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Review article

Utilizing virtual and augmented reality for educational and clinical enhancements in neurosurgery

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ABSTRACT

Neurosurgery has undergone a technological revolution over the past several decades, from trephination to image-guided navigation. Advancements in virtual reality (VR) and augmented reality (AR) represent some of the newest modalities being integrated into neurosurgical practice and resident education. In this review, we present a historical perspective of the development of VR and AR technologies, analyze its current uses, and discuss its emerging applications in the field of neurosurgery.

1. Introduction

Neurosurgery has undergone a technological revolution over the past several decades, from trephination to image-guided navigation. Advancements in virtual reality (VR) and augmented reality (AR) represent some of the newest modalities being integrated into neurosurgical practice and resident education. Resident training in the United States is based on the apprenticeship model developed by Dr. William Halsted in the 1890s [1–3]. The training paradigm of "see one, do one, teach one" functioned well for over a century [4]. However, the evolution of social, economic, and regulatory constraints on medical training, demands innovative responses that allow residents to receive equal standards of training within work-our regulations. The importance of incorporating simulation into resident education and skills assessment is being increasingly recognized [5–9]. Integrating VR and AR into resident education will unequivocally modernize Halsted's model [2,7,10,11].

The operating theater has been the primary classroom for countless surgeons in their apprenticeships, as the acquisition of surgical skills requires repeated exposure and opportunity for hands-on experience [12]. However, this exposes patients to increased risk at the expense of resident education [6,13,14]. Thus, it is imperative that we continually develop new technologies to increase resident exposure to surgical procedures and decrease patient risk [15]. Neurosurgeons are constantly challenged by small anatomical corridors draped with fragile blood vessels and critical neural structures that often lie within millimeters of their surgical instruments. These procedures require vast amounts of knowledge, superior technical skill, and, above all, meticulous preparation. Both VR and AR may serve as integral tools in the preoperative rehearsal and overall development of neurosurgical skills. Consequently, surgical outcomes can be significantly improved with the utilization of one or a combination of these modalities [13,16–18]. In this review, we present a historical perspective of the development of VR and AR technologies, analyze its current uses, and discuss its emerging applications in the field of neurosurgery.

2. Methods

The PubMed databases were queried using a strategic combination of search terms including "virtual reality" AND "neurosurgery," "augmented reality" AND "neurosurgery," "virtual reality" AND "surgery," and "augmented reality" AND "surgery." Titles of all results were screened and abstracts of relevant articles assessed for full-text review eligibility by the first author. English, full-text reviews, randomized-controlled trials, clinical trials, case

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series and reports reporting on VR and/or AR in surgery were included for qualitative synthesis. No restrictions on sample size or publication date were enforced. Articles describing simulation-based protocols were excluded from review. Reference pages for all included articles were assessed for relevant material and cited appropriately.

3. Results

3.1. A brief history

The beginnings of VR and AR can be traced back to the early 1960s when Mort Heilig developed the Sensorama, a multi-sensorial simulator with wind and scent production, vibratory sensation, and a 3D display [19,20]. In the mid- to late-1960s, Ivan Sutherland, a leader in computer graphics, described "The Ultimate Display," a room controlled by a computer in which the user could interact with the graphics, and subsequently developed the "Sword of Damocles," one of the first head-mounted displays (HMDs), which overlaid computer graphics onto the real world (similar to today's augmented/mixed reality systems) [19,20]. At the U.S. Air Force Armstrong Medical Research laboratories, Thomas Furness and his team solved many VR issues (at the time) while developing flight simulators designed to train fighter pilots [19,20]. NASA was also at the forefront of VR technology as they worked on developing HMDs for their astronauts [20].

Despite the work of these early pioneers and others who followed, it was clear that the available technology was not at the level needed to bring VR and AR to the masses. The technology was simply not advanced enough to support a virtual experience that was smooth and immersive enough to be widely appealing. By the mid-1990s, the commercial VR and AR industry hit a stand-still [19]. During this time, VR was continually being developed and utilized primarily by a few remaining small companies, academia, and the U.S. military, which was interested in developing it for training and rehabilitation of soldiers and veterans [19].

It was not until the year 2010 that computer technology advanced enough to support the development of truly immersive VR and AR systems that could reach mass appeal. Large corporations quickly began developing VR and AR systems including the Oculus Rift from Oculus VR and Facebook, HTC Vive from HTC and Valve Corporation, PlayStation VR from Sony Corporation, Samsung Gear VR from Samsung Electronics, and HoloLens from Microsoft Corporation.

3.2. Definition and description

VR and AR technology can be categorized as immersive VR, non-immersive VR, AR, and mixed reality [21]. In immersive VR, the real world is completely occluded from the field of vision, and the user convincingly experiences that he or she is immersed within that virtual world [21]. Examples of immersive VR are Oculus Rift and HTC Vive. Non-immersive VR occludes the real-world with the user remaining cognizant that they are viewing a virtual environment, hence the term "non-immersive" [21]. Samsung Gear VR and Google Cardboard are examples of non-immersive VR systems.

In the immersive and non-immersive VR systems, the user wears an HMD that occludes the real world, and the user can maneuver within the virtual environment through movements of his or her head and by physically walking around. Motion sensors in the HMD track head movements, while external cameras track the user as they walk. These movements are then translated into motion within the virtual world. Alternatively, the user can maneuver through the virtual environment and manipulate objects using a handheld device with haptic feedback that give the illusion of actually interacting with the virtual environment and objects within it. Difficulty in providing haptic feedback is a major limitation of VR that has yet to be fully addressed in the current literature.

The differentiation between AR and mixed reality is more concrete. In both augmented and mixed reality, the real world is not occluded from the user's view. Rather, virtual objects are superimposed onto the real world. Users are able to interact simultaneously with the real world and the virtual objects. In AR, the virtual objects are transparent in the real world in daylight, similar to a hologram. In mixed reality, the virtual images appears solid (unlike a hologram) to the user in daylight [21]. Examples of AR systems are Meta and DAQRI. Microsoft Hololens and Magic Leap are examples of mixed reality systems.

In augmented and mixed reality systems, the user wears glasses that do not occlude the real world but that display holographic images onto the real world for the user to interact with. Since the user still visualizes the real world, augmented and mixed reality systems can be used almost anywhere and in nearly any situation. The interactions with graphics and virtual objects in these systems occur either through voice commands or by hand gestures.

3.3. Barriers to the operative field

VR and AR have yet to achieve commercial success, and this has hindered the development of a system that can be adapted to neurosurgery and the medical field at large. The integration of these modalities into clinical practice is dependent on the following variables: mobility, vision, immersion, usability, flexibility, wearability, and affordability [21,22]. In the operating room, mobility and vision are vital to success. An AR system must allow adequate mobility and vision in the surgical field to augment the procedure. Conversely, VR systems would be most useful in preoperative planning and resident education.

Furthermore, in order to provide an immersive experience that would allow for improved surgical planning and resident training, a VR system must reach a certain threshold of depth of field, depth of focus, field of view, image resolution, and position tracking [21]. Both AR and VR systems must be comfortable enough to wear for long periods of time, and the technology must achieve economies of scale so systems are affordable enough to be used in training and during procedures. Additionally, for VR and AR systems to be adopted into the surgical environment, reliability and validity measures must first be met (e.g. inter-rater and test–retest reliability, internal consistency, and face, content, convergent, discriminant, predictive and concurrent validity) to assure patient safety [23–28].

3.4. Neurosurgical training and outcomes

VR and AR have the potential to create enhanced learning environments compared to traditional pedagogic schemas. 3D learning environments can increase learner motivation/engagement, enhance spatial knowledge representation, improve contextualization of learning, and develop superior technical abilities [29]. These benefits are contingent on the representational fidelity of the 3D virtual environment and interactive potential [29–31]. In neurosurgery, VR may become an extremely valuable tool for education due to the intricate and complex nature of neurosurgical procedures. A formal neurosurgical curriculum utilizing virtual workspaces may advance the training of budding neurosurgeons and has the potential to formulate proper evaluation criteria of surgical skills for both novice and experienced surgeons [14,32]. Ultimately, this would lead to greater efficiency, improved patient care, and minimization of technical errors that are inherent to the surgical learning curve [33–36]. Additionally, VR can provide residents with