Journal of Primary Care & Community Health
Volume 15: 1–13
© The Author(s) 2024
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/21501319241293311
journals.sagepub.com/home/jpc
Sage

Immersive Technologies in Healthcare: An In-Depth Exploration of Virtual Reality and Augmented Reality in Enhancing Patient Care, Medical Education, and Training Paradigms

Arham I. Iqbal[1], Ali Aamir[2], Abdullah Hammad[1], Hafiza Hafsa[2], Abdul Basit[2], Malik Olatunde Oduoye[3], Muhammad Wajeeh Anis[1], Shaheer Ahmed[2], Mohammad Ijlal Younus[1], and Sarwat Jabeen[2]

Abstract

Background: Virtual reality (VR) and augmented reality (AR) are rapidly gaining traction in healthcare, offering transformative opportunities for patient care, medical education, and therapeutic interventions. Despite their potential, challenges remain regarding the implementation and integration of these technologies into existing healthcare practices. **Objective:** This review aims to explore the current applications of VR and AR in healthcare, particularly focusing on their roles in enhancing patient care and medical training, as well as identifying research gaps that hinder their widespread adoption. **Methods:** A comprehensive literature search was conducted across 2 primary databases, PubMed, and Google Scholar. The search was restricted to peer-reviewed articles, systematic reviews, meta-analyses, and randomized controlled trials (RCTs) published from 2000 to 2024. Reference lists of included articles were also examined for additional relevant studies. Inclusion criteria focused on empirical studies addressing the use of VR and/or AR in patient care or medical training, while editorial pieces, non-peer-reviewed sources, and unrelated studies were excluded. A total of 17900 search results were identified on Google Scholar and 300 on PubMed, leading to the inclusion of 89 articles in this review. **Results:** The findings indicate that VR and AR technologies significantly enhance patient experiences and medical training, providing immersive and interactive environments for learning and practice. However, notable challenges include integration issues with existing electronic health record systems, the need for appropriate implementation models, and a lack of substantial evidence supporting the clinical efficacy of AR-assisted procedures. **Conclusion:** While VR and AR hold considerable promise in revolutionizing healthcare practices, further research is essential to address existing gaps, particularly regarding implementation strategies, user acceptance, and empirical evaluation of patient outcomes and training effectiveness. Understanding the needs of healthcare professionals and patients will be critical to maximizing the impact of these technologies in clinical settings.

Keywords

virtual reality, augmented reality, patient care, medical education, medical training

Dates received: 11 June 2024; revised: 29 September 2024; accepted: 1 October 2024.

Introduction

Virtual reality (VR) is gaining popularity in healthcare settings, as new technological breakthroughs enable diagnosis and therapy.[1] VR, as indicated by its name, involves the use of a specialized headset to simulate an environment in which the user is fully immersed, thus creating the perceptual experience of being physically situated in a synthetic 3-dimensional (3D) virtual space and offering diverse

[1]Dow International Medical College, Karachi, Pakistan
[2]Dow Medical College, Karachi, Pakistan
[3]The Medical Research Circle, Goma, Bukavu, The Democratic Republic of the Congo

Corresponding Author:
Malik Olatunde Oduoye, Department of Research, The Medical Research Circle, PO. BOX 73, Goma, The Democratic Republic of the Congo.
Email: malikolatunde36@gmail.com

avenues for engaging with virtual environments or characters. These virtual characters, commonly called avatars, enhance the user experience and facilitate meaningful interactions.[2] Closely related to the elements of VR, augmented reality (AR) connects to it and displays a real-world environment in the form of a live video, where the user can interact with the help of haptic (touch) feedback and audio and visual stimuli.[3,4] In recent years, technological advancements have made VR and AR systems portable, realistic, and user-friendly for real-time navigation. These systems often include sensory and olfactory elements within a range of sensations.[5] Personalized VR and AR devices have been available in the market for several years and continue to evolve and improve. Users can interact with virtual environments using handheld devices, such as joysticks or keyboards, and more recently, through integrated body tracking technologies.[5,6] VR and AR are highly versatile and utilize various systems and setups to accommodate a wide range of content. This content can range from highly immersive, dynamic, and interactive experiences to non-immersive and static ones.[6,7] Despite their potential benefits, the successful utilization of VR and AR necessitates complete integration into current healthcare practices and should be in accordance with the requirements of patients and healthcare professionals. Thus, focusing on implementation strategies is crucial to increasing technological acceptance, uptake, and impact.

The rising stress in public health systems has created a demand for assistance systems, which is one of the reasons for the rapid development of AR and VR.[8] There are numerous advantages to using VR or AR over traditional therapies. These technologies could enable multiple repetitions of simple tasks in a clinical setting within an immersive environment, reducing the need for constant supervision by the medical staff, which could significantly lower the costs associated with training facilities.[1] As technology continues to advance in the healthcare sector, VR is becoming increasingly popular in healthcare settings for diagnostic and therapeutic purposes. Although implementation interventions may aid in the systematic adoption of VR, they are rarely used in practice. Using an implementation model to guide the process can inspire methodical implementation and aid in the development of an intervention. While a large number of implementation models have been established, there is still limited use of these models to structure the adoption of VR in healthcare.[9] Similarly, AR-based technology is revolutionizing various aspects of healthcare and offering unprecedented opportunities for medical imaging and visualization, anatomy education, and telemedicine.[10] The integration of AR into healthcare practices enhances the efficiency and effectiveness of medical care, leading to improved patient outcomes. By increasing patient adherence to treatment and improving the quality of care, AR also alleviates the overall burden on the healthcare system. Additionally, AR holds significant potential as an effective learning methodology for patients, warranting a comprehensive overview of its current status in patient education and health literacy.[11]

VR signifies a change in the approach to educating and assessing the proficiency of healthcare providers. The notion of VR was first proposed in the 1960s by Morton, who created the "Tele Sphere Mask" and the "Sensorama." The initial technologies were designed to immerse the viewer in a video display environment, inducing a sensation of being integrated into the video experience.[12] Ivan Sutherland created the "Ultimate Display," which operated on a comparable premise, enabling the user to experience immersion in a computer-generated environment by employing various input and output devices. Following the introduction of Sensorama and the concept of the Ultimate Display in the 1960s, the next significant surge in VR technology development occurred in the early 2010s.[13,14] Although VR was developed in the 1950s, AR and VR were used interchangeably until 1968, when AR was categorized as a separate entity for the first time and users were able to experience it using a head-mounted display (HMD). In the 1990s, Caudell developed an early prototype, which is being further developed and enhanced to this day. Reflecting the continuous progress in AR technology, the first Google Glass model was launched in 2013, followed by Microsoft's HoloLens in 2016. Since then, both companies have introduced new versions.[15] The area continues to be dynamic as VR and AR technologies evolve and become increasingly integrated into various industries.

Despite the promising advancements in VR and AR technologies within healthcare (refer to Figure 1), several research gaps persist that warrant further exploration. There is a notable scarcity of implementation models that effectively guide the systematic adoption of VR and AR in clinical settings, hindering their full integration into established healthcare practices. Although the benefits of these technologies in enhancing patient education and health literacy are recognized, there is limited empirical evidence evaluating their impact on patient adherence and treatment outcomes. Therefore, more research is needed to understand the specific needs and preferences of healthcare professionals and patients when incorporating these technologies, as well as strategies to increase technological acceptance and usability in diverse healthcare environments. Addressing these gaps is crucial for maximizing the potential of VR and AR in transforming patient care and training paradigms.

Methodology

A comprehensive search was conducted using 2 primary databases: PubMed and Google Scholar. The search focused on identifying relevant studies discussing the applications of VR and AR in healthcare, particularly in patient care and

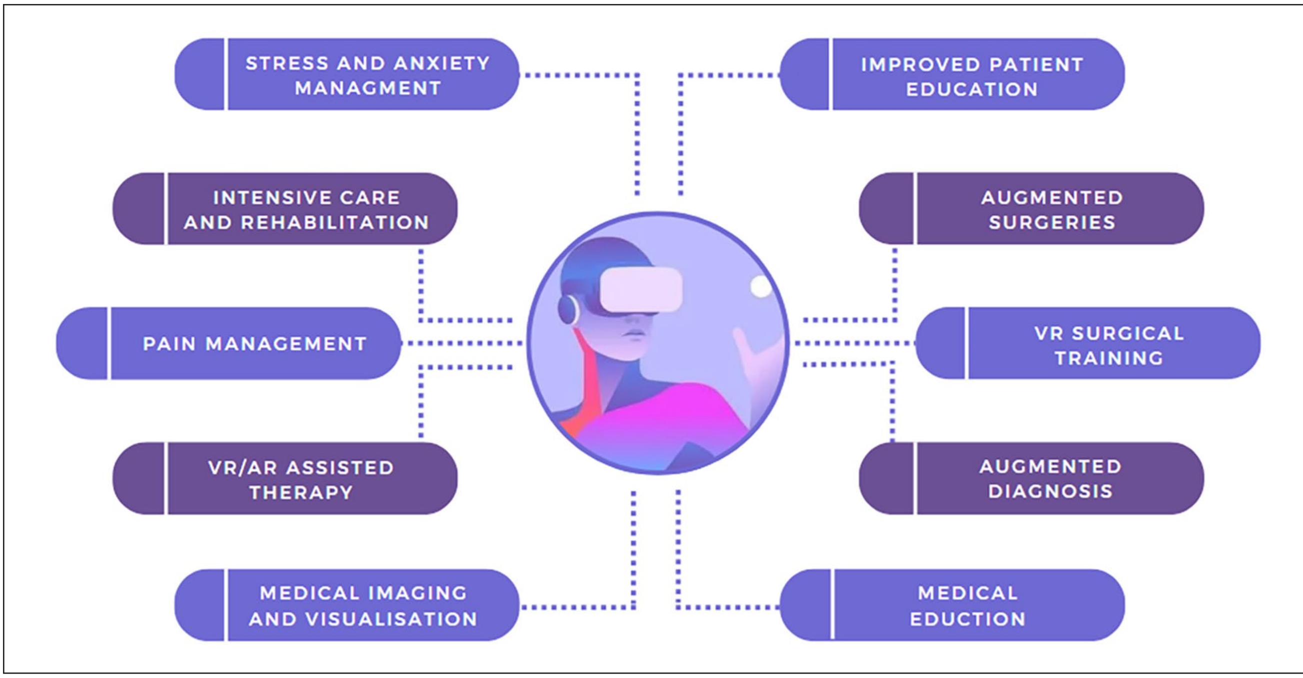

Figure 1. Virtual and augmented reality applications in healthcare.

medical training. The following search terms were used: ("Virtual Reality" OR "Augmented Reality") AND ("Patient Care" OR "Medical Training") AND ("Surgical Training" OR "Medical Education"). The search was limited to peer-reviewed journal articles, systematic reviews, meta-analyses, review articles, and randomized controlled trials (RCTs), published between 2000 and 2024. In addition, the reference lists of included articles were examined.

Studies that addressed the use of VR and/or AR in patient care or medical training, published in English, with full-text availability, and those presenting empirical data were included. Editorials, non-peer-reviewed sources, conference proceedings, and studies unrelated to healthcare applications of VR/AR were excluded. Studies that did not explicitly measure patient outcomes, training efficacy, or clinical integration were also omitted. Approximately, 17,900 search results were obtained on Google Scholar, and 300 results were found on PubMed. Among these, we included 89 articles in our study.

Virtual Reality/Augmented Reality From the Perspective of Patient Care

Alleviating Stress and Anxiety

Patients frequently perceive the hospital as an "unfriendly" environment because of several factors such as overwhelming noise, loss of personal autonomy, and insufficient information.[16] This is exacerbated by stress and anxiety, both of which are recognized as major risk factors for various mental health disorders, including depression and anxiety disorders, as well as physical health issues, such as cardiovascular disease. To reduce the attention available for conscious processing of stress and anxiety, VR is often used to provide straightforward distractions, for example, watching videos or playing video games. While the exact physical mechanisms are not fully understood, this approach shifts the patient's focus away from conscious awareness of stressful situations during occupational activity.[17] In a recent study, Chiu et al[18] examined the effects of a VR preoperative education program on lowering anxiety levels in adult patients scheduled for elective surgery. The findings demonstrated that VR-based interventions are both feasible and effective in mitigating preoperative anxiety. While patients can learn pain-management techniques, such as mindfulness, several experimental results suggest that VR techniques have actual benefits for subjective pain reduction. For example, Oculus Rift uses DEEP, a meditation application, to help users breathe deeply. The application works through a band surrounding the chest to measure the breathing rate. In another pilot study, 44 participants attended a mindfulness conference on an Oculus Rift DK2 VR helmet and floated down a calm 3D computer-generated virtual river while listening to digitized DBT mindfulness skills training instructions. Participants reported significantly less sadness, anger, and anxiety but more relaxation.[19] Virtual reality exposure therapy (VRET) trials for anxiety-related disorders have proliferated in number and diversity.[20]

Dr. Spiegel's team at the Cedars-Sinai Hospital has given chronic patients the opportunity to get out of the hospital through VR and to enjoy the natural scenery. This could reduce a patient's stress and shorten hospital stays.[21] Relaxation and meditation in various VR applications have become increasingly widespread for treating patients at home or in hospitals.[22] Research conducted at the University of Barcelona has demonstrated that using VR with depressed patients can lessen the severity of their depression and self-degradation while enhancing their overall satisfaction.[23] By minimizing real-world distractions and enhancing the sense of presence, VR can facilitate mindfulness practice.

Multifaceted Pain Management

To improve pain management in hospitalized patients, physical and psychosocial treatments must be provided concurrently due to the multifaceted nature of pain, whether acute, intermittent, or chronic.[24] The introduction of VR technology in 1998 by Hoffman marked a significant advancement in pain management, demonstrating its efficacy in reducing burn-related pain and managing pain in various conditions.[25,26] Acute pain triggered by surgery or trauma elicits nociceptor activation, leading to inflammatory, physiological, and behavioral responses, often addressed with pharmacological therapies.[27,28] VR technology offers new possibilities for severe pain treatment, as evidenced by studies exploring the effectiveness of VR-based games in alleviating acute pain.[29] There is strong evidence supporting the effectiveness of VR in managing chronic and post-operative pain.[17] Mosso-Vázquez et al[30] enrolled 67 patients following cardiac surgery and provided them with a VR intervention featuring various immersive environments. After the VR sessions, 59 patients (88%) reported a reduction in pain levels, as measured by a Likert Scale. In a recent study, Hoffmann et al[31] tested a VR game with 48 burn victims aged 6 to 17 years during wound cleaning procedures. The results showed a significant reduction in self-reported pain compared to the control group. However, Faber et al[32] discovered that the effectiveness of repeated VR interventions may diminish after 3 consecutive days.

Augmenting hypnosis with VR technology, known as virtual reality hypnosis (VRH), has shown promise in reducing pain and anxiety.[33] While research on VR for chronic pain management is limited, studies have investigated its potential in conditions like complex regional pain syndrome, demonstrating improvements in analgesic efficacy.[34] Tracker-based VR systems have also been explored for chronic neck pain treatment, showing associations with cervical range of motion, relevant to chronic neck pain pathophysiology.[35] Other research groups have also examined the practicality of VR applications in routine clinical settings. Markus et al[36] reported that the entire process—including VR setup, instruction, therapy, and cleaning—took 59 min.

Virtual Reality for ICU, Rehabilitation, and After Intensive Care

Creating a calm environment and employing relaxation techniques can significantly reduce stress in the intensive care unit (ICU). This is an area where VR has been explored.[3] Delirium affects between 35% and 80% of ICU patients, whether ventilated or non-ventilated, and is linked to prolonged hospital stays and higher mortality rates.[37] Given that pharmacological treatments frequently come with undesirable and severe side effects, non-pharmacologic approaches are crucial for treating and potentially preventing delirium.[38]

The E-CHOISIR (Electronic-CHOIce of a System for Intensive care Relaxation) trial demonstrated the beneficial effects of VR. In this study, 60 alert and non-delirious ICU patients were randomized into 4 groups for relaxation sessions: standard relaxation with television or radio, music therapy, and 2 virtual reality systems featuring either real motion pictures or synthetic motion pictures. The results showed a significant reduction in overall discomfort and stress response in the group exposed to synthetic motion pictures. Both VR systems effectively reduced anxiety; however, only the synthetic motion pictures group experienced lower subjective pain levels. While 3 incidents of claustrophobia, dyspnea, and agitation occurred during the VR sessions, instances of cybersickness were infrequent.[39] Gerber et al[40,41] obtained comparable outcomes in their study, where they utilized VR featuring immersive nature scenes with 33 critically ill patients' post-cardiac surgery. The acceptance of VR was high among patients, with most reporting positive effects on stress levels. These findings were corroborated by a reduction in respiratory rate during the VR sessions. VR has also shown positive effects on sleep quality. In a randomized controlled trial involving 48 ICU patients, the use of VR led to significantly improved sleep quality, although there was no difference in total sleep time and light sleep time between the groups.[42] In conclusion, numerous studies suggest that VR has a beneficial impact on stress, anxiety, and delirium in critically ill patients.

Prolonged ICU stay adversely affects both short- and long-term outcomes. VR applications can aid in supporting rehabilitation programs in the ICU. Gomes et al[43] incorporated a commercially available gaming platform, the Nintendo Wii™, into physical therapy sessions for 60 adult ICU patients without mobility restrictions, aiming to enhance their physical activity. After 100 sessions, 86% of patients expressed a desire to continue using the video game in future physical therapy sessions. Abdulsatar et al[44] evaluated the same gaming platform (Nintendo Wii™) in a pilot trial involving 12 critically ill children. Upper limb activity increased significantly during the Wii™ sessions and no adverse events were attributed to the VR intervention. A

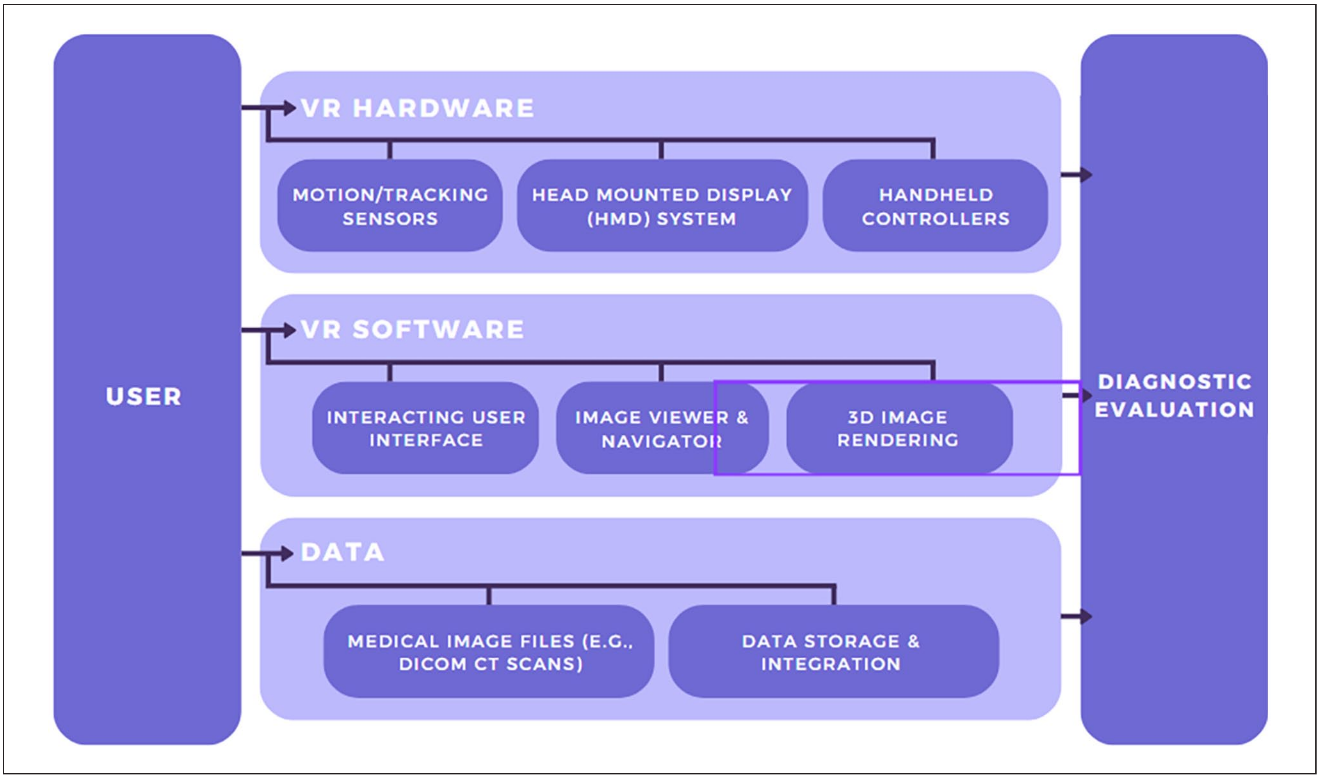

Figure 2. A schematic diagram showing how virtual reality hardware and software are utilized to reach diagnosis.

study by Parke et al[45] aimed to enhance early ICU mobilization using VR support. Twenty adult ICU patients participated in therapy sessions utilizing the Jintronix virtual therapy system, which targeted arm, leg, and trunk strength, as well as range of motion and endurance exercises. The primary objective of this investigation was to assess safety and feasibility, which was successfully achieved. However, nearly all participants reported that the VR activity was enjoyable, improved their body strength and range of motion, and motivated them to continue exercising. Furthermore, Wang et al[46] developed a VR application designed for the early mobilization of critically ill patients, although it has not yet been evaluated in either patients or volunteers.

Virtual Reality in Radiology

Similar to other fields, VR in radiology offers users an immersive 3D experience through wearable technology. Early pilot models designed to replicate reading suite features, such as the one used by King et al,[47] utilized an Oculus Rift HMD system and the 3DSlicer software program to view multiple individual slices of serial CT scans. Users could interact with the displayed images using a commercial gaming controller, allowing them to adjust the window width and level. More recent efforts, such as *VRRRRoom*, employed similar HMD hardware along with a multi-touch frame on a desk surface to enable touch-based input.[48] For visualization, 3D reconstructed models created from individual CT slices were projected onto the desk surface, allowing users to manipulate them through various interactive features. Efforts are currently underway to develop a VR radiology reading room equipped with a fully digital picture archiving and communication system (PACS) workstation. For instance, sieVRt (Luxsonic Technologies, Saskatoon, SK) has recently become Canada's first commercially available VR Digital Imaging and Communications in Medicine (DICOM) viewer. This web-based software is compatible with commercial high-grade VR HMDs and haptic feedback controllers, creating an interactive and personalized 3D radiology reading room experience, as elaborated in Figure 2. Users can display sequential image stacks, adjust window width and level, annotate, and mark images, and perform various measurements, such as lengths, angles, and pixel densities.[49] Cases can be retrieved from a local image repository and displayed virtually on a comprehensive DICOM viewer with up to 3 virtual monitors. The software can integrate with existing PACS, radiology information systems (RIS), and reporting software to seamlessly fit into current workflow practices. The interface also includes built-in collaboration tools, enabling multiple users to review and discuss cases simultaneously within the virtual environment. This technology aims to enhance the accessibility of medical imaging, allowing radiologists to utilize their personalized reading room wherever they are.

Augmented Reality for Medical Imaging and Visualization

With the help of AR, practitioners can visualize human structures better than ever before, enabling them to be highly accurate in various types of surgeries. It was used during dental implant surgery to display alveolar nerve bundles and visualize osseous structures during surgery, which helped avoid damaging important structures within the confined area.[50] Anatomical imaging can also aid in reducing complications and improving overall outcomes during vascular and endovascular surgery.[51] Real-time AR reconstructions projected onto patients for percutaneous and endovascular interventions may provide benefits compared to conventional localization techniques. A pilot study revealed that examining VR reconstructions of splenic artery aneurysms prior to endovascular embolization increased operator confidence.[52] In a comprehensive review by Goo et al,[53] it was demonstrated that AR could be particularly beneficial for minimally invasive cardiac interventions or surgeries. Moreover, AR-enhanced transesophageal echocardiography (TEE) can assist in determining the optimal annuloplasty ring size, especially for surgeons with limited experience, and in performing percutaneous mitral valve repairs.[54] Despite challenges related to patient movement and image mismatch when using AR, advancements in image reconstruction have greatly enhanced the accuracy of lesion localization. These improvements have achieved a discrepancy of less than 5 mm between virtual and actual distances.[55] Currently, studies assessing the objective advantages of AR compared to conventional localization methods in interventional radiology, such as "road-mapping with fluoroscopy," are limited. More comprehensive research beyond "proof-of-concept" demonstrations is necessary to confirm its clinical utility.

Telemedicine

AR can be particularly beneficial for telemedicine, remote assistance, and patient evaluation.[56] First responders have a very tough job, which requires fast and accurate triage of patients to expedite the treatment process. With the help of AR, first responders' accuracy in triaging patients was much greater with only a small increase in time duration when compared to responders who did not use AR.[57] AR also shows benefits during remote post-surgical wound assessment. Using a Microsoft HoloLens, surgeons were able to accurately assess the negative pressure wounds remotely through a live video feed. This ultimately led to a decrease in unplanned surgical revisions and improved patient outcomes.[58] Likewise, AR-compatible Microsoft HoloLens became a life-saving asset during COVID-19. A senior team member used the lens while rotating in COVID-19 wards, while other team members could virtually see the examination and interact remotely.[59] One of the primary contributions of the HoloLens2 was its role in reducing the risk of infection transmission by enabling remote diagnostics and consultations. This technological integration allowed healthcare workers to maintain necessary interactions without physical proximity to patients. The positive outcomes from using the HoloLens2 could encourage further exploration and adoption of augmented and virtual reality technologies in healthcare, particularly in training and remote care scenarios.

Invasive Procedures

During surgery, AR allows surgeons to enhance their view of the surgical field with digital images, particularly highlighting tumors, and anatomical structures. In the context of minimally invasive spinal surgery (MISS), AR has demonstrated great potential as a complementary tool with numerous breakthroughs and research initiatives underway.[60] Felix et al[61] conducted a study in which 7 cadavers were included requiring pedicle screw insertion using VisAR (Hololens 2 headset).[61] The use of AR-guided navigation system significantly improved the accuracy of pedicle screw insertion, suggesting that integrating AR technology into spinal surgery practices can enhance surgical precision, improve patient safety, and optimize clinical outcomes. Stereotactic neurosurgery is a well-established technique, yet it presents several limitations. Frameless stereotaxy with neuronavigation necessitates that surgeons divert their attention from the surgical field to the navigation display and maneuver the needle while maintaining an ergonomically challenging position. Satoh et al[62] noted that several researchers have documented the use of frameless stereotaxy guided by head-mounted display-based AR, which allows surgeons to advance the needle while maintaining a more natural posture. Endoscopic procedures have become an essential component of all surgical disciplines and are now considered standard practice. Conventional laparoscopy has been upgraded to include robotic-assisted surgery. Robot-assisted surgery stands out as the most dynamic form of minimally invasive surgery in contemporary practice. Enhanced visualization through 3D technology and the extension of surgical instruments to 7 degrees of freedom enable the application of minimally invasive techniques even in complex surgical scenarios. Guidance provided by robot-assisted tools enables surgeons to operate with reduced tremors and fatigue, offering significant benefits to both surgeons and patients.[63-65] Central line placement and endotracheal intubation (ETT) are common ICU procedures; however, they can be linked to serious complications. In this case, Gan et al[66] utilized AR in 6 patients undergoing the procedure mentioned, achieving "good success and excellent user feedback." The application of an AR-assisted near-infrared electromagnetic radiation device in older ICU patients undergoing venous puncture reduced the incidence of hematomas; however, it did not shorten the procedure length or reduce the number of attempts required.[66] In conclusion, there is presently no compelling evidence either supporting or opposing the use of AR-supported invasive procedures in patient care.

Virtual Reality/Augmented Reality From the Perspective of Medical Education and Training

For decades, junior doctors have primarily learned surgical skills through direct experience in the operating room under the supervision of seasoned surgeons.[67] However, the growing number of trainees and restrictions on resident work hours have limited opportunities for hands-on practice. Traditional training methods have become insufficient for mastering advanced surgical techniques, leading to the integration of VR into surgical education.[68] VR simulations provide a highly realistic and interactive learning environment, surpassing traditional methods such as animal models, films, or electronic (e)-learning. These simulations feature intuitive 3D visualizations of anatomical structures, allowing trainees to engage deeply with the anatomy and observe the dynamic changes during each surgical phase. The ability to objectively assess performance through metrics like task completion time, path length, identification of anatomical landmarks, and overall satisfaction enhances the evaluation of psychomotor skills and training effectiveness.[69]

In parallel, VR has transformed immersive learning by making educational instruction more engaging and motivating. The development of 360° immersive reality platforms has revolutionized the way pre-clinical disciplines, such as anatomy and physiology, are taught. Learners can now explore blood cells, navigate heart chambers, and examine organs in unprecedented detail, fostering a deeper understanding of complex human anatomy and physiology in a safe and interactive environment. This immersive approach also allows medical students to gain clinical experience from their first year, breaking away from the traditional model where such training began in the fourth or fifth year of medical school.[70] Additionally, VR anatomy tools enhance the learning of sonography by leveraging 3D capabilities to visualize and manipulate sonographic images. This advanced visualization enables students to cut and rotate 3D animations, offering a more detailed understanding of anatomical structures compared to 2D images.[71] Institutions like the Toronto Metropolitan University (TMU) Centre for Education in Medical Simulation, in collaboration with High Tech Computer Corporation (HTC), contribute to the development of these innovative tools.[72] VR's capacity to replicate clinical scenarios within a confined space and with minimal setup time allows for seamless integration with other simulation activities, facilitating customization of curricula and generation of extensive performance data. This adaptability supports the incorporation of the latest protocols and ensures that professionals are proficient before engaging with patients.[60]

AR further enhances medical education by offering interactive simulations and remote learning opportunities.[73] AR enables students to interact with virtual cadavers, exploring anatomical structures from various angles and providing a more immersive and comprehensive understanding of human anatomy.[74] AR's ability to demonstrate complex relationships between muscles, vessels, and nerves, and to show how these structures are affected by different pathologies, significantly improves the learning experience. This approach overcomes the limitations of traditional cadaver-based studies, offering a richer, more detailed educational experience.[75] AR can also support healthcare professionals in critical care procedures like intubation and central line placement. In a controlled trial conducted by Alismail et al[76] with 32 ICU trainees, 15 participants used head-mounted AR glasses during the endotracheal intubation of a training mannequin. The AR display provided repeated guidance on essential procedural steps. Although the AR-assisted group took longer to complete intubation and ventilation, they demonstrated greater adherence to evidence-based practices for intubation. Heo et al[77] carried out a prospective, controlled pilot study in which nurses without prior experience in mechanical ventilation were randomized into either conventional training or AR-assisted training groups. Nurses in the AR group received guidance through AR-based instructions and had the option to request help via the head-mounted display. The results indicated that the AR-assisted group required less assistance and reported higher confidence levels following the training compared to those in the conventional training group. A systemic review of 45 trials across various surgical specialties demonstrated that devices like Microsoft HoloLens, STAR, and ImmersiveTouch significantly improved surgical trainee performance compared to traditional techniques, especially when used as supplements to conventional surgical teaching. Microsoft HoloLens showed promising results in both validity and efficacy, while ImmersiveTouch and STAR exhibited strong validity across all parameters.[78] In conclusion, both VR and AR are thus reshaping surgical education and medical training by providing innovative, effective methods for learning and skill development.

Navigating the Obstacles: Implementing VR and AR in Healthcare Settings

VR has become a game-changing tool in healthcare services, offering an improved patient experience, better medical training, and innovative therapeutic interventions.[60] However, there are challenges to implementing VR in healthcare. One of the primary obstacles is ensuring that VR hardware is seamlessly integrated into existing healthcare systems. Compatibility issues between VR headsets and electronic health record (EHR) systems can hinder adoption.[79] For example, VR headsets that are not compatible with hospital EHR infrastructure may be useless. Achieving minimal latency while maintaining visual fidelity is crucial to prevent motion sickness in VR experiences, particularly for surgeons who rely on VR for preoperative planning. AR and VR applications are not intended to replace personal communication and are unlikely to do so. Similarly, while VR-based training offers promising supplementary methods, it cannot replace traditional learning techniques for healthcare providers. To date, there is no substantial evidence supporting the use of AR-assisted practical procedures, such as endotracheal intubation or central venous line placement, in critical care outside of clinical trial settings.[3]

Cybersickness

Prolonged use of VR can lead to side effects such as headaches, nausea, and vomiting—commonly referred to as "cybersickness"—which are similar to symptoms of motion sickness.[80] Cybersickness is not yet recognized as a defined health condition. While motion sickness arises from a discrepancy between actual and expected motion, this pathophysiological mechanism may not fully apply to cybersickness. Interestingly, cybersickness may be more pronounced in AR than in VR. In 1 study, 15.3% of participants reported experiencing headaches and 17 other symptoms, including nausea, after using AR-based training for gross anatomy dissection (HoloAnatomy®).[81] AR/VR-related side effects appear to differ across various age and gender groups[82]; an effect is not yet fully understood and warrants further investigation. Consequently, careful patient selection and prompt intervention in case side effects arise could be crucial to the successful application of VR-based technologies.

Ethical Perspective

In vulnerable patient groups, such as those who are critically ill, there are ethical concerns surrounding the use of VR/AR technologies. To address this, Kellermeyer et al[83] established 3 core principles: (1) preference for human interaction: when possible, interactions should prioritize human-to-human engagement over human-to-machine interaction, adhering to the principle of "therapeutic alternativism" rather than relying solely on "technological solutionism"; (2) focus on human values: VR technology should be designed with a focus on "critical human values," such as maintaining patient dignity and autonomy, ensuring alignment with "human-oriented value principles"; and (3) patient-centered approach: VR systems should be designed with a primary emphasis on the needs and experiences of patients rather than those of professional users, reflecting a commitment to "patient-centred design."

From our point of view, these principles reflect a thoughtful and ethical approach to integrating VR/AR technologies into healthcare. VR/AR should always enhance, rather than replace, the human elements of healthcare, ensuring that advancements are both ethically sound and aligned with patient-centred care. Some researchers have suggested establishing a new medical specialty, termed "virtualist." This role would encompass not only comprehensive technical and medical training but also a profound understanding of the ethical considerations associated with VR/AR technologies.[84]

Future Directions

The integration of VR and AR in healthcare and medical training presents numerous opportunities for advancing patient care and education (refer to Table 1).[85] Future research should focus on expanding the clinical applications of these technologies, particularly in areas such as rehabilitation, pain management, and telemedicine. While current evidence supports the efficacy of VR and AR in reducing stress, managing chronic pain, and improving patient engagement, more high-quality randomized controlled trials are needed to establish long-term outcomes across diverse patient populations.

In medical training, the future of VR and AR lies in their potential to revolutionize surgical education, allowing trainees to practice complex procedures in a risk-free environment. Further developments should aim to improve the realism and interactivity of simulations, integrating haptic feedback and AI-driven adaptive learning to personalize training. These advancements will enhance skill acquisition and lead to better clinical performance. However, significant challenges related to technology access, cost, and data privacy must be addressed. The future of VR/AR in healthcare will likely be shaped by regulatory frameworks that ensure patient safety while promoting innovation.

FDA Regulations

Recent updates by the U.S. Food and Drug Administration (FDA) have paved the way for more widespread use of

Table 1. Summary of the Different Applications of Virtual and Augmented Reality in Healthcare.

Innovations	Applications	Key points
Virtual reality/augmented reality from the perspective of patient care	Alleviating stress and anxiety	• Patients view hospitals as "unfriendly" due to noise, loss of autonomy, and lack of information. • VR provides distractions (eg, videos and games) to reduce stress and anxiety. • Studies show VR reduces preoperative anxiety and pain and promotes mindfulness.
	Multifaceted pain management	• VR technology enhances pain management, introduced in 1998 by Hoffman. • VR is effective for managing acute and chronic pain, as evidenced by several studies. • VR hypnosis shows promise in reducing pain and anxiety. • Practicality assessed in routine clinical settings is positive.
	ICU, rehabilitation, and after intensive care	• VR can reduce stress and discomfort in ICU settings. • Non-pharmacological approaches are crucial for preventing delirium. • Studies show VR improves stress levels, sleep quality, and rehabilitation in ICU patients through engaging activities like gaming.
	Radiology	• VR provides immersive 3D experiences for radiologists. • Examples include the use of Oculus Rift for CT scans and VR radiology reading rooms. • Technology aims to enhance medical imaging accessibility and collaboration among radiologists.
	Medical imaging and visualization	• AR improves visualization of human structures during surgeries, leading to better outcomes. • Applied in dental surgery, vascular interventions, and cardiac surgeries. • Challenges remain, but advancements in reconstruction enhance accuracy.
	Invasive procedures	• AR enhances visualization during surgeries, improving precision in procedures like spinal surgery and endotracheal intubation. • Initial studies show AR improves accuracy and reduces complications, but conclusive evidence is still developing.
	Telemedicine	• VR integrates into surgical education, allowing realistic simulations and objective performance assessments. • Immersive 3D environments aid in anatomy learning and clinical experience for students from the first year.
Virtual reality/augmented reality from the perspective of medical education and training	Training enhancements	• IT advancements, especially in remote health monitoring, have significantly improved healthcare services. • Physical sensor networks prioritize early detection of disease impairments and prevention. • Smart wireless and wearable sensors enable continuous monitoring of vital signs and quick access to patient data.
	Augmented reality in medical education	• AR offers interactive simulations and remote learning, enhancing understanding of anatomy. • Studies show AR improves procedural training adherence and confidence among healthcare professionals, showing its potential to supplement traditional education methods effectively.

immersive technologies like VR and AR in healthcare. The FDA has provided a Digital Health Innovation Action Plan that promotes the development of software-based medical devices, including VR/AR applications for therapeutic and training purposes. VR systems used for pain management have already received FDA approval, such as EaseVRx, a prescription device designed to treat chronic pain through immersive VR therapy.[86] Similarly, the FDA is working on a Safer Technologies Program (STeP), which aims to streamline the approval process for emerging technologies like VR and AR by ensuring they meet stringent safety and efficacy standards.[87,88]

Looking ahead, further regulatory guidance from the FDA is expected to focus on expanding the clinical use of these technologies, addressing cybersecurity risks, and ensuring that VR and AR devices meet Good Machine Learning Practice (GMLP) guidelines for AI integration.

Conclusion

VR and AR have rapidly emerged as transformative tools in patient care and medical training. Their proven efficacy in managing pain, reducing stress, enhancing rehabilitation, and improving clinical education makes them valuable assets in healthcare. Despite these advancements, challenges such as accessibility, cost, and regulatory frameworks must be addressed for widespread adoption. Ongoing research, technological improvements, and clear FDA guidelines will be crucial in shaping the future of VR and AR, ultimately improving patient outcomes and medical education. As these technologies evolve, their integration into healthcare holds great promise for advancing both therapeutic interventions and professional training.

Author Contributions

A.A. and A.I.: conceptualization, writing-original draft, editing-original draft, final approval, and agreeing to the accuracy of the work. A.H., H.H., A.B., M.W.A., S.A., M.I.Y., and S.J.: writing-original draft, final approval, and agreeing to the accuracy of the work. M.O.O.: funding acquisition, validation, visualization, and final approval, and agreeing to the accuracy of the work.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Ethical Approval

Not applicable to this work.

Guarantor

MOO.

ORCID iDs

Malik Olatunde Oduoye https://orcid.org/0000-0001-9635-9891
Muhammad Wajeeh Anis https://orcid.org/0009-0003-0710-0899

References

1. Yeung AWK, Tosevska A, Klager E, et al. Virtual and augmented reality applications in medicine: analysis of the scientific literature. *J Med Internet Res*. 2021;23(2):e25499. doi:10.2196/25499
2. Kim M, Jeon C, Kim J. A study on immersion and presence of a portable hand haptic system for immersive virtual reality. *Sensors (Basel)*. 2017;17(5):1141. doi:10.3390/s17051141
3. Bruno RR, Wolff G, Wernly B, et al. Virtual and augmented reality in critical care medicine: the patient's, clinician's, and researcher's perspective. *Crit Care*. 2022;26(1):326. doi:10.1186/s13054-022-04202-x
4. Eckert M, Volmerg JS, Friedrich CM. Augmented reality in medicine: systematic and bibliographic review. *JMIR Mhealth Uhealth*. 2019;7(4):e10967. doi:10.2196/10967
5. Slater M, Sanchez-Vives MV. Enhancing our lives with immersive virtual reality. *Front Robot AI*. 2016;3:74. doi:10.3389/frobt.2016.00074
6. Cipresso P, Giglioli IAC, Raya MA, Riva G. The past, present, and future of virtual and augmented reality research: a network and cluster analysis of the literature. *Front Psychol*. 2018;9:2086. doi:10.3389/fpsyg.2018.02086
7. Laver KE, Lange B, George S, Deutsch JE, Saposnik G, Crotty M. Virtual reality for stroke rehabilitation. *Cochrane Database Syst Rev*. 2017;11(11):CD008349. doi:10.1002/14651858.CD008349.pub4
8. Kamphuis C, Barsom E, Schijven M, Christoph N. Augmented reality in medical education? *Perspect Med Educ*. 2014;3(4):300-311. doi:10.1007/s40037-013-0107-7
9. Yakovchenko V, Rogal SS, Goodrich DE, et al. Getting to implementation: adaptation of an implementation playbook. *Front Public Health*. 2023;10:980958. doi:10.3389/fpubh.2022.980958
10. Bhugaonkar K, Bhugaonkar R, Masne N. The trend of metaverse and augmented & virtual reality extending to the healthcare system. *Cureus*. 2022;14(9):e29071. doi:10.7759/cureus.29071
11. Adapa K, Jain S, Kanwar R, et al. Augmented reality in patient education and health literacy: a scoping review protocol. *BMJ Open*. 2020;10(9):e038416. doi:10.1136/bmjopen-2020-038416
12. Bown J, White E, Boopalan A. Looking for the ultimate display: a brief history of virtual reality. In: Gackenbach J and Bown J, eds. *Boundaries of Self and Reality Online: Implications of Digitally Constructed Realities*. Elsevier Academic Press; 2017:239-259. doi:10.1016/b978-0-12-804157-4.00012-8
13. Steinicke F. The science and fiction of the ultimate display. In: *Being Virtual*. Springer; 2016:19-32. doi:10.1007/978-3-319-43078-2_2
14. Anthes C, García-Hernández RJ, Wiedemann M, Kranzlmüller D. State of the art of virtual reality technology. IEEE Conference Publication | IEEE Xplore. 2016. Accessed August 9, 2024. https://ieeexplore.ieee.org/abstract/document/7500674
15. Malta A, Farinha T, Mendes M. Augmented reality in maintenance-history and perspectives. *J Imaging*. 2023;9(7):142. doi:10.3390/jimaging9070142
16. Puel F, Minville V, Vardon-Bounes F. What place for virtual reality in the intensive care unit during medical procedures? *J Intensive Care*. 2021;9(1):30. doi:10.1186/s40560-021-00545-9

17. Jones T, Moore T, Choo J. The impact of virtual reality on chronic pain. *PLoS One*. 2016;11(12):e0167523. doi:10.1371/journal.pone.0167523
18. Chiu PL, Li H, Yap KY, Lam KC, Yip PR, Wong CL. Virtual reality-based intervention to reduce preoperative anxiety in adults undergoing elective surgery: a randomized clinical trial. *JAMA Netw Open* 6(10):e2340588. doi:10.1001/jamanetworkopen.2023.40588
19. Navarro-Haro MV, López-Del-Hoyo Y, Campos D, et al. Meditation experts try virtual reality mindfulness: a pilot study evaluation of the feasibility and acceptability of virtual reality to facilitate mindfulness practice in people attending a mindfulness conference. *PLoS One*. 2017;12(11):e0187777. doi:10.1371/journal.pone.0187777
20. Carl E, Stein AT, Levihn-Coon A, et al. Virtual reality exposure therapy for anxiety and related disorders: a meta-analysis of randomized controlled trials. *J Anxiety Disord*. 2019;61:27-36. doi:10.1016/j.janxdis.2018.08.003
21. Tashjian VC, Mosadeghi S, Howard AR, et al. Virtual reality for management of pain in hospitalized patients: results of a controlled trial. *JMIR Ment Health*. 2017;4(1):e9. doi:10.2196/mental.7387
22. Garrett B, Taverner T, McDade P. Virtual reality as an adjunct home therapy in chronic pain management: an exploratory study. *JMIR Med Inform*. 2017;5(2):e11. doi:10.2196/medinform.7271
23. Falconer CJ, Rovira A, King JA, et al. Embodying self-compassion within virtual reality and its effects on patients with depression. *BJPsych Open*. 2016;2(1):74-80. doi:10.1192/bjpo.bp.115.002147
24. Li A, Montaño Z, Chen VJ, Gold JI. Virtual reality and pain management: current trends and future directions. *Pain Manag*. 2011;1(2):147-157. doi:10.2217/pmt.10.15
25. Hoffman HG, Patterson DR, Carrougher GJ, Sharar SR. Effectiveness of virtual reality-based pain control with multiple treatments. *Clin J Pain*. 2001;17(3):229-235. doi:10.1097/00002508-200109000-00007
26. Hoffman HG, Patterson DR, Carrougher GJ. Use of virtual reality for adjunctive treatment of adult burn pain during physical therapy: a controlled study. *Clin J Pain*. 2000;16(3):244-250. doi:10.1097/00002508-200009000-00010
27. Carr DB, Goudas LC. Acute pain. *Lancet*. 1999;353(9169):2051-2058. doi:10.1016/S0140-6736(99)03313-9
28. Kehlet H, Holte K. Effect of postoperative analgesia on surgical outcome. *Br J Anaesth*. 2001;87(1):62-72. doi:10.1093/bja/87.1.62
29. Das DA, Grimmer KA, Sparnon AL, McRae SE, Thomas BH. The efficacy of playing a virtual reality game in modulating pain for children with acute burn injuries: a randomized controlled trial [ISRCTN87413556]. *BMC Pediatr*. 2005;5(1):1. doi:10.1186/1471-2431-5-1
30. Mosso-Vázquez JL, Gao K, Wiederhold BK, Wiederhold MD. Virtual reality for pain management in cardiac surgery. *Cyberpsychol Behav Soc Netw*. 2014;17(6):371-378. doi:10.1089/cyber.2014.0198
31. Hoffman HG, Rodriguez RA, Gonzalez M, et al. Immersive virtual reality as an adjunctive non-opioid analgesic for pre-dominantly Latin American children with large severe burn wounds during burn wound cleaning in the intensive care unit: a pilot study. *Front Hum Neurosci*. 2019;13:262. doi:10.3389/fnhum.2019.00262
32. Faber AW, Patterson DR, Bremer M. Repeated use of immersive virtual reality therapy to control pain during wound dressing changes in pediatric and adult burn patients. *J Burn Care Res*. 2013;34(5):563-568. doi:10.1097/BCR.0b013e3182777904
33. Rousseaux F, Dardenne N, Massion PB, et al. Virtual reality and hypnosis for anxiety and pain management in intensive care units: a prospective randomised trial among cardiac surgery patients. *Eur J Anaesthesiol*. 2022;39(1):58-66. doi:10.1097/EJA.0000000000001633
34. Sato K, Fukumori S, Matsusaki T, et al. Nonimmersive virtual reality mirrors visual feedback therapy and its application for the treatment of complex regional pain syndrome: an open-label pilot study. *Pain Med*. 2010;11(4):622-629. doi:10.1111/j.1526-4637.2010.00819.x
35. Sarig-Bahat H, Weiss PL, Laufer Y. Neck pain assessment in a virtual environment. *Spine (Phila Pa 1976)*. 2010;35(4):E105-E112. doi:10.1097/BRS.0b013e3181b79358
36. Markus LA, Willems KE, Maruna CC, et al. Virtual reality: feasibility of implementation in a regional burn center. *Burns*. 2009;35(7):967-969. doi:10.1016/j.burns.2009.01.013
37. Chanques G, Ely EW, Garnier O, et al. The 2014 updated version of the Confusion Assessment Method for the Intensive Care Unit compared to the 5th version of the Diagnostic and Statistical Manual of Mental Disorders and other current methods used by intensivists. *Ann Intensive Care*. 2018;8:33. doi:10.1186/s13613-018-0377-7
38. Cavallazzi R, Saad M, Marik PE. Delirium in the ICU: an overview. *Ann Intensive Care*. 2012;2:49. doi:10.1186/2110-5820-2-49
39. Merliot-Gailhoustet L, Raimbert C, Garnier O, et al. Discomfort improvement for critically ill patients using electronic relaxation devices: results of the cross-over randomized controlled trial E-CHOISIR (Electronic-CHOIce of a System for Intensive care Relaxation). *Crit Care*. 2022;26:263. doi:10.1186/s13054-022-04136-4
40. Gerber SM, Jeitziner MM, Wyss P, et al. Visuo-acoustic stimulation that helps you to relax: a virtual reality setup for patients in the intensive care unit. *Sci Rep*. 2017;7:13228. doi:10.1038/s41598-017-13153-1
41. Gerber SM, Jeitziner MM, Knobel SEJ, et al. Perception and performance on a virtual reality cognitive stimulation for use in the intensive care unit: a non-randomized trial in critically ill patients. *Front Med*. 2019;6:287.
42. Lee SY, Kang J. Effect of virtual reality meditation on sleep quality of intensive care unit patients: a randomised controlled trial. *Intensive Crit Care Nurs*. 2020;59:102849. doi:10.1016/j.iccn.2020.102849
43. Gomes TT, Schujmann DS, Fu C. Rehabilitation through virtual reality: physical activity of patients admitted to the intensive care unit [Reabilitação com uso de realidade virtual: atividade física para pacientes admitidos na unidade de terapia intensiva]. *Rev Bras Ter Intensiva*. 2019;31(4):456-463. doi:10.5935/0103-507X.20190078

44. Abdulsatar F, Walker RG, Timmons BW, Choong K.“Wii-Hab” in critically ill children: a pilot trial. *J Pediatr Rehabil Med*. 2013;6:193-204. doi:10.3233/PRM-130260
45. Parke S, Hough CL, E Bunnell A. The feasibility and acceptability of virtual therapy environments for early ICU mobilization. *PM R*. 2020;12(12):1214-1221. doi:10.1002/pmrj.12352
46. Wang J, Zhang C, Jia Y, Shi C, Choi T, Xiao Q. Development of a virtual reality system for early mobilization of critically ill patients. *Stud Health Technol Inform*. 2019;264:1805-1806. doi:10.3233/SHTI190657
47. King F, Jayender J, Bhagavatula SK, et al. An immersive virtual reality environment for diagnostic imaging. *J Med Robot Res*. 2016;01(01):1640003. doi:10.1142/s2424905x16400031
48. Lopes DS, Jorge JA. Extending medical interfaces towards virtual reality and augmented reality. *Ann Med*. 2019;51(sup1):29. doi:10.1080/07853890.2018.1560068
49. Wu Y, Mondal P, Stewart M, Ngo R, Burbridge B. Bringing radiology education to a new reality: a pilot study of using virtual reality as a remote educational tool. *Can Assoc Radiol J*. 2022;74(2):251-263. doi:10.1177/08465371221142515
50. Ayoub A, Pulijala Y. The application of virtual reality and augmented reality in Oral & Maxillofacial Surgery. *BMC Oral Health*. 2019;19(1):238. doi:10.1186/s12903-019-0937-8
51. Eves J, Sudarsanam A, Shalhoub J, Amiras D. Augmented reality in vascular and endovascular surgery: scoping review. *JMIR Serious Games*. 2022;10(3):e34501. doi:10.2196/34501
52. Devcic Z, Idakoji I, Kesselman A, Shah R, AbdelRazek M, Kothary N. 4:03 PM Abstract No. 30 Augmented virtual reality assisted treatment planning for splenic artery aneurysms: a pilot study. *J Vasc Intervent Radiol*. 2018;29(4):S17. doi:10.1016/j.jvir.2018.01.037
53. Goo HW, Park SJ, Yoo SJ. Advanced medical use of three-dimensional imaging in congenital heart disease: augmented reality, mixed reality, virtual reality, and three-dimensional printing. *Korean J Radiol*. 2020;21(2):133-145. doi:10.3348/kjr.2019.0625
54. Ender J, Koncar-Zeh J, Mukherjee C, et al. Value of augmented reality-enhanced transesophageal echocardiography (TEE. for determining optimal annuloplasty ring size during mitral valve repair. *Ann Thorac Surg*. 2008;86(5):1473-1478. doi:10.1016/j.athoracsur.2008.07.073
55. Solbiati M, Passera KM, Rotilio A, et al. Augmented reality for interventional oncology: proof-of-concept study of a novel high-end guidance system platform. *Eur Radiol Exp*. 2018;2(1):18. doi:10.1186/s41747-018-0054-5
56. Dinh A, Yin AL, Estrin D, Greenwald P, Fortenko A. Augmented reality in real-time telemedicine and telementoring: scoping review. *JMIR Mhealth Uhealth*. 2023;11:e45464. doi:10.2196/45464
57. Follmann A, Ohligs M, Hochhausen N, Beckers SK, Rossaint R, Czaplik M. Technical support by smart glasses during a mass casualty incident: a randomized controlled simulation trial on technically assisted triage and telemedical app use in disaster medicine. *J Med Internet Res*. 2019;21(1):e11939. doi:10.2196/11939
58. Hill R. Using augmented reality to improve patient outcomes with negative pressure wound therapy. *Wounds*. 2022;33(2):47-50. doi:10.25270/wnds/2022.4750
59. Martin G, Koizia L, Kooner A, et al. Use of the HoloLens2 mixed reality headset for protecting health care workers during the COVID-19 pandemic: prospective, observational evaluation. *J Med Internet Res*. 2020;22(8):e21486. doi:10.2196/21486
60. Pottle J. Virtual reality and the transformation of medical education. *Future Healthc J*. 2019;6(3):181-185. doi:10.7861/fhj.2019-0036
61. Pierzchajlo N, Stevenson TC, Huynh H, et al. Augmented reality in minimally invasive spinal surgery: a narrative review of available technology. *World Neurosurg*. 2023;176:35-42. doi:10.1016/j.wneu.2023.04.030
62. Felix B, Kalatar SB, Moatz B, et al. Augmented reality spine surgery navigation: increasing pedicle screw insertion accuracy for both open and minimally invasive spine surgeries. *Spine*. 2022;47(12):865-872. doi:10.1097/BRS.0000000000004338
63. Satoh M, Nakajima T, Watanabe E, Kawai K. Augmented reality in stereotactic neurosurgery: current status and issues. *Neurol Med Chir*. 2023;63(4):137-140. doi:10.2176/jns-nmc.2022-0278
64. Alkatout I, Mechler U, Mettler L, et al. The development of laparoscopy-a historical overview. *Front Surg*. 2021;8:799442. doi:10.3389/fsurg.2021.799442
65. Zorzal ER, et al. Laparoscopy with augmented reality adaptations. *J Biomed Inform*. 2020;107:103463. doi:10.1016/j.jbi.2020.103463
66. Gan A, Cohen A, Tan L. Augmented reality-assisted percutaneous dilatational tracheostomy in critically ill patients with chronic respiratory disease. *J Intensive Care Med*. 2019;34(2):153-155.
67. Aïm F, Lonjon G, Hannouche D, Nizard R. Effectiveness of virtual reality training in orthopaedic surgery. *Arthroscopy*. 2016;32(1):224-232. doi:10.1016/j.arthro.2015.07.023
68. Stirling ER, Lewis TL, Ferran NA. Surgical skills simulation in trauma and orthopaedic training. *J Orthop Surg Res*. 2014;9:126. doi:10.1186/s13018-014-0126-z
69. Jin C, Dai L, Wang T. The application of virtual reality in the training of laparoscopic surgery: a systematic review and meta-analysis. *Int J Surg*. 2021;87:105859. doi:10.1016/j.ijsu.2020.11.022
70. Kumar PA, Jothi R, Mathivanan D. Self-directed learning modules of CT scan images to improve students' perception of gross anatomy. *Educ Health (Abingdon)*. 2016;29(2):152-155. doi:10.4103/1357-6283.188778
71. Hu KC, Salcedo D, Kang YN, et al. Impact of virtual reality anatomy training on ultrasound competency development: a randomized controlled trial. *PLoS One*. 2020;15(11):e0242731. doi:10.1371/journal.pone.0242731
72. Jiang G, Chen H, Wang S, et al. Learning curves and long-term outcome of simulation-based thoracentesis training for medical students. *BMC Med Educ*. 2011;11:39. doi:10.1186/1472-6920-11-39
73. Dhar P, Rocks T, Samarasinghe RM, Stephenson G, Smith C. Augmented reality in medical education: students' experiences and learning outcomes. *Med Educ Online*. 2021;26(1):1953953. doi:10.1080/10872981.2021.1953953
74. Trelease RB. From chalkboard, slides, and paper to e-learning: how computing technologies have transformed

anatomical sciences education. *Anat Sci Educ*. 2016;9(6):583-602. doi:10.1002/ase.1620
75. Sheikh AH, Barry DS, Gutierrez H, Cryan JF, O'Keeffe GW. Cadaveric anatomy in the future of medical education: what is the surgeon's view? *Anat Sci Educ*. 2016;9(2):203-208. doi:10.1002/ase.1560
76. Alismail A, Thomas J, Daher NS, et al. Augmented reality glasses improve adherence to evidence-based intubation practice. *Adv Med Educ Pract*. 2019;10:279-286.
77. Heo S, Moon S, Kim M, Park M, Cha WC, Son MH. An augmented reality-based guide for mechanical ventilator setup: a prospective randomized pilot trial. *JMIR Serious Games*. 2022;10(3):e38433.
78. Suresh D, Aydin A, James S, Ahmed K, Dasgupta P. The role of augmented reality in surgical training: a systematic review. *Surg Innov*. 2023;30(3):366-382. doi:10.1177/15533506221140506
79. Kouijzer MMTE, Kip H, Bouman YHA, Kelders SM. Implementation of virtual reality in healthcare: a scoping review on the implementation process of virtual reality in various healthcare settings. *Implement Sci Commun*. 2023;4(1):67. doi:10.1186/s43058-023-00442-2
80. Gavgani AM, Walker FR, Hodgson DM, Nalivaiko E. A comparative study of cybersickness during exposure to virtual reality and "classic" motion sickness: are they different? *J Appl Physiol*. 2018;125(6):1670-1680. doi:10.1152/japplphysiol.00338.2018
81. Wish-Baratz S, Gubatina AP, Enterline R, Griswold MA. A new supplement to gross anatomy dissection: HoloAnatomy. *Med Educ*. 2019;53(5):522-523. doi:10.1111/medu.13845
82. Rynio P, Witowski J, Kamiński J, Serafin J, Kazimierczak A, Gutowski P. Holographically-guided endovascular aneurysm repair. *J Endovasc Ther*. 2019;26(4):544-547. doi:10.1177/1526602819854468
83. Kellmeyer P, Biller-Andorno N, Meynen G. Ethical tensions of virtual reality treatment in vulnerable patients. *Nat Med*. 2019;25(8):1185-1188. doi:10.1038/s41591-019-0543-y
84. Oran DP, Topol EJ. The rise of the virtualist. *Lancet*. 2019;394(10192):17. doi:10.1016/S0140-6736(19)31498-9
85. Xiong J, Hsiang EL, He Z, Zhan T, Wu ST. Augmented reality and virtual reality displays: emerging technologies and future perspectives. *Light Sci Appl*. 2021;10(1):216. doi:10.1038/s41377-021-00658-8
86. Garcia LM, Birckhead BJ, Krishnamurthy P, et al. An 8-week self-administered at-home behavioral skills-based virtual reality program for chronic low back pain: double-blind, randomized, placebo-controlled trial conducted during COVID-19. *J Med Internet Res*. 2021;23(2):e26292. doi:10.2196/26292
87. U.S. Food And Drug Administration. Safer Technologies Program (SteP) for Medical Devices. U.S. Food And Drug Administration. 2021. Accessed August 25, 2024. https://www.fda.gov/medical-devices/how-study-and-market-your-device/safer-technologies-program-step-medical-devices
88. Fumagalli S, Torricelli G, Massi M, et al. Effects of a new device to guide venous puncture in elderly critically ill patients: results of a pilot randomized study. *Aging Clin Exp Res*. 2017;29(2):335-339.