ARSN system demonstrated a statistically higher accuracy of PSP compared to the freehand technique, primarily spinal deformity cases. The proportion of cortical breach was twice in the freehand group than in the ARSN group. | ARSN (Philips Healthcare, Best, the Netherlands). Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT. |
| Dennler, et al., 2020 | Phantom | Lumbar | Pedicle screw instrumentation | Comparative analysis of the beginners with experience by freehand or AR navigation | The AR headset improved the precision of drilling pilot holes for PSP by non-experienced surgeons and primary drill pedicle perforation by 7.5% in the freehand group and 2.5% in the AR group. | HMD: Microsoft HoloLens 3D triangular surface model (Siemens Healthineers, Erlangen, Germany) |
| Hu, et al., 2020 | Clinical | Thoracic | Vertebroplasty | AR-assisted navigation system | AR had less frequency of fluoroscopy and shorter operative time during entry point identification and local anesthesia. Also, it had a more significant proportion of “good” entry points. | Planar-based calibration system Industrial camera (XCD 5.90, SONY, Japan) Projector (DLP W7000, BENQ, Taiwan) |
| Balicki, et al., 2020 | Cadaver | Thoracic Lumbar | Pedicle screw instrumentation | Robotic guidance combined with ARSN system | A fully integrated robotic guidance system can improve workflow and provide all clinical acceptable pedicle screw guidance with less than 2 mm of targeting error. | ARSN (Philips Healthcare, Best, the Netherlands). Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT. |
| Edström, et al., 2020 | Clinical | Thoracic | Pedicle screw instrumentation | ARSN system in different spinal procedures | The ARSN can perform highly accurate surgery, decreasing the risk for complications while minimizing radiation exposure to the staff. The workflow for ARSN preparation only occupied 8% of the total surgical time. | ARSN (Philips Healthcare, Best, the Netherlands). Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT. |
| Burström, et al., 2020 | Cadaver | Thoracic Lumbar Sacrum | Pedicle screw instrumentation | Robot-guided system for semi-automated pedicle screw | The system provided a clinically acceptable level of PSP without robotic assistance. Also, the technical accuracy was superior to their own previously reported ARSN data. | ARSN (Philips Healthcare, Best, the Netherlands). Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT. |
| Nguyen, et al., 2020 | Phantom | Cervical Thoracic Lumbar | Pedicle screw instrumentation | Machine vision image-guided system | The system’s magnification increased the possible angle sensitivity of pedicle screw angle placement, executing screw insertion trajectories with more acceptable precision and increased control. | Operation light head of the 7D MvIGS system (installed with IR tracker and the stereoscopic cameras) Two embedded cameras |
| Liu, et al., 2020 | Phantom | Lumbar | Pedicle screw instrumentation | Comparative analysis of the AR-guided compared to fluoroscopy | AR-guided percutaneous lumbar PSP was acceptable and more efficient than radiograph-guided placement, and the automatic-alignment method was as accurate as the manual method, but more efficient. | HMD: Microsoft HoloLens (Microsoft Corporation, Redmond, WA, USA) |
| Carl, et al., 2020 | Clinical | Cervical Thoracic Lumbar | Various | Microscope-based AR navigation system | Automatic image registration by intraoperative CT combined with the non-linear registration of preoperative image data ensured a high visualization accuracy that had been successfully applied in all cases. | HUD of the operating microscopes Pentero or Pentero 900 (Zeiss, Oberkochen, Germany) |
| Edström, et al., 2020 | Clinical | Thoracic Lumbar | Pedicle screw instrumentation | Evaluate the staff and the patient radiation exposure in ARSN system | The low-dose protocol used for the final 10 procedures yielded a 32% effective doses reduction per spinal level treated, and the study demonstrated significantly lower occupational doses compared to previous reports. | ARSN (Philips Healthcare, Best, the Netherlands). Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT. |
### Table 1. Studies on AR Navigation in Spine Surgery (Continued)

| Authors, yr         | Model         | Segments     | Surgery                  | Purpose                                                                 | Important conclusion                                                                                   | Working system                                                                                       |
|---------------------|---------------|--------------|--------------------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|
| Burström, et al., 2021 (26) | Clinical      | Thoracic        | Pedicle screw instrumentation | Frameless reference marker system for patient tracking                  | The mean technical accuracy of the frameless marker system was 1.65 ± 1.24 mm, and there were no statistical differences in accuracy between pedicle devices spanning up to seven vertebral levels. | ARSN (Philips Healthcare, Best, the Netherlands) Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT |
| Gu, et al., 2020 (27) | Clinical      | Thoracic        | Pedicle screw instrumentation | Comparative efficacy of AR with the conventional methods               | The AR group showed minor bleeding, shorter operation time, and better ODI and VAS scores with fewer postoperative complications. | HMD: Microsoft HoloLens (Microsoft Corporation, Redmond, WA, USA)                                      |
| Xu, et al., 2020 (28) | Phantom       | Thoracic        | Pedicle screw instrumentation | Spatial AR-based surgical navigation system for PSP                     | The accuracy of the pedicle screw insertion point on the skin was 0.441 ± 0.214 mm, the average time of the AR navigation system was around 14.1 mins, and the system avoided the use of glasses. | Spine surgical treating planning system Camera-projector system                                        |
| Gibby, et al., 2020 (29) | Phantom       | Lumbar         | Spinal injection          | Percutaneous image-guided spine procedures using AR                    | OpenSight AR provided a direct visualization with a high degree of anatomical accuracy. Also, it decreased the procedure time and reduced exposure to ionizing radiation for stuff. | HMD: Microsoft HoloLens OpenSight AR (Novarad, American Fork, UT, USA) NOVAPACS (Novarad, American Fork, UT, USA) |
| Reh, et al., 2020 (30) | Cadaver       | Thoracic        | Pedicle screw instrumentation | Comparative accuracy of ARSN with fluoroscopy                         | The overall accuracy of PSP with ARSN was 94% compared to 88% for fluoroscopy, and there were no unsafe screws in the scoliotic cases by the ARSN system without radiation exposure. | ARSN (Philips Healthcare, Best, the Netherlands) Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT |
| Buch, et al., 2021 (31) | Clinical      | Thoracic        | Pedicle screw instrumentation | Optimized pipeline realignment in intraoperative holographic models of patient landmarks | The intraoperative pipeline was successfully employed to generate patient-specific holographic models, and the registration accuracy dramatically improved with optimization of pipeline and techniques. | HMD: Microsoft HoloLens Segmentation software (ITK-SNAP v.3.6) StealthStation Neuronavigation (Medtronic Sofamor Danek, Memphis, TN, USA) |
| Molina, et al., 2021 (32) | Cadaver       | Thoracic        | Pedicle screw instrumentation | Evaluate the clinical accuracy of AR-mediated spine surgery            | The overall clinical accuracy was 99.1%, and 99.12% implants were noted to be Gertzbein-Robbins grade A or B. Precision analysis of the inserted pedicle screws yielded a mean screw tip linear deviation of 1.98 mm. | AR-HMD (vision: Augmedics, Chicago, IL, USA). CT-integrated table (AIRO, Brainlab) Medical Image Interaction Toolkit (MITK, Germany) |
| Molina, et al., 2021 (33) | Clinical      | Lumbar          | Pedicle screw instrumentation | Evaluate the clinical accuracy and technical precision of AR-mediated spine surgery | All six screws were Gertzbein-Robbins grade A without perioperative complications. The clinical trial showed no difference compared to cadaveric data. None of the surgeons reported difficulty in navigating views. | AR-HMD (vision: Augmedics, Chicago, IL, USA). Intraoperative CT scan (O-arm; Medtronic, Ireland) Medical Image Interaction Toolkit (MITK, Germany) |
| Burström, et al., 2021 (34) | Clinical      | Thoracic        | Pedicle screw instrumentation | Compare the intraoperative CBCT scans to postoperative CT scans       | Intraoperative CBCT with the ARSN system is reliable for ruling out pedicle screw breaches and can be used for intraoperative breach detection and revision, making routine postoperative CT scans unnecessary. | ARSN (Philips Healthcare, Best, the Netherlands) Hybrid operating room: maquet table, motorized ceiling-mounted C-arm system, 3D Cone Beam CT |
| von Atzigen, et al., 2021 (35) | Phantom       | Lumbar          | Rod bending               | Marker-less surgical navigation to reconstruct 3D pedicle screw head positions | The machine learning-based proof-of-concept achieved better accuracy compared to the benchmark navigation approach requiring contact with the anatomy while requiring less time to acquire the screw head position. | HMD: Microsoft HoloLens Segmentation software (Mimics version 19.0, Materialise NV, Leuven, Belgium) |
| Molina, et al., 2021 (36) | Clinical      | Thoracic        | Osteotomy                 | ARMSS                                                                  | Osteotomy execution was successfully implemented to resect an en bloc-wide marginal of chordoma while avoiding a tumor capsule breach through a posterior-only approach using ARMSS. | AR-HMD (vision: Augmedics, Chicago, IL, USA). BoneScalpel (Misonix) Integrated tracking camera |

AR, augmented reality; ARSN, augmented reality surgical navigation; HMD, head-mounted displays; PSP, pedicle screw placement; VIPAR, virtual protractor with augmented reality; 3D, three-dimensional; 2D, two-dimensional; HUD, heads-up device; CBCT, cone-beam CT; ARMSS, AR-mediated spine surgery; ODI, Oswestry Disability Index; VAS, Visual Analogue Scale.
Spine Surgery Assisted by Augmented Reality

Spinal injections and percutaneous biopsy
Degeneration and trauma to the facet joints are the decisive factors affecting the progression of arthritis and lower back pain. Previous studies have reported on the use of ultrasound for needle placement on facet joints. However, beginners may not obtain transparent images of bone and nearby structures through ultrasonography. Fritz, et al. reported on an AR image overlay system that consisted of a semitransparent mirror that displayed the planned epidural injection trajectory. The patient’s body and virtual guidance images were infused and displayed on a semitransparent mirror, and the image did not move when the observer’s visual angle changed. However, the system may not work if the tilted-angle intervertebral disc was more than 27°. The same device was then used to perform a bone biopsy on four metastatic cadavers, and 93.8% of the specimens were sufficient for pathological evaluation.

Tumor resection
Cerebrospinal fluid loss or spinal cord movement are hazardous as they may trigger brain displacement. Therefore, accurately locating the extent of the tumor and minimizing complications may present a challenge in spinal tumor resection. Carl, et al. used intraoperative navigation combined with microscopy-based AR-HUD systems to treat internal or external dural lesions. Virtual images of close real-time tumor boundaries and important nerve and blood vessel structures were observed with an optical microscope. The average error in this system was reported to be approximately 1 mm. Carl, et al. then evaluated the time ratio of AR by analyzing the video records obtained microscopically in 10 cases of intradural tumor surgery. The average time of AR-HUD during the operation was about half of the total display time using a surgical microscope. Meanwhile, the operator only switched the AR function on and off about five times. Therefore, this kind of AR-assisted surgery was shown to ensure complete resection of the lesion site safety, control soft tissue dissection precisely, and significantly reduce the rate of cerebrospinal fluid leakage intraoperatively.

Osteotomy
Osteotomy is frequently used for multiplane correction of spinal deformities. It is challenging to develop a preplanned osteotomy plane accurately to attain the expected correction angle. Kosterhon, et al. created a virtual surgical resection plane based on a congenital wedge-shaped half-pyramid, and exported the virtual image combined with navigation guidance to the surgical microscope. The virtual 3D contour display facilitated the visual control of the direction of the high-speed drill bit safely and avoided excessive resection of the posterior pedicles and laminas. Molina, et al. recently introduced another technique, which uses the newly released AR-HMD xvi-sion Spine System for an en bloc chordoma spondylectomy, allowing the surgeon to visualize the contralateral surgeon’s operation progress with a tracked pointer.

Vertebroplasty
Vertebroplasty is a percutaneous treatment for osteoporotic fracture that can contribute to iatrogenic neurovascular injury or bone cement leakage, even under fluoroscopy guidance. Hu, et al. introduced a planar-based calibration system to superimpose the merged intraoperative 3D image created by the camera-projector system onto the actual anatomical structure to create an AR visualization. However, the image that the machine generates can easily block the surgical area, and the operator may also block the projected image. Soon after that, Abe, et al. reported on an AR-assisted virtual protractor system enabling holographic visualization of the planned osteotomy needle trajectory. This allows surgeons to observe a 3D virtual image from different angles by rotating the head. However, this system cannot be combined with intraoperative computed tomography navigation or used in complex spinal cases.
DISCUSSION

For ARSN systems that rely on optical tracking without lead-based protective equipment, high-precision surgical trajectories can be created with the help of a built-in navigation system that can be used to augment the actual surgical field of view with 3D image overlays. The camera in the ARSN system tracks from four different directions. A standard tracking procedure can be adopted as long as four cameras detect at least five skin markers. This can significantly prevent the loss of tracking from accidental movement or deep surgical interventions. Additionally, this kind of noninvasive adhesive skin marker will not be affected by breathing movements or the distance from the reference. However, due to the limited space between the detector and the patient, it is impossible to set an appropriate instrument spacing for obese patients. Moreover, increased surgical time is also a challenge. A good optimization of the operation workflow, such as scanning multiple segments at once, could significantly reduce the operation time. In addition, for the AR-HUD system which is installed on the microscope, various virtual objects can be set up as translucent, contoured, or stereoscopic 3D patterns. These can be temporarily hidden to avoid excessive interference. Also, the AR-HUD system does not require the operator to switch attention to the monitor, which can negatively impact hand-eye coordination. Currently, visual immersion HUD is insufficient, and 3D images must be more precisely merged with actual anatomy instead of simply projecting the image on top of the target area.

As for HMDs, such as the HoloLens, they can construct computer-generated 3D imagery holograms from a transparent visor projected in the real world. It seems that the most mature part of the AR technique has already been put to public use. However, a review of previous literature suggests that related clinical practices were not so optimistic. First, the series registration approach with the necessary bony landmarks is time-consuming. Second, the manual calibration of holograms and models is tedious due to inaccurate mobile hologram gestures or voice control. Due to the aforementioned concerns, Buch et al. introduced a generalizable pipeline for improving registration accuracy, and the results significantly reduced registration errors. Furthermore, the excessive hardware head weight caused operator discomfort after a long period of use. In addition, shading of important anatomical structures by the translucent virtual image was also an unsatisfactory factor. Moreover, we must consider the impact of radiation exposure with the techniques mentioned above. Fortunately, most of these technologies can rely on a single scan to perform an entire surgical procedure, or adopt a particular strategy to reduce radiation. For example, Carl et al. found that the radiation exposure was reduced by about 70% using a low-dose protocol, and that the radiation exposure could be further reduced by restricting the scan range to the surgical area.

FUTURE PERSPECTIVES

AR-assisted spinal surgery comprises a newly emergent technology. As relevant literature becomes published and more attention is drawn, related hardware and software are also updated, providing an accurate registration process with low-latency connections. Furthermore, it should be possible to control the operative trajectory accurately, as well as detect and provide feedback on the distribution of abnormal blood vessels and nerves in advance. Meanwhile, this may standardize and optimize the workflow, formulating evaluation standards and quantifying the analysis of the results based on the actual situation. Today, artificial intelligence and robotic technique are proliferating and evolving. In a recent cadaveric experiment, a fusion technique in which the ARSN system cooperated with a highly flexible arm robot, was reported. Surgeons can use the instrument tracking feedback system to calibrate the robot without any human-controlled registration. This feedback system also reduces the risk of an inaccurate screw entry point location, and protects the robotic instrument from slipping off when the drill bit reaches the surface of the bone.

LIMITATIONS

Nowadays, various AR-enabled technologies are emerging without specific criteria for judging them. Meanwhile, the limited publications with few supporting randomized clinical trials and meta-analyses make it impossible to use statistics to explain the practical value of these techniques in spinal surgery. Nevertheless, we must recognize that it is essential not to rely solely on the grading or accuracy of clinical technology to finalize the value of emerging techniques. The value of AR will gradually expand with the long-term tracking of patients and the accumulation of surgical experience.

CONCLUSION

This systematic review presents an overview of AR technology from its earliest conception to the current evolution of spine surgery. It is feasible to incorporate this with other surgery-assisted technologies to enhance surgical radiological guidance and improve its efficacy in clinical treatment. The overall number of AR clinical applications is still limited. With the improvement of medicolegal processes and the advancement of surgical automation, it is undoubtedly true that the development of AR techniques will soon open a new era of spinal surgery.

AUTHOR CONTRIBUTIONS

Conceptualization: Jin-Sung Kim. Data curation: Min-Gi Lee and Yanting Liu. Formal analysis: Yanting Liu. Investigation: Yanting Liu.
Methodology: Min-Gi Lee and Yanting Liu. Project administration: Jin-Sung Kim. Resources: Min-Gi Lee and Yanting Liu. Software: Min-Gi Lee and Yanting Liu. Supervision: Jin-Sung Kim. Validation: all authors. Visualization: all authors. Writing—original draft: Yanting Liu. Writing—review & editing: Jin-Sung Kim and Yanting Liu. Approval of final manuscript: all authors.

ORCID iDs

Yanting Liu https://orcid.org/0000-0002-9591-3042
Min-Gi Lee https://orcid.org/0000-0001-8905-2920
Jin-Sung Kim https://orcid.org/0000-0001-5086-0875

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