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Augmented Reality as a Tool for Enhancing Neurosurgery: An Exploration of Mixed Reality Surgical Technologies

REVIEW

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ABSTRACT

The purpose of this narrative review is to summarize the utility of augmented reality (AR) and virtual reality (VR) in neurosurgery in both enhancing surgical performance and subsequently improving patient outcomes. We identified papers that cover the use of AR/VR in neurosurgeries in a variety of clinical settings and surgical dilemmas, particularly highlighting how these advancements have improved tumor resections for neurosurgical oncologists and have aided in accurate placement of pedicle screws during spine cases. As a result of such improvements, patients may reap better postsurgical outcomes with shorter lengths of hospital stay. We also identified papers on resident education and communication among surgeons, identifying yet another fruitful avenue for these technologies. Despite such promising outcomes, challenges remain prior to acceptance into mainstream practice and widespread availability of these technologies, thus further research and development are crucial for future implementation.

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INTRODUCTION

The technological revolution of the 21st century is fast, expansive, and seemingly limitless. If physicians are to keep pace with this rapid evolution, they must continue to not only integrate these technologies into their practices, but also aim to innovate new technologies with the goal of advancing their field. The field of neurological surgery is uniquely prepared to embrace this development. The drastic growth this field has experienced in conjunction with the emergence of promising neurosurgical technologies speaks to the field's propensity to richly progress through time [1].

The first records of neurosurgical interventions can be found in ancient Egypt, Greece, and China, where trepanation was performed for symptomatic relief of hemorrhage following traumatic brain injuries, or for the treatment of mental illness, seizures, and headaches [2]. The 20th century brought progression in technologies enabling changes to surgical techniques: illumination, magnification, and operating room (OR) equipment. Imaging modalities such as pneumoencephalography and cerebral angiography–and later advances with Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) scans–changed how physicians accurately and efficiently diagnose various pathologies [1]. Particularly for neurosurgeons, the addition of precise, minimally invasive surgical techniques such as endoscopy and frame-based surgery along with the inclusion of intraoperative microscopes and neuronavigational modalities [3] highlight a specific avenue for a profound breakthrough: improved surgical visualization of patient-specific anatomy that will enhance operative precision resulting in better patient outcomes. Augmented reality (AR), in which digital elements are overlaid or blended into the real-world environment, and virtual reality (VR), which completely substitutes the real-world visual environment with a digital environment, provide unique outlets for neurosurgeons to enhance their operative capacity and thus perform more accurately during complex cases, which can not only improve surgical workflow but also improve patient outcomes and satisfaction. The aim of our review is to explore how such mixed reality (AR and VR) technologies have accomplished this feat while addressing aspects that require development and anticipating challenges that accompany such progression.

As the application of these tools grows, it is necessary to evaluate specifically how this will improve neurosurgical practices while also anticipating the pitfalls in hopes of making integration as seamless and effective as possible. In the subsequent review we evaluate a range of studies predominantly conducted by institutions in the United States (with additional references to European, Chinese, and Japanese contributors), highlighting how these innovations offer enticing alternatives to traditional means of practicing, training, and collaborating.

QUALITY IMPROVEMENT

Improvement in patient outcomes via individualized medicine is a goal of medical innovation. AR allows for the use of highly personalized treatment plans that consider each patient's unique anatomy, leading to better outcomes through precise localization of surgical targets and shorter procedures and recovery times [4]. With the help of AR, surgeons have been able to access the data and imaging necessary to perform an accurate surgery in one plane of vision, thus eliminating the need to continuously reorient throughout a procedure and allowing for improved ergonomic efficiency and concentration on the surgical field [5].

Additionally, neurosurgeons have been able to utilize AR to preoperatively plan surgical trajectories and then verify their intraoperative progress in real-time with AR imaging modalities, ultimately allowing for more accurate localization of targeted brain lesions [6], which has been demonstrated in both animal and human studies. Chan and colleagues [7] developed and tested an AR device that combined real-time tracking with a laser pico-projector that was tested in four animal-model tumor resections. The device superimposed images from numerous imaging modalities including over the animal anatomy to highlight relevant anatomic structures and accurately describe tumor locations. Procedures performed using the device were all effective, with the device accuracy ranging from 0.6 ± 0.3 mm [7].

Schwam, Z.G., et al. conducted a case series of nearly 40 lateral skull base tumor resections in which they found the use of AR was most beneficial in the preparatory and planning stages [8]. A series of segmenting of structures from a perioperative scan were placed in a navigational system which projected the trajectory onto an accessible viewing screen. The imaging system worked well in displaying bony structures, and soft tissues were susceptible to only minimal changes post retraction. Overall, viewing the 3D models of lesions and their complex relationships with surrounding anatomy was beneficial in the preoperative stages [8].

In human trials, neurosurgeons tasked with glioma resection utilized aspects of combined AR and VR to visualize tumors as 3D and 2D planes intraoperatively, which allowed for a significantly greater percent of complete glioma resection in the test group (69.6%) compared to the control group (36.4%) ($p < .01$) [9]. A study on skull base tumor removal observed a higher rate of tumor resection using VR perioperative preparation (83.3%) compared to control groups (71.4%), although the difference was not statistically significant ($p > .05$). However, within this same cohort, patients that underwent VR-assisted surgeries experienced shorter length of hospital stay and improved postoperative quality of life in comparison to the control, thus highlighting the capability of mixed reality surgeries to improve cost and satisfaction associated with surgery [10]. A retrospective study of surgeons using AR head-mounted displays in spine surgery reported 100% accuracy in percutaneous pedicle screws placement in nine patients, with 96.8% experiencing graded Gertzbein-Robbins grade A (96.9%) or B (3.2%) outcomes [11].

The use of AR has also found to be effective in a study of microscope-assisted neurosurgeries in 79 patients with 84 pathologies (19 unique pathologies total) who underwent neurosurgery assisted with microscope equipped with AR. Surgeons self-reported no complications associated with this setup [12]. Furthermore, 20.2% of AR uses in the series showed minimal overlay displacement of AR projection and 71.4% of AR uses were classified as excellent with perfect overlay, with deep lesions having higher accuracy [12]. Note that surgeons could choose to utilize AR during numerous points in the setup and procedure, and they deactivated the AR at some point during surgery in almost 60% of cases. Here, AR does not hinder, but rather strengthens, the surgeon's real time awareness during operations, allowing them to easily transition to and from virtual assistance.

A 2022 review of 34 studies shows how AR and VR have promise not only in neurosurgery but also in various other surgical subspecialties, showcasing their wide-ranging applicability and feasibility [13]. Inclusion criteria for the articles analyzed in this review were: studies published between 2007 and 2022, study titles that included "augmented reality" and "surgery", and studies that assessed the value of AR usefulness in neurosurgery, orthopedic surgery, and/or surgical oncology. A total of 64 studies met inclusion criteria, and after literature review, 34 studies were included in this paper. Summative analysis of the AR benefits included reduction in intraoperative complications, improvements in surgical quality, and reduction in length of surgery. Specifically for orthopedics, AR is used to improve procedural accuracy and efficiency, while also decreasing frequency of radiographic imaging throughout the procedure. The use of AR in surgical oncology potentiates better patient outcomes, as it helped accurately define tumor borders and visualize surrounding anatomy. A separate analysis performed by Hallet et al. [14] echo this notion as they have used AR to assist with transthoracic hepatic resection in a patient where a laparoscopic approach was deemed inappropriate. Here, AR was used to interactively assess the patient's anatomy preoperatively, and later assisted with more precise tumor localization during the procedure in real-time.

Another systematic review of AR in surgical applications included 91 articles published between 2013 and 2020 [15]. AR devices were primarily employed for intraoperative guidance ($n = 58$) and preoperative visualization ($n = 40$). The review noted that phantom experiments that lack human or animal subjects were the dominant model in experiments ($n = 43$), with patient case studies ($n = 19$) and system setup experiments ($n = 21$) being less common [15]. System setup experiments allowed researchers to validate aspects of AR devices through controlled and segmented approaches in which they could test calibration and accuracy. Despite the increase in publications, the authors pointed out a lack of robust studies detailing the clinical benefits of AR in surgery. Although Hallet et al. [14] and Barcali, E., et al. [13] make attractive appeals for the potential of AR, this tool is still nascent, requiring additional trials and investigations to confirm its validity in terms of surgical quality improvement.

EDUCATION

AR and VR have emerged as promising tools for enhancing training and education in neurosurgery, providing residents with a more immersive and interactive experience of complex procedures without the associated risks of operating. Studies support the benefit of AR or VR in medical training, specifically in improving the knowledge and spatial reasoning skills of surgeons along with the accuracy and time to complete procedural tasks [16–19].

A comprehensive review in 2023 of the roles of AR in surgical training encompassed 45 studies across various surgical specialties and AR training models to evaluate the impact of AR on surgical trainees' performance and educational outcomes [20]. Many results from these studies supported the integration of AR into simulation and surgical training, with a study stating that 95% of participants responded that AR devices had a beneficial role in surgical training [21]. Another study described that 83% of participants reported that their ideal learning environment would combine traditional learning models with AR [22]. Despite the promising outcomes, the review noted the need for more comprehensive investigations beyond the aim for "face-validity" into AR's long-term impact [20]. The type of AR device also impacted the assessed validity. Additionally, studies suggest that AR increases skill retention, results in positive trainee behavior changes, and is associated with decreased financial liability due to reduced operative error [5, 23–25].

AR training systems have begun to provide tactile feedback similar to touch sensitivity in the real world—one example is the AR system ImmersiveTouch, which combines stereo-optic displays with haptic response to provide users with a more immersive and realistic environment [26]. In addition to the ability to simulate varying pathologies and patient anatomies to acclimate the surgeon to a multitude of stressors in the OR, VR and AR technologies may reduce the cost of training compared to physical models [27] as these systems allow for widespread use through the development of a single software, which promotes a consistently reproducible standard of education for all trainees using the device.

AR and VR technologies' impact in surgical education is not limited to neurosurgeons. A study in Denmark found that medical students trained in mastectomies using self-directed VR training were able to better retain learned procedural skills through time-distributed practice when compared to massed practice [23]. Although both groups grossly retained skills over an average of a 3-month period, both also saw cognitive load levels revert to similar levels as their initial procedure, supporting the need for frequent practice [23]. Providing a low-stakes virtual environment to reinforce cognitive and motor steps involved in operating allows an opportunity for consistent interval practice. This is beneficial at all levels of training, especially for those working at low-volume sites or learning new procedures.

AR technology can also be used to supplement patient education. Showing patients their anatomy or pathologies in an intuitive and digestible form can help them to better understand their condition and treatment options. Patients were shown a preoperative VR rendering of their surgery based on their volumetric scans as well as a view of what the surgical site would look like post-operation. Patients reported higher levels of overall satisfaction, understanding, and communication with their physician following a preoperative VR consultation compared to previous experiences with a traditional consultation [28].

COLLABORATION

AR-simulated environments facilitate remote consultations between healthcare professionals, allowing them to discuss treatment options and to holistically visualize medical cases together in real-time [24]. Widespread incorporation of these technologies could drastically increase accessibility to care and improve the management of complex medical dilemmas. This practice has already been implemented using cadavers and eventually with patients for over a decade through the creation of virtual interactive presence and augmented reality (VIPAR) and other similar technologies [25, 29]. This prototype iPad-based software positions a surgeon in front of a stereoscopic display capable of remote interaction with a workstation situated in a different region or country. Using the software, the remote surgeon provides instruction and feedback on cases that require surgical assistance and training. Remote neurosurgery may soon be possible with the development of such ancillary teleoperated robotic devices which allow surgeons to perform procedures away from the operative field [16, 30]. However, progress is much slower for these devices compared to software-oriented developments, and most current developments assist in preoperative planning and trajectory rather than functioning as a tangible tool the surgeon can command. Furthermore, development of these devices is hindered by increased costs and regulations compared to AR/VR software development [31].

CHALLENGES AND LIMITATIONS

Although both promising and intriguing, AR will need to overcome an array of obstacles before becoming widely accessible in neurosurgical ORs across the world.

Firstly, the cost of implementing state-of-the-art technologies may be prohibitive, making it a controversial investment, especially if the technology is not widely supported or accepted. Our review did not identify any studies that have evaluated the cost-effectiveness of AR in neurosurgery, which presents a critical gap in literature. This is further complicated in that much of the literature has failed to evaluate metrics that will further promote purchasing of these technologies such as ability to alleviate technician stress, comfort, and/or wearability of the devices. There are no biomarkers in the reported studies to measure metrics such as device comfort and ergonomics, which would be an effective data point to collect as this may objectively highlight how AR and VR may alleviate additional intraoperative stressors. As such, the papers explored in this review have not commented on this aspect of AR in surgery but rather focused on primary surgical outcomes like tumor resection, pedicle screw placement, duration of operation, or length of hospital stay. Additionally, to gain widespread efficacy, neurosurgeons across different institutions and countries must commit specifically to engaging in randomized controlled trials with appropriate study designs and sample populations that adequately evaluate the impact of AR/VR-assisted surgeries compared with traditional surgeries in live populations. To date, randomized controlled trials have been conducted on cadavers; an example of such can be seen in the case-control study performed by Elmi-Terander et al. [32] that shows the feasibility and superiority of AR-guided pedicle screw placements compared to free hand pedicle screw placement in cadaveric thoracic spines. However, we are unaware of such study designs in living humans. Such expansion of mixed reality investigations requires academic institutions, AR/VR manufacturers, surgeons, and patients to take a risk and implement mixed reality in an era of relative uncertainty that lacks profound utilization. Thus, the future regulatory process for AR surgical technologies will be lengthy and complex, which may further slow continued adoption into the OR [33].

Several workflow issues must be addressed if AR is to be integrated into a neurosurgical workforce that has a diverse scope and methodology of practice. There will have to be some overlap between current ways of operating and AR-assisted means of operating, which will require extensive coordination with existing practices. If neurosurgeons must consult other teams intraoperatively, these colleagues too will have to be aware of how AR is at play with their mutual case. As with all transitions, this will not be easy or quick.

Significant technical challenges must also be addressed by AR and VR developers regarding functionality, software, and user experience. Many of these technologies are not user-friendly or do not efficiently co-exist with other foundational OR technologies such as intraoperative MRIs, CTs, and other neuronavigational systems [21, 23]. Even with AR headset designs in 2023 [34], there is the possibility that the device may obscure the field of view, which can prohibit the surgeon from obtaining unobstructed visualization and access to the patient and/or their surroundings. This can be particularly problematic if the surgeon is required to unexpectedly reorient themselves during an intense procedure. Finally, it is necessary for engineers and surgeons in the neurosurgical AR space to anticipate and troubleshoot possible intraoperative malfunctions. Avoiding these errors will be paramount to the future relationship between AR and neurosurgery.

CONCLUSION

Naturally, something as profound and unestablished as AR may be met with skepticism and challenge. Will this feedback depress the evolution of virtually assisted surgeries? Upcoming generations of surgeons will be tasked with further exploring the benefits that AR provides while navigating the obstacles that will meet its acceptance. Studies are promising and suggest opportunities for more precise surgeries [5–8]. Research also supports the notion that AR assisted surgeries may reduce the time the patient spends both in surgery and recovering in the hospital [9]. Simultaneously, both practicing and training physicians can collaborate [11–15], study, and practice [18–20] via educational initiatives supported by AR technologies. However, will these benefits provide enough momentum to overcome challenges that many medical innovations initially face? Most recent data indicate attractive benefits associated with

AR surgeries, so the first step will be to either validate or negate these claims with additional multi-institutional randomized controlled trials. With more investigations it will become easier to better understand exactly how AR will work with neurosurgery. If this truly is a tool that provides better outcomes for both the patient and the surgeon, then it becomes much easier to financially commit to new software and technologies. With more robust integration, additional systems will have to be created to ensure a smooth transition that allows for widespread integration of AR in the neurosurgical OR.

Regardless of the current use of AR in medicine, the evolution of healthcare is trending toward embracing the many benefits of new technologies which show incredible promise in surgical specialties such as neurosurgery. AR and other such technologies will push neurosurgery and all fields of medicine forward.

COMPETING INTERESTS

The authors have no competing interests to declare.

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