Biostatistics and Biometrics
Open Access Journal
ISSN: 2573-2633

Research Article
Volume 12 Issue 2 - May 2025
DOI: 10.19080/BBOAJ.2025.12.555832

Biostat Biom Open Access J

The Essential Importance of Virtual and Simulation Technologies in Modern Medical Education

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Submission: May 01, 2025; **Published**: May 28,2025

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Abstract

Background: The increasing focus on virtual and simulation technologies as innovative interactive teaching methods is becoming more prominent in undergraduate medical education by offering immersive, risk-free environments for trainees. The rapid advancement of contemporary computer simulation technologies is leading to a continuous rise in sophisticated instructional practices aimed at enhancing medical education in various formats.

Methods: This scoping review intends to clarify the drivers for XR (VR/AR/MR) technology in medical education. Secondly, the investigation highlights the technical obstacles and ethical implications of virtual reality being incorporated into medical education. Literature search was conducted systematically to search relevant articles and reviews in five main databases which including PubMed, Scopus, Embase, Web of Science, and CINAHL from 2020 to present.

Results: The evidence for the effectiveness of the use of XR (VR/AR/MR) in medical education to help improve learner knowledge and skills, reduce error and practice repeatedly with virtual patients without risk is strong. Simulation using virtual patients has increasingly been implemented for various types of medical training in recent years, including surgery, emergency medicine, pediatrics, simulation for teaching of basic medical sciences, medical imaging, radiation, catheterization and puncture techniques, and interprofessional medical education, as well as a variety of case-based-learning.

Conclusions: The benefits of virtual simulations, including safe experimentation, the ability to replicate complex scenarios, and the potential for personalized learning, are comprehensively examined. The impact of these simulations on fostering critical thinking, enhancing communication skills, and improving adaptability is analyzed. However, XR's expansion raises serious concerns, such as the reduction of in-person interactions, inadequate infrastructure, data privacy, financial constraints, and the need to enhance student motivation and engagement must be addressed. Despite these issues, these technologies are still evolving and necessitate significant investment and widespread customization to satisfy the growing educational demand.

Keywords: Medical education; Clinical Scenarios; Simulation; Skills acquisition

Abbreviations: XR: Extended Reality; VR: Virtual Reality; AR: Augmented Reality; MR: Mixed Reality; AI: Artificial Intelligence

Introduction

The seamless integration of virtual and simulation technologies in modern medical education and clinical practice has significantly revolutionized the training of medical students. This approach not only focuses on the enhancement of their technical competencies, but also strengthening their non-technical skills, which allow them to deal with the traditional challenges and face new ones in practical settings. The latest developments in education have been enabled by the advances in simulation that provide realistic, risk-free experiences. Referred to as Extended Reality (XR) technologies, these innovations enhance not only technical and procedural abilities of students but also can help them to create opportunities to apply didactic content to clinical practice, which allows them to bridge knowledge, foster improved vocational training, collaborative skills, and decision-making. Grounded in virtual reality (VR), augmented reality (AR), and mixed reality (MR), simulation provides immersive and interactive scenarios that replicate real-world medical education and training with exceptional precision. Such methodologies deliver a profoundly engaging learning experience that transcends the constraints of physical environments without exposing patients to real risks [1].

The traditional model of medical education, which typically encompasses hospital-based training and the utilization of mannequins, presents several limitations, particularly when it comes to time, space, and inadequate clinical material for teaching. In the past, medical training relied heavily on direct patient interaction, which frequently raised ethical concerns and limited opportunities for correcting mistakes. Consequently, the range and depth of clinical experiences that students can access are somewhat restricted. This is where simulators become essential, providing consistent and repeatable scenarios. They allow learners the chance to hone complex skills repeatedly, whether in surgical procedures or diagnostic evaluations, all while ensuring patient safety is not compromised. High-fidelity simulations, like advanced mannequins and virtual reality technologies, prepare trainees to handle rare or critical situations, ultimately enhancing their readiness for real-world clinical practice [1,2].

Virtual reality (VR) is creating a revolutionary change in medical education through the provision of realistic, interactive, and highly engaging environments that have a positive impact on learning across multiple fields. VR-based educational programs enable medical students to develop complex skills, including surgical techniques, emergency procedures, and diagnostic methods, in a risk-free environment, thus providing the possibility of running through training scenarios as often as necessary and from any place. Such an approach not only helps in resolving ethical issues associated with practicing on real patients but also facilitates repetitive training, which in turn results in the acquisition of both technical and procedural skills. In addition to the above, the technology behind VR also enables the development of detailed 3D models of the human anatomy that, once utilized, can lead to better spatial comprehension and visualization of the human body, thus compensating for the limitations of traditional 2D materials and cadaver-based learning. VR, thanks to its adaptability and scalability, has become an indispensable tool in the quest to narrow the gap in medical education. By ensuring access to resources of high quality, VR helps to even the playing field for educational institutions across the globe, including those located in areas that are not well-endowed in terms of resources, thus enabling them to provide better training to the students. What is more, VR has been found to be very effective in recreating rare or complex clinical situations, for example, in pediatrics or robotic surgery, and therefore in preparing students to be confident and competent enough to deal with similar situations in a real-life setting [2-8].

Conversely, augmented reality (AR) is changing how medical education works, making it more engaging by placing digital content in the real world and giving birth to an interactive learning process that fuses book theories with practical skills. To give an example, AR in anatomy is all about having 3D models of human anatomy projected on cadavers or bodies in the real world, and students get to touch, and learn from them. This hands-on tactic is amazing for students as it brings about a deep understanding of the 3D order and aspects of the anatomy, that are often difficult to comprehend by reading books or looking at static models. Furthermore, AR is the go-to tool for practice-based training as it offers step-by-step instructions and immediate feedback during surgeries or diagnostic procedures done in a simulated environment. With all these visual and audio cues, the learner's vision is presented with information, tips, and feedback at every stage of the process through AR systems which help them to understand better and act with precision. To illustrate, to teach the techniques of suturing, catheter placements, and other practical tasks, AR is very instrumental as it gives prompt and context-aware feedback without the presence of a human instructor [9-15].

The Mixed Reality (MR) term refers to an interactive combination of the digital and real worlds. The combination of real and virtual environments along a continuum that ranges from completely real environments to completely virtual environments is what makes up this definition. Both real and digital components can be manipulated by users simultaneously due to this combination. MR is a game-changer in the field of medical education, tackling various challenges like enhancing patient interactions across different clinical areas, managing infection control, and boosting remote learning opportunities. Additionally, it assists students in applying what they have learned to the treatment of actual patients. Learning can become more dynamic through the integration of digital tools into physical spaces through MR. Students are able to view 3D models, superimpose digital data on real-time patients, and highlight points with gestures. Moreover, incorporating audio-visual elements can assist in reducing the cognitive burden and thus making learning more efficient in general. It is worth mentioning that MR-enhanced clinical practice may enable learners to correlate fundamental science principles-such as the structure and function of the human body-with actual patient cases, thus promoting a two-way, experiential learning process that integrates theoretical concepts with their application in real-life scenarios [16-19].

Extended reality (XR) is an umbrella term that includes virtual reality (VR), augmented reality (AR) and mixed reality (MR) technologies (see Figure 1). Extended reality (XR) covers technologies like virtual reality (VR), augmented reality (AR), and mixed reality (MR). These technologies introduce novel solutions to learning, responding to its changing demands. They are affordable, readily accessible, and can scale to accommodate greater demands at lower risks-a very valuable aspect amid the Covid-19 pandemic. This worldwide crisis introduced strict social distancing measures, which have adversely affected medical education. Yet, XR tools enable teams to work from various locations in virtual spaces, promoting collaboration and communication. This flexibility guarantees training goes on even during emergencies, making simulation more vital for training.

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In spite of problems like restricted resources, differences in infrastructure, and the necessity for training teachers, simulation technologies are seen as a necessity. They provide scalable, equitable, and efficient means for the provision of medical education across the world. This represents a critical change in medical training, with a focus on skill acquisition and patient safety, leveraging technology to address future healthcare needs [20-23].

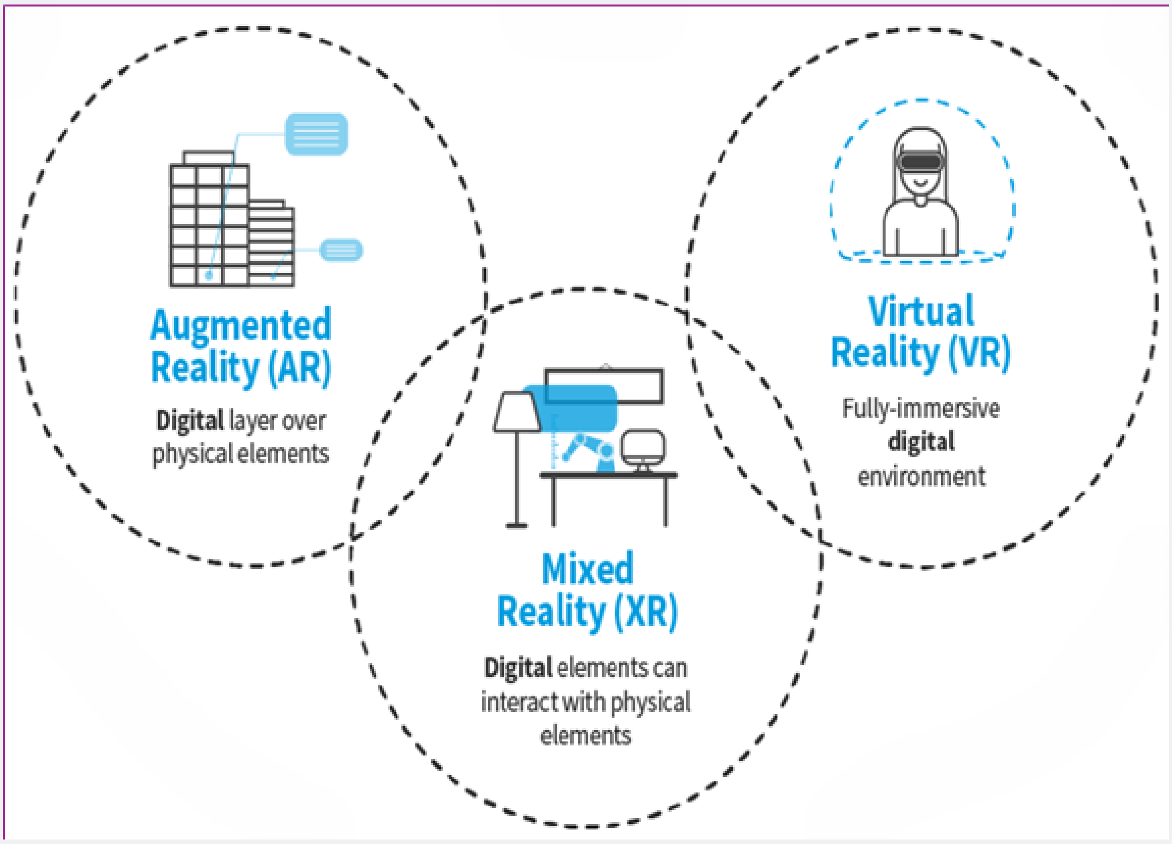

Figure 1: The Relationships among VR, AR, MR, and XR.

Methods

Purpose of the study

This study offers a critical analysis of the increasing application of simulation technologies, i.e., virtual reality (VR), augmented reality (AR), mixed reality (MR), and extended reality (XR), in medical education development. The mentioned technologies provide a cost-efficient, accessible, reproducible, and adaptable means of learning on a mass scale with the added benefit of minimizing risk.

Material and Analysis

In order to conduct this systematic review, the researchers followed guidelines offered by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). They used a five-step process that involved identifying relevant studies, studying selection, mapping data, synthesizing the results, and reporting the findings. A literature systematic review was undertaken in January and February 2025, yielding 2,984 studies from the five top databases: PubMed (n=94), Scopus (n=1,832), Embase (n=653), Web of Science (n=324), and CINAHL (n=81) with studies published since 2020. Inclusion criteria were established on any empirical research on extended reality (XR), including virtual reality (VR), augmented reality (AR), and mixed reality (MR), particularly in the fields of medicine and education/training. The information specialist of the research team exported the findings to Zotero, eliminating duplicates and keeping 1,122 articles. After the initial filtering, two reviewers evaluated the abstracts and titles to determine the appropriateness to the research purpose of the study, basing their evaluations on those giving insights of wider application. This excluded 251 of the retrieved 871 articles. The same reviewers then critically appraised the full texts of the remaining articles and made judgment calls based on suitability to the research purpose of the study. 29 articles were finally

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excluded after this systematic review, and 135 articles were found to be eligible for inclusion in the qualitative synthesis. A PRISMA flow diagram (Figure 2) is presented to illustrate the process of inclusion and the decision-making strategy [24-26].

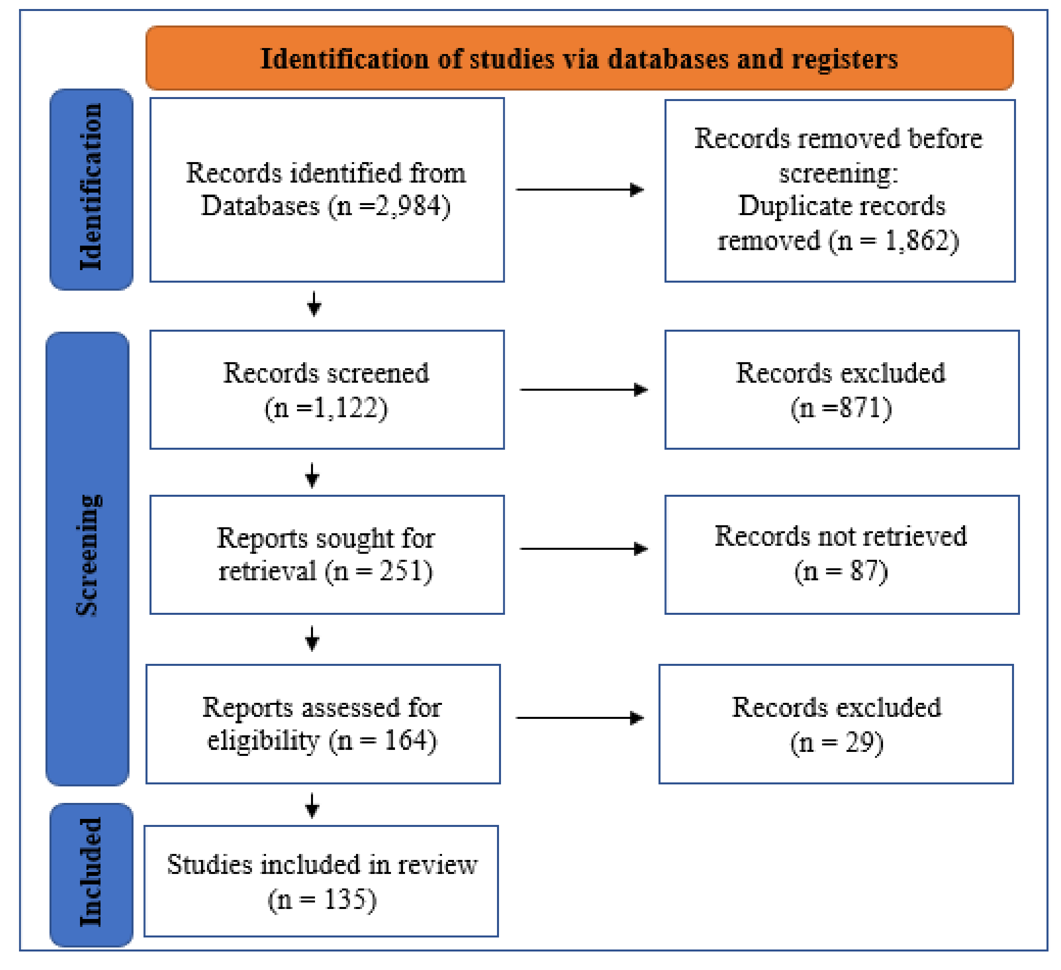

Figure 2: PRISMA Flow diagram of the systematic review [24].

Results

Innovative Technology in Healthcare Facilities

New technologies have always played a crucial role in the field of medicine. Take Pasteur's groundbreaking work on microorganisms, for example; it shows how innovation shapes the connection between doctors and their patients. Since the 18th century, the medical field has been navigating a whirlwind of evolving theories, while the patient has remained a constant presence. The emergence of clinical medicine brought a new focus on direct, scientific interactions, redefining illness in terms of lesions and symptoms, and placing practice firmly within clinical and laboratory settings. The adoption of medical technologies is often spurred by national and institutional efforts. Organizations like the National Research Council and NIH are at the forefront, advocating for internet-based healthcare, remote surgeries, and telesurgery to boost efficiency and improve outcomes. These advancements also aim to minimize the size of surgical teams, enhance procedural accuracy, and make training more efficient [27-31].

In medical education, emerging technologies bridge experienced practitioners and students to better learning outcomes and application in real life. They also contribute to diagnostics and therapeutics, but their complexity is intimidating to practitioners. Emerging innovations in surgery, such as minimally invasive technologies and virtual simulators, improve outcomes, training, and recovery rates and are critical for the next generation of medical professionals. The revolution towards technologically facilitated education subverts established practices. Technological advances like virtual reality and telesurgery break down skills into specialist skills needed for individual procedures, encouraging inter-surgeon collaboration across geographic sites. The shift calls

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for challenging questions on the impact of increased access to medical information on redesigning healthcare systems, changing professional competencies, and the dynamics of physician-patient relationships. Insurance firms and hospital managers can utilize these systems to reduce risk and contain costs, impacting the delivery of healthcare [30-35].

The impact of Hands-On Learning and Digital Technologies on the revolution of Medical Education

Technical skill and procedural knowledge are acquired by medical trainees through exposure. Teachers of anatomy and surgery teach students to think intuitively and judge, skills required for patient care. Surgeons must judge patients and respond on "perception, memory, and repetition". Learning by doing in surgery is inherently complex. Devices like X-rays aid procedures but can complicate interactions, such as guiding catheters during cardiac catheterization. Mastery of such tools is essential, and simulators offer reproducible curricula to measure performance reliably. As such, surgeons must master both practical skills and anatomical knowledge, reasonably, observation extends beyond seeing. It involves clinical analysis and the medical gaze, which integrates knowledge with action. In this context, seeing complements the "embodied work" of surgeons as they interact with devices. From the above, it is understood that traditional surgical training techniques have numerous limitations since they were primarily relied on cadavers or animal models. These methods not only posed risks of transmitting infectious diseases but were also costly, ethically problematic, and not readily accessible. [34,36-38].

In the field of surgical practice, XR (VR/AR/MR) is employed to replicate procedural scenarios, allowing trainees to engage in lifelike environments that closely resemble real surgical circumstances without the associated risks. These XR technologies enhance visual comprehension and enable immediate identification of errors, thereby promoting a more profound grasp of three-dimensional anatomy, intricate procedures, and surgical methodologies. Notably, VR offers a fully interactive simulation experience through a three-dimensional environment displayed on a head-mounted device, facilitating 360-degree visual immersion and real-time interaction with virtual elements, effectively substituting the user's actual surroundings with a digital landscape. Moreover, XR systems can be tailored to fit the specific needs of each trainee, offering personalized simulations of particular anatomical scenarios to enhance their learning experience. Plus, virtual simulations and medical devices like simulators and robotics are integrated into information management systems, serving not just as tools but as a means to manage medical knowledge. These collaborative efforts have led to the development of new practices in surgical education, where technology and teaching methods evolve alongside computer-based models. Surgical simulation enables medical trainees to acquire and hone skills outside the clinic, without relying on the active presence of a teacher. Through enabling remote instruction and exchange of information, XR enhances educational performance, as well as being a significant change in the educational landscape of surgery. In addition, XR enables the sharing of knowledge among students and teachers from various times and locations, which is particularly advantaged by locations where access to corresponding expertise is limited [39-45].

Anatomical Practice and Body Knowledge

Anatomy has traditionally been learned through dissection of human cadavers, supplemented by lectures and textbook use, and is defined as a complex learning process that is strongly reliant on physical experience. In-depth knowledge of human anatomy is crucial to the correct conduct of physical examinations, clinical findings assessment, performance of surgical operations, and involvement in other medical interventions. Most anatomy instructors possess some level of anatomical insight that their students do not have, employing verbal instructions or gestures to communicate about internal organs, this knowledge is critical in the medical and life sciences. Historically, cadaver dissection has been a favorite technique of anatomical teaching, providing a hands-on, experiential exposure to the human form. Medical students have typically acquired their anatomical knowledge in laboratory environments, where they could investigate both theoretical and tangible representations of the body. However, there are often problems in performing anatomy, challenges such as the lack of cadavers, the limited number of anatomy instructors, and the sustainability of donor programs have contributed to this shift [16, 46-48].

In this special field of anatomy and body knowledge, a shift is observed that leads to the formation of "bodily objects" designed for computer-aided education. The introduction of these technologies even changes the embodiment of doctors, requiring them to acquire new technical skills different from traditional clinical practice. This shift emphasizes technical perfection over clinical skills, thus redistributing medical practice. The rationality of digital technologies has three main characteristics: first, the bodies of patients and professionals are transformed into digital "bodily objects" that can be reused, redistributed and reconfigured. second, medical knowledge is redistributed between technologies and professionals. and third, the digitization of anatomy enhances trainees' spatial skills and understanding of body structures in virtual environments. Additionally, mental models developed by surgeons-such as imagining the structure of a shoulder-can mirror the advantages of virtual technology. These models allow practitioners to "travel" through the body in a three-dimensional space, illustrating how virtual technologies facilitate detailed visualization of organs, tissues, and blood vessels. Virtual tools offer a deeper understanding of the body, blending imagined and technological exploration [49-52].

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Additional Factors Influencing the Acceptance and Utilization of XR Technology Within the Realm Medical Education

Beyond the surgical and anatomical domains where XR technology is extensively applied, numerous other significant factors-both technical and non-technical-affect the adoption and utilization of this technology in medical education, and are analyzed below:

i. Balancing of Visualization with Embodied Skills

The cognitive emphasis frequently prioritizes visual perception, indicating a bias prevalent in Western medical practices. This predominance of visual input disrupts the relationship between observation and action, necessitating that surgical trainees employ alternative techniques to inform their procedures in situations where visual acuity is diminished. However, this visual-centric approach usually overlooks other vital sensory modalities, including tactile, olfactory, and auditory senses, which are indispensable for effective medical practice. The different types of XR (VR,AR,MR) technology has the ability to create realistic and vivid clinical scenarios, enable medical students to extract information through visual, auditory, olfactory and other sensory stimulations, immerse themselves in clinical practice and operations, and allow them to utilize medical knowledge for brainstorming, integrated analysis, and judgment, study and guidance of clinical operations [53-55].

ii. Engaging Learning Experience, Motivation and Knowledge Retention

Traditional methods of teaching, such as passive lectures, limited lab access, and textbook learning, are giving way to immersive, interactive training that enhances retention and comprehension. XR provides students with the opportunity to engage in medical simulations within a safe and regulated setting. Current findings suggest that VR is effective for imparting fundamental laparoscopic techniques, facilitating intentional practice in a structured environment that promotes concentrated skill acquisition. Additionally, VR training proves to be accessible and advantageous in settings with limited resources, showing promise in enhancing performance, particularly in the development of cognitive abilities under stress. Modifying the duration, frequency, and support systems for students can further improve the efficacy of VR surgical training tools, which seem especially useful in specialized fields such as cardiology, otolaryngology, ophthalmology, radiology, oncology, urology, and neurosurgery, where challenges arise from case availability and technical constraints. Ultimately, studies demonstrate that participation in active learning through immersive experiences significantly boosts information retention. XR provides a vibrant learning framework that allows students to interact directly with the content, leading to improved comprehension and enduring retention of knowledge. Simulations offer objective and standardized evaluations of skills, thereby ensuring that trainees achieve the necessary competencies prior to being certified for independent practice [56-60].

iii. Effort expectancy

The findings indicate that both VR and AR interfaces are seen to be user-friendly, even for participants with different levels of technical expertise. This is especially the case with VR, where the designs are made to be easy and simple to use. Surgeons view AR as a more effective and convenient learning tool compared to traditional techniques. By taking advantage of existing technologies like C-arm imaging, usability is improved and real-time images are available for AR training sessions. Additionally, VR simulations are very good at presenting realistic environments that closely approximate actual surgical situations, allowing trainees to rehearse safely and to obtain immediate feedback. AR, particularly with head-mounted displays (HMDs), also presents realistic task depictions that are beneficial for pre-surgical practice [61-63].

iv. Autonomy and Critical thinking abilities

Physician autonomy is required in providing high-quality patient care and in keeping the healthcare system running smoothly. Autonomy allows physicians to draw on instinct in decision-making that is tailored to the needs of patients and encourages their participation in discussions about quality and health system changes. On this front, VR and AR technologies provide the capacity to simulate actual clinical scenarios and practice intricate procedures to cultivate rapid, accurate decision-making and problem-solving abilities in difficult procedures within realistic settings [64-66].

v. Certification and accreditation processes

Simulation technology is very important in the certification and accreditation of medical students. They offer objective and standardized evaluation of competencies and hence guarantee that students achieve the necessary competencies prior to their certification to practice medicine independently. This is particularly beneficial for students who are specializing in surgical specialties or scientific equipment usage. It is widely believed that having good accreditation is paramount to enhancing healthcare education and guaranteeing consistency of standards to all stakeholders-students, educators, patients, healthcare providers, institutions, and society as a whole. In order to apply these standards, we need to evaluate a multitude of aspects from different vantage points, which sometimes requires conscientious study and a degree of judgment. That is the reason why the bodies tasked with evaluation and assessment play such a fundamental role in the accreditation process. In the end, not only do these processes guarantee quality, but they also foster a culture of ongoing improvement [67,68].

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vi. Facilitating conditions

The findings demonstrate that VR is a potent tool for imparting critical laparoscopic skills, facilitating intentional practice within a regulated setting that promotes concentrated skill enhancement. Recent research suggests that a structured environment allows users to move freely, interact with objects (including picking them up and manipulating them), and influence their experiences through their choices and actions. Additionally, VR training proves to be accessible and advantageous in areas with limited resources. Moreover, immersive VR training has the power to boost performance, especially when it comes to developing cognitive skills under pressure. Plus, customizing the length, frequency, and support systems of training sessions can really enhance the effectiveness of VR surgical training tools. On a related note, several studies have indicated that VR can help lighten the cognitive load for medical students. Factors like task complexity and prior VR experiences are key in shaping how users perceive the training and its overall success [7, 69-72].

vii. Student-centered learning and the advantages of reversibility

The student-centered learning approach emphasizes active engagement of students in the educational process, allowing them the autonomy to determine what, when, where, and how they will develop their skills and competencies. Simulation also offers the benefit of reversibility, as students can practice as much as they need, with their progress tracked and documented. Basic surgical skills can be developed in simulators before trainees enter clinical practice, a shift made possible by changes in surgical curricula. However, building effective virtual simulators for surgery remains complex, requiring an in-depth analysis of clinical practices, bodily structures, and including lack of infrastructure [1,42,73-76].

viii. Collaborative learning experiences and Accessibility

Research indicates that using simulations with virtual instructors or expert peers can greatly enhance skill development for novice surgeons. Medical students have access to several tech platforms that encourage collaboration in real-life scenarios and allow them to adopt a common model that is updated in real time. Through this setup, students can devise and share surgical techniques that people in other parts of the world can also benefit from, thus eliminating geographical constraints. Moreover, interprofessional education provides a forum for students from different health disciplines to collaborate, thus deepening their understanding of different backgrounds and viewpoints. This method inculcates mutual respect and understanding, thereby greatly bolstering teamwork dynamics in clinical settings. Additionally, cross-disciplinary training has become a trend, with many surgical programs including team training which involves not only surgeons but also nurses, anesthesiologists, and other medical professionals. Through simulated operations and collaborative problem-solving exercises, the coordination among the team members is reinforced. Additionally, educational programs that make use of virtual reality can create environments that give students the feeling of being present in various situations, making it possible to continue with teaching even when the safety of both students and educators is threatened by infectious disease outbreaks or natural disasters. The adaptability and accessibility of computer-based simulations make them an essential resource for ongoing learning and self-assessment [77,78].

ix. Communication skills

An essential aspect of medical education is the understanding of human behavior. Effectively interacting with patients and their families, addressing their worries, and communicate effectively as it is to have solid medical knowledge. XR technology provides a safe space to build those interpersonal skills, like delivering tough news and reading non-verbal signals. Training programs often include role-playing, interactions with standardized patients, and simulation exercises to boost both verbal and nonverbal communication abilities [78,79].

Limitations and Challenges of Simulation

Although XR (VR, AR and MR) technology is widely embraced, the use of simulation presents certain difficulties and noteworthy limitations. Engaging with simulated bodies does not provide the kinesthetic feedback and tactile interaction that are integral to actual surgical procedures. While mannequins used in minimally invasive surgery attempt to replicate tactile sensations, virtual models still do not fully capture the sensory experience associated with handling a real human body. Some medical professionals observe that the images generated by virtual tools can be excessively abstract, potentially impeding comprehension when compared to the tactile knowledge acquired during live surgical operations. For instance, in the context of shoulder arthroscopy, even with enhanced magnification, the visual representation may prove insufficient when juxtaposed with the authentic experience of open surgery. Furthermore, certain critics argue that these technologies might reduce the independence and discernment of surgeons because they are often incorporated into decision support systems that rely largely on technology. In particular, surgeons worry that computer programs and data systems can take the place of their technical skills and, as a result, influence the way surgeries are performed. While electronic devices have changed the face of surgical training, the fact that they rely heavily on technology makes it difficult to continue the practice of traditional skills and the development of independent expertise [1,39,80-82].

When we talk about VR, the criticisms are mainly centred on a number of notable constraints. To start with, it's unable to

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perfectly replicate the complete surgical process. Additionally, the absence of tactile feedback and pressure sensations significantly diminishes its value in tasks such as the treatment of intracranial aneurysms that involve a high level of detail and precision. On top of that, there's a noticeable gap between how realistic VR looks and what you actually experience in an operating room, which definitely needs more research. When it comes to AR surgical training tools, studies reveal that interacting with 2D and 3D anatomical overlays can be quite tricky. There are also some technical issues, like short battery life and overheating in head-mounted displays (HMDs), which can make training sessions uncomfortable for users. Moreover, to encourage broader acceptance of AR technology, we really need to find a way to deliver realistic haptic feedback, something that traditional training methods using cadaver models already provide [41,83-86].

The challenge with anatomy lies in the fact that digital technologies prioritize the "normal" representation of the human body, which is a standardized anatomical model, over the "instantiated" body, which refers to the individual physical characteristics of a patient. While these digital tools prove beneficial for anatomical research, they are unable to substitute the tactile experience of anatomy, which is crucial for achieving a thorough comprehension of bodily structures and their variations. Anatomy allows students to appreciate the intricate details and spatial relationships within the body, aspects that digital technologies often fail to effectively convey. While digital platforms offer the convenience of replays and repetitions, they cannot replicate the tactile interaction with real tissues, a critical element when interacting with patients in practical settings, as such remain supplementary to traditional dissection practices [17, 87-89].

The widespread use of VR is being held back due to economic issues. The expenses of the initial setup for the entire VR system, which entail not only head-mounted displays (HMDs) but also the additional equipment and programs necessary for a complete VR experience, are a major financial obstacle for individuals and companies alike, and that is why many shy away from it. In this respect, one more thing worthy of our attention is that AR simulation investigations are in agreement that the high cost of HMDs is the biggest impediment to the more extensive use of VR. Additionally, traditional networking technologies generally do not possess the capabilities to maintain stable connections, which are essential for VR and AR systems that need to be synchronized with their growing demands [62,90,91].

Alongside these aforementioned challenges to consider, there are also issues related to privacy, security, and ethics that arise as these technologies gain global popularity. Let's take mobile AR browsers, for example - a hijack can happen, and AR content can be changed if a person who is not allowed to gets access to the camera and GPS of the device. The privacy and security threats that arise from different 'always-on' input sensors like cameras, microphones, and GPS, are a case in point. Moreover, in XR environments that many users interact with, people with malicious intentions may easily replicate the digital content, thereby undermining intellectual property rights and user privileges [84,85,92-94].

Discussion

The growing requirement for an increased amount and complexity of information, combined with a reduction in practical teaching and the shortage of real learning opportunities, has sparked the creation of very creative and practical ways of using educational technologies in medical education. The discussion on the implementation of virtual and simulation technologies in medical training reflects the groundbreaking nature of these tools and, at the same time, delves into the wider implications and issues they entail. XR not only facilitates the process of acquiring technical skills but also transforms the way medical knowledge is passed on, perceived, and retained. These technologies, by supplying immersive and reproducible training environments, overcome the inherent drawbacks of traditional educational techniques and present new ways of handling moral dilemmas, lack of resources, and restricted accessibility. The use of XR technologies hinges on several crucial determinants in four main areas: performance expectancy, effort expectancy, social influence, and facilitating conditions. The concept of performance expectancy revolves around the tangible improvements that XR technologies offer to the learning process, evident in both technical and non-technical skills, and is particularly helpful in situations of great stress, such as during surgery. Such interactive and true-to-life environments are skill-enhancing and empowerment and confidence-boosting for aspiring surgeons. As for effort expectancy, most users find XR technologies to be easily accessible and quite intuitive, although virtual reality gadgets are often singled out for being even more immersive and real than other XR devices. Here, social influence is a significant factor since the direct approval of authorities can serve as an added incentive for the trainees to accept XR as a valuable teaching tool. Facilitating conditions underscore the importance of properly designed curricula and immediate access to resources. However, barriers like the transfer of skills to real-world situations and technical glitches that prevent a full utilization of XR technologies still persist [95].

Nonetheless, the incorporation of VR/AR technologies casts serious questions on their long-lasting applicability, cost-effectiveness, and the balance between technological progress and traditional experiential learning. These innovations do level and democratize access to medical education, especially for remote and underserved areas. But variations in technological setups and trainings inevitably remain barriers in such cases. Institutions must tackle these inequalities to allow everyone to benefit from the advancement. Another crucial point concerns how technologies affect educational approaches. The bias

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towards virtual and simulation-based pedagogies has generated the need to reconsider the faculty role, the design of curricula, and the assessment scheme. Faculty training and acceptance are paramount, as teachers move from fronting conventional teaching to facilitating technology-based learning experiences. This demands sustained investment in professional development and institutional support. Further investigations are still needed regarding the ability of VR-AR technologies to equip medical students with crucial non-technical competencies such as empathy, communication, and teamwork. While simulations provide important clinical scenarios for learning experiences, they cannot replace the real-life experience with patients, which gives so much contextual and emotional learning [96,97].

Conclusion

Virtual and simulation technologies are fast emerging as a very helpful tool for training highly skilled medical students. Research conducted into the evolution of the modern virtual reality in education and learning as part of its implication shows the increasing acceptance of this technology, mainly because of its likely transformative effects on the entire educational setting. This article claims that VR and AR can change medical education; they can make it much more attractive, immersive, and safe: overcoming historical barriers and present-day ones. With their application, students are enabled to master very complicated skills, like highly technical surgical procedures and management of real emergencies, in the controlled and secure environment. In this way, students can improve the level of proficiency and their confidence without putting patients at risk. Some key results of this integration include spatial understanding judged through 3D anatomical visualizations and procedural accuracy improvement through real-time feedback in AR-based training with improvement in interprofessional collaboration among learners. With these technological innovations, learners from different segments of the geographical spread can participate in a team-based simulation, thus developing competencies in communication and teamwork. In an unparalleled way, VR and AR bring accessibility and scalability, which would be most relevant to democratizing medical education, especially in low-resource settings. It came to light in a real sense during the Covid-19 pandemic. These technologies were able to ensure the continuity of medical training despite travel restrictions.

Even with the many benefits that they offer, there will still be the prevailing problems of existence with unequal access to the technological infrastructure, lack of training of the faculty, and initial cost of implementation. The acceptance of these tools, nevertheless, is wide-ranging in terms of their crucial role in education, where they provide equitable, efficient, and effective solutions toward a competency-based system of education.

The introduction of XR technology into medical education represents a massive paradigm shift that enhances medical learning as well as patient safety. It provides healthcare practitioners with training to counter challenges that arise with the fast pace of change in medical practice in a technology-driven world. While traditional physical models are often deemed to be low cost, providing haptic feedback and great access to training, VR simulators come with their own unique advantages, such as being freely available, reusable, and reducing the ethical and infection risk issues associated with animal models. While cadavers have long been deemed the gold standard for training, novel advanced, perfused three-dimensional printed models may soon take their place by being more friendly than the cadaver in replicating procedures while taking into consideration anatomical variations and challenges met during surgery. Such simulators, however, are not deemed a “technological marvel”; nevertheless, they serve as valuable tools in skills enhancement of particular procedures, serving as adjunctive training to traditional training in clinical setups.

Declaration of Interest: The authors declare no conflict of interest.

Conflict of Interest: Each author declares that he or she has no commercial associations (e.g., consultancies, stock ownership, equity interest, patent/licensing arrangement etc.) that might pose a conflict of interest in connection with the submitted article.

Ethical approval: The ethical approval was not required, as the study conducted did not involve any ethical concerns or issues.

Funding: None

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How to cite this article: Dimitris K , Dimitra B, Yannis P. The Essential Importance of Virtual and Simulation Technologies in Modern Medical Education. Biostat Biom Open Access J. 2025; 12(2): 555832. DOI:10.19080/BBOAJ.2025.12.555832

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How to cite this article: Dimitris K , Dimitra B, Yannis P. The Essential Importance of Virtual and Simulation Technologies in Modern Medical Education. Biostat Biom Open Access J. 2025; 12(2): 555832. DOI:10.19080/BBOAJ.2025.12.555832

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How to cite this article: Dimitris K , Dimitra B, Yannis P. The Essential Importance of Virtual and Simulation Technologies in Modern Medical Education. Biostat Biom Open Access J. 2025; 12(2): 555832. DOI:10.19080/BBOAJ.2025.12.555832

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How to cite this article: Dimitris K , Dimitra B, Yannis P. The Essential Importance of Virtual and Simulation Technologies in Modern Medical Education. Biostat Biom Open Access J. 2025; 12(2): 555832. DOI:10.19080/BBOAJ.2025.12.555832