Review

The Use of Virtual Reality in Surgical Training: Implications for Education, Patient Safety, and Global Health Equity

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Abstract: As medicine becomes more complex, there is pressure for new and more innovative educational methods. Given the economic burden associated with in-person simulation, healthcare, including the realm of surgical education, has begun employing virtual reality (VR). Potential benefits of the addition of VR to surgical learning include increased pre-operative resident exposure to surgical techniques and procedures and better patient safety outcomes. However, these new technological advances, such as VR, may not replicate organic tissues or accurately simulate medical care and surgical scenarios, creating unrealistic pseudo-environments. Similarly, while advancements have been made, there are ongoing disparities concerning the utilization of these technologies. These disparities include aspects such as the availability of stable internet connections and the cost of implementing these technologies. As such, VR may further widen educational quality between high- and low-resource nations. This analysis integrates recent innovations in VR technology with existing discourse on global health and surgical equality. In doing so, it offers preliminary guidance to ensure that the implementation of VR occurs in an equitable, safe, and sustainable fashion.

Keywords: surgical training; virtual reality; global health; education

1. Introduction

As clinical scenarios in medicine become more complex, there has been an increase in the pace of change in medical education [1]. With new treatment options available, patient populations with higher comorbidities, and the rise of interdisciplinary and specialty modes of care, medical trainees are faced with issues that may not be easily taught in traditional classroom settings or in medical textbooks [2,3]. As such, there has been a rise in the implementation of in-person simulation sessions where trainees practice how to ‘be a doctor’ before transitioning to real-life situations where the stakes are higher [4]. Not only have these been positively received by trainees, but studies have also suggested their role in improving education quality as well as patient safety and outcomes [5,6]. However, the cost associated with in-person simulation, often requiring an actor to play the patient’s part, precludes equitable implementation among settings with lower resources allocated to education [4].

Virtual reality (VR) has emerged as a potential option to mitigate this issue. First developed in the 1950s, VR made its way into multiple industries, including videogame entertainment, military training, public safety, and construction. VR was first used in healthcare in the 1990s, when surgeons began incorporating it as a planning tool for complex operations [3]. Since then, VR systems have improved their graphics and system speeds, allowing the creation of realistic environments. They are now able to create auditory, olfactory, and visual sensations for users and provide them with haptic feedback [7]. VR’s
ability to create realistic pseudo-environments can be useful in medical education. Putting on equipment that tracks head, eye, body, and hand positions can immerse users in many potential scenarios and allow them to practice procedures multiple times while still experiencing visual, auditory, and tactile feedback within a virtual world [7].

Likewise, VR education can have a global impact if brought to rural, remote, and low-resource settings to train health professionals [8]. Oftentimes, education in these communities is limited due to a lack of local educators and limited access to textbooks [9]. VR could be a valuable resource in these regions through its ability to connect such communities with others that have the resource capacity to provide education. Yet, introducing VR into these settings would entail access to the equipment and an internet connection. These challenges also come with significant financial costs for obtaining and maintaining the hardware and software [9].

Considering the advantages and disadvantages of VR, we aim to explore the implications of using VR in surgical training. As VR system advancements make it a future addition to surgical education and training, it is important to evaluate the potential benefits and harms this platform can have for both healthcare professionals and patients. Additionally, we discuss the coordination of incorporating VR into surgical curricula.

2. Potential Benefits of VR in Surgical Training

2.1. The Impact of Digital Learning Tools on Surgical Education: A Review

Virtual reality has emerged as an innovative teaching tool in surgical training as it offers a cost-effective and highly realistic alternative to textbooks and lectures. One of the most promising benefits of VR in surgical training is its impact on skill acquisition and confidence among medical professionals [10]. A study involving plastic surgery residents investigated the use of a simulation-based cleft surgery website on surgical skill acquisition [11]. The residents were assessed based on the ten required steps in the digital simulator, which were verified by expert craniofacial surgeons. The participants in the digital simulation group significantly improved their surgical knowledge, procedural confidence, and surgical performance. The control group, which used textbooks, did not have significant improvement in the categories mentioned previously. Moreover, the digital simulator was significantly favored over the textbook according to the students’ evaluation of educational quality. The simulator’s advantages were that it was more stimulating and effective and had more clarity. It was also more likely to be recommended over textbooks as a teaching tool. The favorable results of the simulation are an indicator of the potential success of using VR in education and training [11]. Students valued the simulator’s interactivity, which facilitated an effective learning process. VR goes beyond the simulation website with its immersive sensations and potential for haptic feedback, as if users were performing the procedure live. This realism would be particularly useful for anatomically intricate surgeries. Similar conclusions were drawn in other surgical fields, including cardiothoracic, obstetrics and gynecology, transplantation, and urology [12–15].

2.2. The Potential of Virtual Reality in the Improvement in Patient Safety

Medical errors are a significant cause of death in the United States [16]. Residents and medical students often work long hours in high-pressure environments [17]. The traditional teaching method in medical education has been “see one/do one/teach one”, which can leave room for error as students and residents may not have sufficient hands-on practice prior to carrying out a procedure [18]. Fatigue from long workdays and inexperience from a lack of practice combined with a heavy workload can contribute to medical errors [19]. A study conducted on two critical care units at a major urban teaching hospital indicated that about 20% of patients suffered from an adverse event when first-year residents were following a traditional working schedule, with 45% of those adverse events being preventable. The error rate per 1000 patients was 80.5 for all adverse events and 36.2 for preventable adverse events [20].
Given the importance of patient safety, VR offers medical students and residents an opportunity to develop and hone their skills in a safe environment before transitioning to real-life cases [21]. Further, VR allows them to advance their skills to full competency. To assess the effect of VR training on cholecystectomies’ outcomes, thirteen surgical residents participated in a study; all had experience assisting with laparoscopic procedures but had no experience performing laparoscopic cholecystectomies (LCs). The residents were randomized into two groups: the intervention group received VR training, and the control group did not. For the first ten LCs, the VR-trained group demonstrated significantly higher performance than the control. The control group made three times more errors, on average, in comparison to the intervention group. Similarly, the control group had a 58% longer surgical time. It had greater variability through the series of surgeries performed, whereas the VR-trained group’s performance was more consistent [22]. Similar results have been found in orthopedic procedures, neurosurgery, ophthalmologic cataract interventions, general surgery, and salpingectomy [23–28]. These findings suggest that VR can be used effectively to teach skills that are transferable to the operation room (OR). In addition, reducing operating time allows more surgeries to be performed each day, increasing resident exposure to in-like cases, and improving patient outcomes by lowering the length of anesthetic events.

In this way, as the benefits of VR in surgical education continue to emerge in different fields, research on the topic aims to demonstrate improved trainee competence following VR exposure as well as improved models that are more faithful to the surgical procedures being taught [29].

2.3. The Role of VR in Remote Learning

VR offers more flexible learning modalities to help alleviate limitations on education and training caused by pandemics and mandatory social distancing, for example. COVID-19 significantly affected not only patient care but also access to training time and facilities [30]. A surgeon’s technical skill is essential for successful postoperative outcomes. Combined with the already limited practice opportunities for trainees and the relative frequency of preventable medical errors, VR could enhance outcomes for patients by expanding opportunities for trainees to accrue important technical skills. VR platforms allow trainees to practice their procedures and approaches repeatedly outside of the OR [29]. Considering the costs associated with OR time, VR may also offer a cost-effective training option. Another randomized trial has shown that students who partook in VR-simulator training for surgical skills significantly improved their visual–spatial imagination, surgical performance, and completion time [31]. Additional studies have presented evidence that skills learned in VR training platforms are transferable to the OR, as those who reached proficiency in simulation-based training performed better and faster in real-life settings [12,25,32–34].

Beyond education, VR may improve surgical care in lower-resource settings. Telesurgery and virtual education have shown potential to improve surgical education, access, and quality in Africa by improving collaborations, decreasing surgeon shortages, and eliminating the need for long-distance travel [35]. For example, during the COVID-19 pandemic, students in their final year of a general surgery program at the University of KwaZulu-Natal had to transition to online learning. An evaluation of their experiences demonstrated that most of the students had access to the necessary devices for remote learning and steady internet connectivity [36]. The positive reception of e-learning by these medical students may be a promising start for the further development of technology-based learning. These results support the clinical effectiveness of VR, suggesting that this resource may benefit learners, educators, and patients in LMICs [37].
2.4. VR Can Impact Global Health by Addressing Challenges with Surgical Training Access

VR could provide trainees in lower-income regions with an opportunity to advance their skills using a new training tool that benefits their career prospects, as well as alleviate the issue of mentors remaining in the host country for only short training periods.

In low- and middle-income countries (LMICs), there is an ongoing shortage of skilled surgeons due to a lack of proper local training programs; however, the need for these specialists is increasing [38]. While medical school enrollment has increased in such regions, there is limited focus on postgraduate medical education (PGME) [39]. Retention rates for PGME professionals are impacted by career prospects and employment opportunities [39]. Developing training programs to grow the skills of PGME professionals has a positive impact on patient outcomes in local communities [40]. The use of online case studies at the College of Surgeons of East, Central, and Southern Africa shows that there is already a presence of e-learning [41]. This is helpful for the incorporation of more advanced virtual education tools, such as VR, in surgical training since a foundation for technological learning already exists.

Similarly, wireless networking, computer technologies, and 3D cameras allow surgeons in remote areas to connect with experienced supervisors in real time. These supervisors can be located anywhere, from regional practitioners to master surgeons in other parts of the world [42]. The assistance of these specialists via remote communication allows surgeons on the ground, who may have less training, to resolve complications that they encounter during surgical procedures and achieve better results [42]. With the increased use of mobile phones in Africa, the incorporation of information and communications technology in healthcare is more likely [35]. In addition, current VR technology allows for programs to be downloaded in advance via Wi-Fi and utilized offline [43]. Trainees would then be able to download modules ahead of time in their respective academic institutions and practice at home or in community hospitals in preparation for surgeries. This structure can be expanded to also accommodate VR training, as telesurgery is establishing some of the necessary infrastructure needed for VR, such as available headsets and the internet needed to download learning modules [3]. Integrating VR into health training in LMICs would allow surgeons to learn and develop proficiency in procedures, which could decrease their reliance on outside supervision during surgeries.

As a case example, a successful program for training specialty surgeons exists in Kenya. CURE started out in Kenya in 1996 and has led to the establishment of an Orthopedic Surgery Residency. This program brought structure to orthopedic training by introducing didactic, clinical, and online learning and providing the opportunity to attend training conferences. Furthermore, CURE residents need to successfully pass exams analogous to the boards to complete their training. The program thrived due to the emphasis placed on quality education and training and the mentorship of international board-certified orthopedic surgeons who served as educators. Nine residents have completed the program and continue to practice in their home country. Five of these residents are involved in teaching the next class of orthopedic surgeons. While these numbers may not seem large, specialty care access for patients is improved with each additional qualified orthopedic surgeon. One of the challenges in maintaining the CURE program, aside from funding, was finding skilled board-certified surgeons who would be willing to relocate to Kenya for several years to train the residents [44]. VR surgical training could alleviate this stressor and increase the longevity of the program by possibly decreasing the amount of time international educators have to remain in the host country. This would incentivize surgeons to participate in the program, as education could take place in a virtual environment. The local trainees would have multiple attempts to repeat procedures as they sharpen their skills. Certainly, this would also entail familiarity with VR surgical training for international educators themselves and the establishment of these systems within the current curriculum.
2.5. The Use of VR Can Foster Continuity of Care and Training

VR can revolutionize the way medical mission trips are conducted in low- and middle-income countries (LMICs), providing a sustainable solution to improve healthcare access and outcomes. Mission trips constitute a large part of healthcare outreach to LMICs. A drawback of such mission trips is that they only temporarily alleviate problems without addressing the root causes [45]. This delivery model does not foster independence in local providers, nor does it establish any sort of structure for continuity of quality care [44]. In fact, local medical providers often criticize this mode of care as it tends to overlook the needs of local populations and apply principles that are effective in high-resource settings but not necessarily in areas with limited access to care and resources [45,46].

More specifically, in the case of the COVID-19 pandemic, medical mission trips face two dilemmas: on the one hand, if a country is asking for assistance, there is a duty for physicians to provide treatment; on the other hand, providing this treatment may put the local population at a greater risk by creating a COVID-19 ‘super-spreader’ event. Telemedicine may be an appropriate substitute for mission trips; however, it is not effective in cases that necessitate surgical intervention [47]. This further solidifies the need for specialty training programs that incorporate VR. Training on simulation-based platforms would facilitate the independence of local practitioners and decrease their reliance on outside interventions. In addition, the traditional model of mission trips focuses on operating locally and leaving postoperative care to local providers. This may be economically and academically impractical, with the continuous increase in demands for specialty surgical care in growing populations, while training local doctors may be more sustainable [48–50].

Virtual reality and continuous training of local physicians by international experts would decrease this additional cost and create a local community of experts that could then be empowered to teach the next generation of physicians [42] (Table 1).

Table 1. Advantages of virtual reality in surgical education.

<table>
<thead>
<tr>
<th>Patient safety</th>
<th>Opportunity to make mistakes</th>
<th>Global health outreach</th>
<th>Remote learning</th>
<th>Mentorship opportunities</th>
<th>Improved longitudinal training</th>
<th>Assessment of trainee competencies</th>
</tr>
</thead>
</table>

3. Potential Risks of VR in Surgical Training

3.1. Limitations of Virtual Reality in Simulating Surgical Cases

While VR technologies have advanced since their development and can simulate realistic environments, there are still noteworthy limitations. VR training platforms for minimally invasive skills use surgical interfaces that employ a simple, non-force feedback apparatus that converts mechanical events into mathematical information that signifies instrument position and status. The limited tactile sensations lessen the realism of the training experience. For instance, in an instrument–instrument collision, the user would only understand that a mistake occurred through visual cues. Yet, even with the current efforts to develop more precise force feedback in VR, there are few data to support the idea that the lack of such precludes skill acquisition [51].

The biggest challenge with VR is the lack of realistic models mimicking tissues that are fully responsive to surgical techniques. Accurate real-time simulation needs to combine the anchoring of biological structures with the viscoelastic properties of organs to achieve dynamic characteristics. The lack of data on the physical characteristics of organs in vivo is limiting VR simulators from recreating these tissue properties [52]. There are several ways developers are approaching this issue. First is the use of virtual-reality tissue construction based on computerized models. Pioneered by the spring mass model, which creates real-time topological changes by representing the physical object as distributed masses,
current simulators employ more advanced polyhedral meshes, tetrahedral meshes, and homologous skin surface models [53,54]. These models are based on particle position and shape by sections, allowing the user to not only cut the meshes according to voxels but also be able to suture with slide constraints according to the entry and exit points of the simulated wire [54]. These have improved the tactile and visual properties of tissues during virtual manipulation, simulating interventions that have high degrees of complexity and morbidity, such as a hepatectomy [54]. Additionally, with the current advances in robotic surgery using machines that allow the surgeon to have a tacit and spatial feel of the operative window, surgical training incorporating the use of the potential of virtual reality environments with mechanical surgical instruments may better prepare trainees not only for mastering surgical techniques but also for operating the machinery employed in said surgeries [55].

3.2. Users Will Need to Get Accustomed to VR Technology to Maximize Their Learning Experience

Although shortcomings in the accurate creation of digital surgical environments may be overcome with improvements in modeling, a full integration of virtual reality in surgical education is mediated by the ease or difficulty with which learners are able to adapt to this new learning modality. Firstly, unfamiliarity with the use of VR headsets would require a preemptive understanding of the usage of the technology prior to a learner’s ability to extract information from virtual reality. This is an added drawback when compared to traditional sources of education, such as textbooks and lectures, which do not require, for the most part, preemptive teaching. As an additional step is required for VR education, the investment in this technology may be redundant when similar expenditures could be made in digitalizing books or making lecturers and surgical videos freely available. The lack of contact with VR technology could be further exacerbated in low- and middle-income countries where access to digital education is still lagging [56,57]. This in turn could create further inequity between those who would have access to tools to maximize the educational potential of VR and those who would be unable to fully grasp how to operate the technology.

Additionally, the reported side effects of virtual reality have been widely documented and could impact learners. Similar to motion sickness, cybersickness stems from a “discrepancy between the sensory signals, which provide information about the body’s orientation and motion” [58]; that is, optic flows induce a sensation of movement in a certain direction, which is contradicted by the stagnation detected by the user’s proprioceptive and vestibular senses [58]. This can induce symptoms of nausea, vomiting, eye strain, dizziness, lightheadedness, and ataxia, which can be deleterious to the learning experience [59]. As the severity of cybersickness has been proposed to be dependent upon the total duration of VR exposure, especially for those experiencing symptoms, the teaching of long surgical procedures may be precluded [60,61]. For example, Liu (2014) found that the severity of symptoms in users worsened when the VR task increased from 5 to 15 min [62]. As the majority of surgeries last longer than this, surgical education with VR may be better applied to simplified step-by-step instructions instead of a full walk-through of the whole surgical procedure at its real length. This is further problematized by the possibility that cybersickness symptoms fail to recede immediately after the cessation of the VR activity but rather linger following exposure [63]. Although current developments do exist to prevent cybersickness, including designing VR environments with stable visual references or galvanic stimulation of vestibular senses, it is unknown whether this technology could be applied to VR in the setting of surgical education [64,65].

All in all, from a learning-curve standpoint as well as from cybersickness issues, individual learner characteristics may impact the full and equitable applicability of VR. Rather, individualized learning based on the learner’s preferences, comfort level, and interest in digital educational resources is preferred.
3.3. VR Supplementation with Additional Learning Methods and Tools

While there is true potential for the development of mathematical models that support surgical learning, they do pose their own shortcomings. Although they can properly create an environment that illustrates the general anatomical boundaries involved in each surgical procedure, interpersonal anatomical differences may not be properly accounted for [66, 67]. As such, the transition from the ‘virtual’ to the ‘real’ world may still require cadaveric studies as well as recurrent intraoperative experience. In addition, while possible to mimic, intraoperative adverse events are intrinsically linked to an individual patient’s comorbidities, and prompt intraoperative management, especially in urgent or emergent circumstances, may not be properly learned [68]. Finally, from a psychosocial standpoint, artificial intelligence, while advanced, cannot fully equip VR simulations to be appropriate platforms to practice patient interactions where the user must deliver difficult news to the patient. As with any technological equipment, VR will need faculty support and troubleshooting. Trial periods can ease the transition to using VR, allowing faculty to familiarize themselves with the technology.

Despite the improvements that VR training simulations need to make, VR should not be dismissed as a valuable learning modality. VR would not replace any elements of medical education curricula, such as hands-on clinical training, but instead would enhance student learning. Educators can determine which skills or procedures are best suited for training on the VR platform and incorporate VR into their teaching methods [3]. The flexibility in terms of the repeatability of procedures and the choice to practice at times and in locations convenient to them are notable VR advantages. As use increases, more data on student performance can be collected to identify areas for improvement.

3.4. The Implementation of VR in Low- and Middle-Income Countries Can Face Financial Barriers

Introducing modern technology into medical training and educational curricula comes with a financial cost. System hardware, software, and payment for installation are some of the initial costs to consider in the VR purchasing process. For LMICs, this may be a burden in addition to existing challenges, including shortages of specialty healthcare workers, resources, and limited budgets [35]. Immersive virtual reality (iVR) could be a lower-cost alternative to conventional VR as it is portable and uses commercially available hardware [16]. Past studies have reported that iVR headsets cost about USD 1500, and the software can range from USD 4000 to USD 8000 [17–19]. While there are undoubtedly upfront costs associated with VR, they are an investment in an effective learning tool that is cost-effective overall. Estimates suggest that VR training is 34.1 times more cost-friendly than traditional training options when used biweekly for a one-year period [25]. Considering the possibility of quickly downloading newly updated modules, VR mitigates the economic and environmental non-sustainability associated with textbooks and other methods of learning [69]. In addition, similar to the phenomenon seen with cell phones, as VR technology develops and becomes more widely implemented and used, the costs associated with headsets are expected to decrease [70].

Monetary resources could be employed in priority health care areas in LMICs, such as the treatment of HIV and malaria, rather than in VR. Yet, a recent study challenged this paradigm: by comparing 30-day mortality postoperatively to other major causes of mortality in LMICs, postoperative mortality is the third greatest contributor to deaths worldwide, surpassed only by stroke and ischemic heart disease. In fact, 4.2 million people are expected to die per year due to operative and postoperative complications—a number almost twice as high as the rate of patients dying from malaria, HIV, and tuberculosis combined (2.97 million) [71]. In addition, while ischemic diseases are multifactorial, surgical outcomes can be improved by improving the safety of the operations being conducted. As mentioned previously, medical errors account for the largest mortality associated with surgical outcomes. In countries with scarce training resources, VR could improve the safety of surgeries by supporting surgeons’ education pre-operatively. With declining prices, accessibility issues relating to this technology are expected to decrease, and its
implementation in LMICs may be more easily conducted. As efforts to improve educational equity between areas with high and low resources expand, VR may emerge as a potential viable option that is cheaper and more sustainable than current ongoing projects [72]. This opportunity, however, still requires a significant capital investment, which may not be feasible in many regions. As efforts to improve educational equity between areas with high and low resources expand, VR may emerge as a potential viable option that is cheaper and more sustainable than current ongoing projects.

3.5. VR Technology Requires Stable Internet Connectivity, and Lack Thereof May Preclude Equitable Implementation

Apart from financial barriers that may preclude widespread implementation of VR teaching programs in LMICs, a potential lack of internet connection may impair the implementation of digital methods of learning in these regions [35]. There have been numerous reports of issues transitioning to virtual learning due to a lack of stable internet connection during the COVID-19 pandemic, with approximately one in every six students claiming poor access to broadband coverage. Not surprisingly, these students often came from socioeconomically disadvantaged areas with large geographic disparities [73]. While valid, it is also true that internet access is increasing in LMICs. The most recent report from the United Nations International Telecommunication Union indicates that over 66% of the world population has access to an internet connection [74]. Similarly, over the past few years, there has been an increase in internet-based surgical simulation resources. For instance, in 2012, a cleft surgery simulator was launched to improve access to surgical cleft care. This is a free and globally available resource that has more than 4000 active users from both high- and low-resource locations [75]. The global success of this platform suggests that internet access may preclude surgical e-learning. Nevertheless, to ensure VR benefits all who need care, not only the privileged, policies should also include equitable access to VR apparatuses and connectivity (Table 2).

Table 2. Disadvantages of virtual reality in surgical education.

<table>
<thead>
<tr>
<th>Financial barriers</th>
<th>Decreased human interaction</th>
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<tbody>
<tr>
<td>Imperfect fidelity</td>
<td>Access to internet connectivity</td>
</tr>
<tr>
<td>Possible potentiation of educational inequity</td>
<td>No interaction between intraoperative team members</td>
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4. Future Directions: Avenues to Improve Currently Existing Virtual Reality Models and Increase Their Applicability

Current and future research efforts are directed toward the eventual application of virtual reality to the standard surgical residency curriculum. The studies discussed herein provide evidence to guide support for the use of VR, albeit the limitations for its widespread implementation are numerous. Beyond the financial and patient safety considerations reviewed in this article, there are key steps that need to be considered prior to the implementation of virtual reality in all areas of surgical education.

Firstly, one major drawback of currently existing virtual reality models is the lack of intercollegiate interaction during the surgical simulation. It is well studied that cooperation and organic and smooth interaction between surgical team members improve surgical outcomes [76]. In fact, poor communication intraoperatively has been associated with worse intervention results [77]. While technical skills have been found to improve with virtual reality, VR could also be utilized to effectivize surgical team dynamics. This could be through the simulation of surgical emergencies, changes in operative planning, or even honing communication soft skills between team members. The implementation of a multi-user platform where different trainees could collaborate in the virtual environment could potentiate the role of VR beyond mere technique acquisition.
Similarly, in addition to teaching, virtual reality models could be utilized to standardize competencies for surgical trainees. Although certain qualifications are required for certification in surgical specialties, such as board exams, these fail to capture the quality of a trainee’s surgical skills [78]. As the evidence for effectively evaluating physicians is lacking, virtual reality could augment written exams and facilitate the implementation of practical examinations without compromising patient care [78]. In doing so, there would be a standardization of competencies that all trainees would have to demonstrate before becoming board-certified.

Finally, one major drawback of virtual reality is intrinsic to the divergence between anatomical simulation models and those encountered in reality. As humans are anatomically different, trainees may be poorly equipped to adapt from virtual reality models to real-life interventions. With the advent of virtual surgical planning, computer-aided design, and manufacturing, the possibility of incorporating virtual reality could support pre-operative preparation. Inputting CT and MRI images into the virtual environment would allow surgeons to interact with those images and visualize the anatomy in detail, especially in the setting of anatomic variants. Improved spatial understanding might lead to greater understanding of major vessels and structures involved in the operative field and avoid iatrogenic damage [79]. The ability to better visualize such differences could then make surgeries faster and improve patient outcomes [79].

5. Conclusions

Virtual reality (VR) presents a multifaceted opportunity to enhance various aspects of medical education, training, and patient care. By offering a flexible and immersive learning modality, VR can significantly improve surgical skill acquisition and confidence among medical professionals. It addresses the critical issue of medical errors by allowing trainees to practice in a safe and controlled environment before transitioning to real-life cases. Furthermore, in LMICs, where there is a shortage of skilled surgeons and access to quality training is limited, VR emerges as a powerful tool to empower local practitioners, improve surgical care, and reduce the reliance on external intervention. The potential for remote collaboration and the ability to download training modules offline make VR a practical solution for regions with limited internet connectivity. While initial costs are a consideration, the long-term cost-effectiveness and the decreasing prices of VR technology suggest a promising future. In light of these advantages, it becomes evident that VR is a valuable addition to medical education that complements hands-on clinical training and contributes to the continuous improvement in healthcare. As medical institutions and professionals continue to explore and adapt to this transformative technology, VR can revolutionize the field, improving patient safety, surgical outcomes, and healthcare access globally.

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References


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