Virtual Reality and Augmented Reality as Support for Neurosurgery

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ABSTRACT

Introduction: Virtual reality (VR) and augmented reality (AR) emerge as promising technologies that can provide support for neurosurgery in various aspects, such as intraoperative use, educational purposes, and patient applications. VR is a technology that creates an immersive and three-dimensional environment simulating reality, allowing the user to interact with virtual objects.

Objective: To conduct an integrative review of the literature on the application of virtual reality (VR) and augmented reality (AR) as support for neurosurgery, addressing the benefits and outcomes in intraoperative settings, educational practices, and patient use. Additionally, it will explore the limitations and future prospects of these technologies.

Methods: Integrative literature review of qualitative and investigative nature. The search was conducted based on the following methodological steps: identification of the theme and guiding research question; definition of inclusion and exclusion criteria; literature search and subsequent extraction of information from the analyzed articles; analysis and interpretation of results; and presentation of the review.

Results: Findings were divided based on the utilization of VR and AR technology in neurosurgery; the use of VR and AR as practical training support for students and neurosurgery residents; the use of AR and VR by patients during surgical procedures. The discussed technologies set a basis for a promising future in neurosurgical practice. The versatility of applications in the field is one of the most positive aspects of the researched visualization devices.

Conclusion: Associations with intraoperative practices were well-evaluated by professionals who utilized them, and statistically, postoperative outcomes showed virtually nonexistent adverse results. The application in education was also well-received by the students involved in the studies, providing increased exposure for residents to rare and complex surgical procedures without relying on an actual patient and without risking the patient’s life.

Keywords: Neurosurgery; Virtual reality; Augmented reality

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The Virtual Reality (VR) and Augmented Reality (AR) emerge as promising technologies that can provide support for neurosurgery in different aspects, including intraoperative use, educational purposes, and patient applications. VR is a technology that creates an immersive and three-dimensional environment simulating reality, allowing the user to interact with virtual objects. AR is a technology that overlays digital information onto the real environment, enriching the user's perception. Both technologies can offer better visualization of anatomical structures, a deeper understanding of pathology, increased safety and efficiency in surgical procedures, enhanced training and simulation capabilities, and improved quality of life and rehabilitation for patients.

In addition to having a quick training system setup, saving time for training sessions, these technologies (VR and AR) have the potential to create enhanced learning environments compared to traditional pedagogical schemes. 3D learning environments can increase learner motivation/engagement, improve spatial knowledge representation, enhance learning contextualization, and develop superior technical skills.

The objective of this article is to conduct an integrative literature review on the application of VR and AR as support for neurosurgery, addressing the benefits and outcomes in intraoperative settings. It also discusses the limitations and future prospects of these technologies.

This is an integrative literature review of qualitative and investigative nature. The search was conducted based on the following methodological steps: Identification of the theme and guiding research question; definition of inclusion and exclusion criteria; literature search and subsequent extraction of information from the analyzed articles; analysis and interpretation of results; and presentation of the review. The PubMed database was consulted using a strategic combination of search terms and methodological elucidation variables. To compose the theoretical framework, the Health Sciences Descriptors (DeCS/MeSH) of “Neurosurgery,” “Augmented Reality,” “Virtual Reality,” crossed with the boolean operator “AND,” were used in the PubMed and
Virtual Health Library (VHL) databases, and initially 91 articles were found. Inclusion criteria were defined as articles addressing the use of virtual reality and augmented reality in neurosurgical practices. Exclusion criteria included title reading, abstract review, and full reading (conducted by at least two authors), review articles, duplicates, and other articles not addressing the topic in question. In the end, 16 articles were selected for the review.

### RESULTS

**Virtual reality and augmented reality as intraoperative resources**

Regarding the intraoperative use of these technologies, 13 articles were found. In one study, images of brain tumors were projected onto head models using 5 fiducial markers. Additionally, the image projection technique was applied intraoperatively in 5 patients and compared to a standard navigation system. Augmented reality visualization of tumors was successful in all cases. The average registration time was 3.8 minutes (range 2-7 minutes). The average projection error was 0.8 ± 0.25 mm. There were no notable differences in accuracy concerning to the tumor location and size. The clinical feasibility and dependability of the augmented reality system were affirmed intraoperatively in 5 patients, with a projection error of 1.2 ± 0.54 mm.

In a study involving 79 patients with glioma and 55 individuals in the control group, full resection was attained in 69.6% of the patients and 36.4% of the control group, achieving resection rates of 95.2% and 84.9%, respectively. The groups demonstrated notable differences in both complete resection rates and the average extent of resection (P < 0.01). Subsequent to 2 weeks and 3 months, the preservation rate of neural functions (motor, visual field, and language) in the control group was lower in comparison to glioma patients (P < 0.01). The study also compared pre- and postoperative neurological functions, and the preservation rates for all three functions were lower in the control group at 2 weeks and 3 months after surgery, with statistically significant differences (P < 0.05).

Seventy-seven patients with cerebral glioma, treated between 2015 and 2022, were selected for a retrospective study. The patients were divided into an experimental group (EG, n = 38) and a control group (CG, n = 39) based on surgical modalities. In the EG group, the use of DICOM images from PET-CT and MRI allowed 3D image reconstruction and preoperative planning. This group showed better results, including a higher number of total resections, a higher total resection rate, shorter postoperative hospital stay, and shorter surgery time compared to the CG group (P < 0.05). Additionally, after treatment, the Karnofsky Performance Scale (KPS) score was significantly higher in the EG than in the CG group (75.66 ± 4.01 vs. 65.36 ± 5.23, P < 0.001).

In another retrospective analysis involving 93 patients, parameters of operative performance, histopathological findings, surgical outcomes, and complications were evaluated. The use of three-dimensional virtual reality (VR) magnetic resonance images significantly influenced the recommended surgical strategy (P = 0.02) but had no impact on patient position (P = 0.37) or craniotomy site (P = 0.09). The surgical approach varied, with 59% of patients undergoing the supracerebellar-infratentorial approach and 41% undergoing the suboccipital-transcerebellar approach. Tumor resections had a complication rate comparable to the literature.

In a prospective pilot study aiming to test the clinical feasibility and accuracy of the Hololens mixed reality device for preoperative neurosurgical planning in brain tumors, a comparison was made between standard neuronavigation and the Hololens. Twenty-five patients were included in this study, and holograms were successfully created in all cases. In 9 patients, the tumor location with Hololens did not differ from the standard neuronavigation system, and the total median difference was 0.4 cm (interquartile range 0-0.8).

During an investigation involving 6 patients with supratentorial gliomas undergoing surgery between January 2019 and March 2021, the 3D VR technique was used for preoperative planning. The 3D VR technique proved to be useful for simulating skin incisions, craniotomy, navigation for deep gliomas, visualization of cortical and venous anatomy, identification of surgical corridors in surface and deep gliomas, and highlighting the location of residual tumors and extent of resection in low-grade gliomas.

A mixed reality device with a precise spatial registration method was used to align virtual anatomy with patients before surgery. Experiments on mannequins showed a registration accuracy of 1.18 mm, while in clinical applications, the accuracy was 1.86 mm. Motion and spatial displacement compensation methods
increased the accuracy of the mixed reality-guided glioma resection system.³

Three-dimensional printed markers from CT and MRI, along with mobile devices and LiDAR-AR cameras, were used to overlay virtual tumor images. The targeting error ranged from 0.5 to 3.5 mm (average of 1.70 ± 1.02 mm). The preoperative preparation time was 35.7 ± 5.56 minutes, while the time for registration and intraoperative marker placement was short, with an average of 1.02 ± 0.3 minutes, comparatively faster than other neurosurgical navigation systems.⁴

A portable Augmented Reality Navigation (ARN) system was tested on 20 patients, 10 consecutively and 10 selected after pre-surgical discussions. The utility of ARN significantly improved with case selection and pre-surgical discussions, with “useful” ratings increasing from 50% to 88% across all surgical stages. Utility varied from 50% to 90%, 67% to 100%, and 40% to 80% during skin incision and craniotomy, dura mater incision, and intradural procedures, respectively. ARN proved to be more useful for the resection of superficial tumors, especially with transcortical and interhemispheric approaches⁵.

In a study involving ten patients with glioma in the central sulcus, neuroimaging resources such as CT, CTA, DSA, MRI, and fMRI were used to create 3D models in virtual reality. These models aided in surgical planning, simulation, decision-making during surgery, and medical training. The consistency between preoperative simulation and actual surgery was notable, enhancing procedural accuracy and medical training by transforming abstract learning into a practical virtual reality experience⁶.

A research investigation was conducted on gliomas located in language areas or Rolandic regions, encompassing 35 cases at the Department of Neurosurgery of the Third Hospital of Peking University, spanning from January 2015 to January 2019. This retrospective analysis used surgical programs executed through the Dextroscope virtual reality system. Preoperative data, including magnetic resonance imaging (MRI), magnetic resonance angiography (MRA), and diffusion tensor imaging (DTI), were transferred to the virtual reality (VR) computer for reconstruction purposes. The VR system facilitated the reconstruction of tumors, neural fiber tracts, and blood vessels, enabling the simulation of surgical procedures and the planning of individualized interventions. The assessment of neurological function occurred at intervals of 1 week, 1 month, and 3 months post-operation. Successful attainment of virtual reality three-dimensional images was achieved for all 35 cases, incorporating neural fiber tracts, blood vessels, and lesions⁷. The execution of surgical simulation and the VR surgical program for the 35 patients was accomplished without complications. Among the cases, 10 were identified as tumors in Rolandic regions, 14 as tumors in language areas, and 11 involved both language and Rolandic regions. Notably, complete resection of the highlighted tumor (CRET) was achieved in 30 cases (85.7%), with subtotal resection in 5 cases (14.3%). Postoperatively, neurological function exhibited improvement in 34 cases (97.1%), while 1 case showed no improvement compared to the preoperative state (2.9%)⁸. Thirteen cases without preoperative neurological deficit experienced transient neurological deficits, which were solved around 10 days after the operation. Among the 22 cases with preoperative neurological deficits, 12 cases demonstrated improvement one week after the operation, and 9 cases exhibited improvement one month after the operation. Unfortunately, one case experienced glioblastoma recurrence, manifesting worsened hemiplegia symptoms after the operation, ultimately leading to death from cerebral herniation 2 months later⁹.

Between January 2016 and January 2017, a cohort of 20 patients with deep intracranial lesions affecting critical brain regions underwent needle biopsy assisted by MNVR. Prior to the surgical procedure, MNVR was employed to propose and refine the biopsy planning. Throughout the surgery, navigation was utilized to steer clear of crucial structures along the biopsy trajectory. Intraoperative magnetic resonance imaging (iMRI) was conducted to validate the precision of the biopsy and identify any intraoperative complications. Essential details such as perioperative neurological status, iMRI findings, intraoperative complications, surgical outcomes, and pathological diagnosis were meticulously documented.¹⁰ The Wilcoxon test was executed to compare neurological scores before and after surgery. MNVR played a crucial role in modifying 45% (9/20) of the initial biopsy trajectories, which otherwise might have jeopardized nearby critical structures. Navigation facilitated the adjustment of biopsy trajectories to circumvent critical structures during the operation. Interestingly, despite all lesions being in proximity to vital areas, there was no statistically significant difference between postoperative and preoperative neurological statuses. Moreover, the 20 patients underwent a total of 21 iMRI examinations. In one case, iMRI aided in rectifying the biopsy site, while in another case, it detected intraoperative bleeding, both of which were
Virtual Reality and Augmented Reality as Support for Neurosurgery

D'ivanenko N, Caetano LAV, Costa HLS, Tiba MN, Souza JJ, Bem Junior LS - Virtual Reality and Augmented Reality as Support for Neurosurgery

Using multiple CTA/MRI data, 41 patients undergoing surgery for sphenoid-orbital meningioma from July 2009 to June 2013 were included. The data were transferred to the Dextroscope system, allowing users to obtain measurements and simulated intraoperative visualizations of the lesion and adjacent anatomical structures. A sophisticated preoperative plan was defined. Operation duration, total resection rate, complication rate, and KPS scores were compared with a control group undergoing routine surgery (n = 27). Stereoscopic 3D VR images were reconstructed for 41 cases. In comparison with the control group, the VR preoperative plan could shorten the operation duration and reduce the complication rate (P < 0.05). However, there was no improvement in the total resection rate or KPS score (P > 0.50).

DISCUSSION

A significant hurdle in Neurosurgery and intraoperative processes is the challenge of visualizing deep structures within the brain. In contrast to traditional neuronavigation systems, the utilization of image projection afforded the neurosurgeon the ability to examine the patient's head, initiate the planning of the skin incision, and perform the craniotomy with a direct view of the tumor on the brain surface. This eliminated the need for simultaneous monitoring of the navigation display and the handling of the pointer. The augmented reality system implemented in the study demonstrated precision and reliability in projecting images onto the head, skull, and brain surface during surgery. This system facilitates the immediate visualization of regions of interest (ROIs) on the patient's head, skull, or brain surface, while offering surgeons real-time guidance and enhancing spatial perception. The ergonomic advantages of this system contribute to improved planning of neurosurgical procedures, enabling surgeons to employ direct visualization in image-guided neurosurgery.

There is emphasis on the need for more realistic and complex scenarios in VR surgical simulation to replicate the visual and tactile realities of complex neurological procedures, demanding further development and investment in technology. The generation of new, complex simulated neurosurgical VR procedures, by surgeons for surgeons, with the assistance of computer scientists and engineers, can enhance the assessment and training of residents and ultimately improve patient care. There is a need to create more realistic and complex scenarios with appropriate visual and haptic realities to maximize the potential of virtual reality technology.

Through the application of AR, surgeons gain the capability to directly observe the original lesion and functional areas by peering through the scalp and brain tissue via microscopy. This valuable information is instrumental in shaping an appropriate flap and establishing the optimal surgical trajectory. The surgical planning system, leveraging VR technology, uses cortical positions and fiber tracts delineated by functional magnetic resonance imaging (fMRI) and tractography, respectively. This enables the visualization of preoperative 3D structures, allowing the neurosurgeon to ascertain the lesion's position in relation to these structures from various angles. The incorporation of iMRI serves to validate brain displacement and ensures quality control throughout the surgical process. Consequently, the integration of these advanced techniques holds the potential to significantly augment the resection of gliomas situated in eloquent areas of the brain.

As the integration of these technologies into various professional fields becomes increasingly evident, one of its intrinsic demands is the need to train professionals and students for their use. The use of these as pedagogical tools for immersive teaching in neurosurgery is a topic found in the literature. A notable advancement has been achieved through the development of an innovative microsurgical training system using VR goggles and a smartphone-based webcam. The study revealed significant improvements in the performance of trainee surgeons over time, along with a notable reduction in the time required for suturing. These results indicate not only an acceleration in practical learning but also increased efficiency during training sessions, with the potential to revolutionize how surgeons are trained by providing more effective and precise methods for surgical skill development.

There were indications that educational groups using VR demonstrated a superior response in several crucial aspects. They not only absorbed the basic theory better but also showed greater understanding in the precise location of structures, clinical manifestations, and the diagnosis and analysis of cases. Additionally, this group also exhibited an improved mastery of the studied surgical methods. Among the results obtained, there was a notable progression in the performance of medical students...
in tumor removal over four sessions, significantly enhancing the volume of removed tumors, indicating an upward learning curve as they gained experience. On the other hand, neurosurgery residents maintained a similar amount of tumor and healthy brain tissue removal in all sessions, suggesting remarkable consistency in their performance. Established neurosurgeons also demonstrated greater dexterity in another study, achieved by applying less force to brain tissues. Among medical students and residents, there was a statistically significant increase in the amount of tumor removed.

A specific case serves as a focused illustration of the enhanced utility of virtual reality headset (FEX-VRH): a patient who underwent an awake craniotomy, coupled with intraoperative mapping of the optic tract using the headset, did not exhibit any enduring visual field defects following the surgery. This outcome not only underscores the technology’s capability to aid surgeons but also highlights its pivotal role in safeguarding postoperative visual function.

**CONCLUSION**

The technologies discussed set a basis for a promising future in neurosurgical practice. The versatility of applications in the field is one of the most positive aspects concerning the researched visualization devices. Associations with intraoperative practices were well-evaluated by professionals who used them, and statistically, postoperative outcomes showed virtually non-existent adverse results. The application in education was also well-received by assigned students, facilitating increased exposure of residents to rare and complex surgical procedures without depending on a patient and without risking their life. The use of VR and AR in patients is also a possibility, as direct and controlled sensory stimulation can provide better monitoring of neurofunctionality at risk during surgeries, especially awake ones.

It is important to acknowledge that the technology currently faces limitations, including its restricted accessibility and high costs. Further research is essential to advance neurosurgical procedures and broaden applications within the field. Challenges such as limited success and obstacles in achieving widespread commercial and professional application can impact funding and hinder the development of a system specifically tailored to neurosurgery and the medical field. Addressing these challenges is crucial for overcoming graphic and functional limitations, ensuring the technology’s success and adaptation in the healthcare domain.

**REFERENCES**


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