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Virtual and Augmented Reality in Anatomy Education: Exploring New Horizons

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Abstract
This review explores how virtual and augmented reality technologies are transforming medical education and clinical practice, particularly in anatomy instruction. Virtual and augmented reality technologies are reshaping our perception and interaction with anatomical structures. Their integration into medical practice has introduced opportunities in diagnostics, surgical training, rehabilitation, and patient education. With the increasing number of U.S. Food and Drug Administration approvals, these technologies offer a transformative shift in the teaching and practice of medicine. Virtual environments facilitate detailed anatomical visualization, offering students and trainees immersive and interactive experiences. This paper highlights the role of these technologies in enhancing educational methods, improving knowledge retention, and overcoming traditional limitations, such as the scarcity of cadavers. **Conclusion.** Virtual and augmented reality offer novel educational tools in the health sciences, providing cost-effective, accessible, and innovative approaches to anatomy education and clinical application. Further research is required to elucidate the benefits of these technologies in the education and training of medical students.

Key Words: Anatomy Education ▪ Virtual Reality ▪ Augmented Reality ▪ Medical Technology ▪ Health Sciences.

Introduction

Reminiscent of the 1966 science fiction film "Fantastic Voyage", we were amazed to see how medical professionals 'traveled' inside a patient's body to treat a brain injury. Virtual Reality (VR) and Augmented Reality (AR) now offer a similar, albeit safer, immersive, and interactive visualization of a patient's anatomy as never before. These technologies provide operators with the opportunity to "travel" through the body, merging the real world with digital imaging of anatomical structures and their associated pathologies.

The impact of these technologies on every aspect of patient care is expanding as the U.S. Food and Drug Administration (FDA) begins approving them for applications in all areas of the health sciences, including medicine, nursing, surgery, and psychology. These applications in clinical practice are considered to be technologies poised to transform the way healthcare is delivered across nearly all specialties. These technologies play an increasingly important role in education, preoperative planning, intraoperative guidance, and even perioperative pain management and rehabilitation (1).

Augmented and Virtual Reality

By definition, augmented reality adds digital information to the real world, whereas virtual reality completely replaces the real world with a digital one, offering an immersive experience that excludes the physical world entirely. Augmented digital information is embedded in the real world and perceived by one or more senses. In this way, videos or computer-generated images are overlaid onto the physical world.

According to Azuma et al. (2), an augmented reality system must: 1) combine real and virtual objects in the physical environment, 2) operate interactively and in real time, and 3) align real and virtual objects with each other. Such a system usually includes a camera to detect the user's movements, which are then merged with the virtual objects. An optical display enables the user to see digital objects overlaid on the real physical world.

In the early 1990s, Boeing introduced the first augmented reality system to assist workers with assembling wiring systems (3). Loomis introduced the first medical application in 1993 (4). It involved a GPS-based system that helped blind individuals navigate by adding cues to convey spatial information. Fuchs et al. (5) demonstrated the clinical benefits of augmented reality with a system that superimposed anatomical images onto a patient during biopsy procedures.

In the past decade, software tools for developers, such as "HoloLens SDK" and "ARToolkit", have accelerated the development of augmented reality applications. The "Total Immersion" of D'Fusion enabled developers to design simpler applications, making them more accessible to users. Google developed "Google Glass", and in 2016, Microsoft developed "HoloLens", both of which have been used in clinical research and FDA-approved commercial applications. Their usability is currently being tested in many areas of daily clinical practice (6). These technologies have enormous potential to transform the education of students and trainees in human anatomy and invasive clinical interventions. For example, through interactive simulations, students can explore the human body and study its physiological processes. The simulations can also integrate other digital biomedical data, such as CT and MRI images. Additionally, simulation can be particularly useful for learning anatomy and its processes, as it allows learners to prepare, practice, and review their performance repeatedly in a risk-free environment (7).

Virtual reality educational applications can provide satisfactory quality and fidelity virtual environments capable of providing incentives for active learning (8). A plethora of such educational applications have been developed over time, featuring a variety of tools to support subjects such as physics, chemistry, mathematics, biology, history, engineering, and many other cross-curricular approaches. The basic principle of utilizing virtual reality in education lies in experiential learning (the experience of direct contact) with the object of study, along with a participative approach to the course material.

Methods

Purpose and Objectives of the Study

This section presents the methodology for the systematic review of empirical studies and reviews on the application of virtual and augmented reality in education in health sciences schools. Specifically, we searched for and analyzed the studies that met the research criteria based on the research questions of this paper.

The first research question distinguishes between two emerging digital technologies—virtual and augmented reality—exploring their educational role in the training of health professionals, as well as the contributions and usefulness of each technology. The second question examines the potential for integrating these technologies into both educational processes and clinical applications within the healthcare industry.

Bibliographic Search Strategy

The purpose of this systematic review is to document the findings of studies conducted between

2010 and 2025 on the use of virtual and augmented reality in medical education and surgery. The search was conducted online, specifically on the NCBI website (National Center for Biotechnology Information, USA), using the PubMed, Google Scholar, and ResearchGate databases, which include authoritative articles and reports published in scientific journals and conferences of health organizations. The keywords used in the search were: "Virtual Reality", "Augmented Reality", "Health Sciences", "Medical Education", and "Medical Applications".

The terms used in the field of new digital technologies are often employed interchangeably. In this study, we define the terms as follows:

- Virtual reality refers to a fully digitized environment.
- Augmented reality refers to the real world, enhanced by superimposed digital information.
- Medical education is defined as the teaching, training, and testing of knowledge and skills used by students in health sciences schools.
- Medical surgery is defined as a medical specialty that uses surgical protocols and instruments to investigate or treat a medical condition in a person.

We performed two searches using the following key terms. To search the literature in the field of "medical education", we used a title search ("virtual and augmented reality") AND a subject search ("medical education"). To search the literature in the field of "medical surgery", we used a title search ("virtual and augmented reality") AND a subject search ("medical surgery").

Data were collected from the NCBI online database to answer our research questions regarding the integration of these technologies into the fields of medical education and surgery. Fields that overlap with other professions, such as nursing, were included. However, veterinary and dental studies were excluded to maintain our focus solely on medical investigations. This decision was based on the fact that different universities have distinct anatomy fields, use technologies differently, and apply diverse methodologies in training and teaching.

Methodological Framework

More specifically, we reviewed titles and abstracts to exclude studies not relevant to the topic of discussion. For this reason, we established inclusion and exclusion criteria for the studies under evaluation. We considered abstracts eligible if the study met the following inclusion criteria:

- The articles reported a correlation between virtual and augmented reality in medical education and clinical application.
- The articles were written in English and/or Greek.
- The articles were published after 2010. The literature search was completed in 2025.

On the other hand, we excluded from this review studies that did not show a clear correlation between new technologies and the health sciences. Specifically, we did not include the following in the search:

- Reports and studies related to fields outside the health sciences (e.g., the commercial sector).
- Articles written in languages other than English or Greek.
- Articles published before 2010.

The search identified 366 articles. However, not all were included in the literature review, as some were not relevant to the search purpose and did not meet the keyword criteria. Of the 230 highlighted articles, only 107 were systematic or original studies that met the inclusion criteria. The authors identified a total of 81 freely accessible scientific studies, which they included in this study.

Figure 1 schematically illustrates the process followed to search and evaluate the studies included in this systematic review.

Advances in computing, communications, and technology since 1990 may have contributed to the increase in research on virtual reality, while the advent of the smartphone in 2008 may explain the rise in research on augmented reality. Both virtual and augmented reality technologies are used in surgical training and anatomy teaching. However, we identified potential applications of virtual reality in counseling and of augmented reality in practical skills training. Although research has

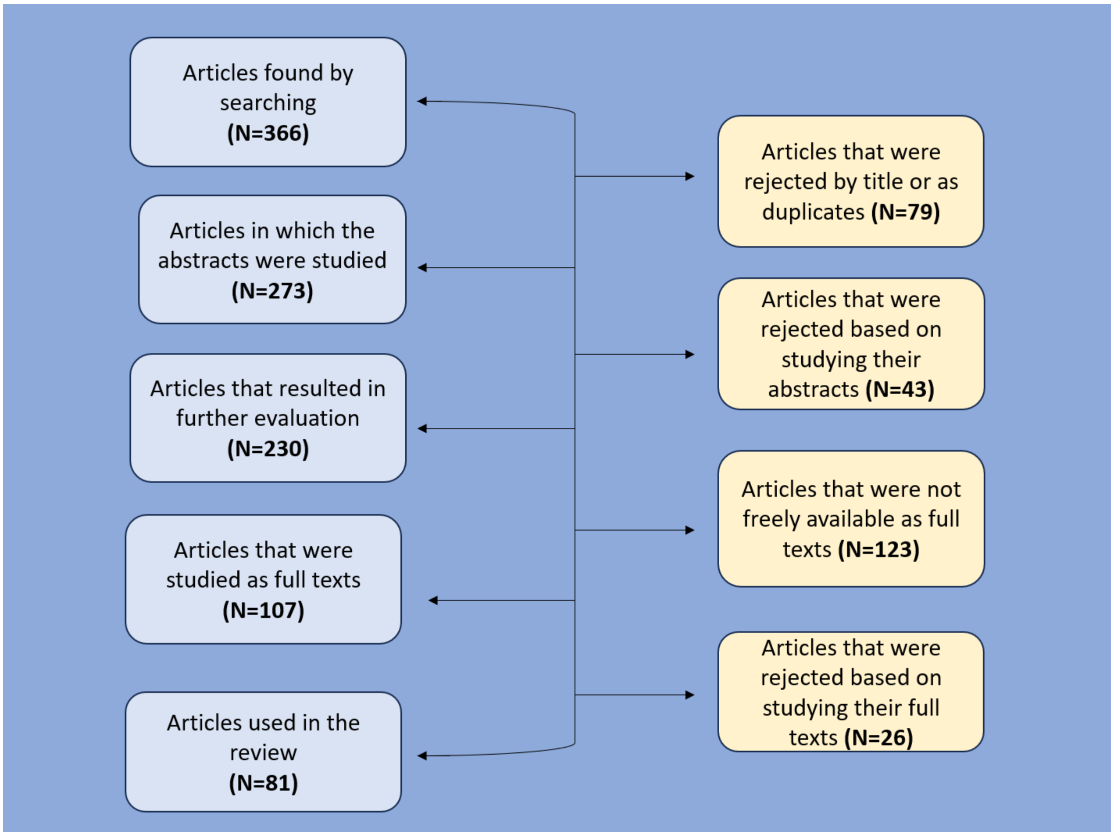

Figure 1. Flow diagram of the article selection process for this critical review.

validated the use of virtual and augmented reality in medical education, few studies have examined the integration of these new technologies into the education of health scientists.

Results

Anatomy is one of the most complex subjects in the health sciences due to the vast amount of knowledge that students must acquire (9). The use of cadaveric material is inextricably linked to the teaching of anatomy and is superior to anatomical atlases, which only provide two-dimensional images. Throughout history, the use of cadaveric material in medical and allied health curricula has been a source of serious social controversy. One such controversy revolves around whether the use of cadaveric material is an appropriate modern method for teaching human anatomy. On the other hand, some advocates argue that the use of cadaveric material is one of the most fundamental components for comprehensive knowledge and that students may not acquire sufficient anatomical knowledge if it is absent. Medical professionals often refer to anatomy as the language of medicine. However, the 21st-century medical curriculum has shown a significant reduction in the hours devoted to anatomy education (10). This decline is partly due to economic factors related to the preservation of cadaveric material and the limited access to human cadavers. Additionally, the maintenance of modern laboratories and storage facilities that meet health and safety standards for students and staff adds an additional financial burden.

Cultural and ethical considerations also play a crucial role, as they create limitations that make it difficult for educational institutions to obtain or access human cadavers for health science education. Consequently, many medical schools and departments that teach anatomy are seeking alternative or complementary methods for teaching the human body, such as laminated anatomy charts and two-dimensional (2D) and three-dimensional (3D) imaging (11).

With the advancement of technology, particularly 3D imaging and virtual reality, teaching anatomy has become easier. The use of this technology by educators has led to the development of models that represent anatomical structures more effectively than cadavers, while also eliminating the need for the time-consuming and complex process of cadaver dissection (12). Additionally, this technology has greatly assisted instructors in explaining the features or functions of anatomical structures that may not be immediately visible.

Virtual and Augmented Reality in Anatomy Education

The use of 3D models is widespread in anatomy education. Virtual and Augmented reality enable users to bypass the hassle and complexity of cadaver preparation and can provide a better understanding of the features or functions of anatomical structures that may not be immediately apparent (13). Moreover, these models are particularly useful in explaining anatomical relationships and functions that may not be clearly discernible in a cadaver or may be obstructed by other structures. Consequently, anatomy education is enhanced and facilitated through the use of digitized anatomical models (14). These models can focus on specific features of anatomical structures that are relevant to the curriculum's educational goals.

The goal of incorporating digital anatomical models into the curriculum is to enhance student learning. These models can be used as stand-alone learning tools or in combination with other learning resources to help students develop knowledge and achieve their educational objectives (15).

Discussion

This paper highlights the various advantages of virtual and augmented reality in medicine, particularly in the field of surgery:

1. Using VR and AR atlases of the human body, with detailed analyses of physiology and pathology, provides better knowledge transfer and job training for trainees.
2. Virtual and augmented reality can closely mimic the clinical environment of the operating room while simultaneously depicting the patient's anatomy and physiology.
3. Radiological data can be integrated into VR or AR applications to visualize anatomical structures—such as organs and various pathologies—providing a realistic representation of human anatomy or even a patient's clinical condition. In addition, VR/AR-based preoperative planning can help users become familiar with complex surgical procedures.
4. Intraoperative guidance reduces the likelihood of serious complications and enhances trainees' surgical skills.
5. The use of 3D models in specialized training programs contributes to anatomy education, providing students with a more practical approach. Virtual and augmented reality create a friendly learning environment, enabling learners to engage in independent learning and research activities.

Beyond these educational and surgical advantages, virtual and augmented reality technologies can also play an active role in telemedicine, ranging from remote diagnosis to complex tele-interventions. In such contexts, good knowledge of anatomy, physiology, and pathophysiology, supported by VR and AR technologies, could help physicians in diagnosing, providing initial management, and providing treatment instructions for a patient's disease (16, 17). As an example of this application, McCoy et al. showed that live streaming and real-time connection made it possible to assess the viability and efficiency of using telesimulation and wearable/mobile technology to teach medical professionals abroad about mass casualty incidents in emergency medical services (18). The FDA approves these technologies based on their continuous evolution. While there is still room for improvement, it is evident that these technologies have the potential to impact every aspect of medical care.

Understanding human anatomy is essential to the practice of medicine, as anatomical knowledge supports the formulation of diagnoses and their communication to patients and colleagues. Traditionally, anatomy training has been performed using cadaveric dissection. According to Winkelmann (19), anatomical dissection is the "systematic exploration of a preserved human cadaver through the sequential division of tissue layers and the liberation of certain structures by removing regional fat and connective tissue, with the aim of supporting the learning of gross anatomy through visual and tactile experience".

Recent literature further supports the role of immersive technologies in healthcare education. For instance, the systematic review by Faizan S. et al. underscores the transformative potential of immersive technologies such as extended reality, VR, and AR in healthcare, ranging from enhancing surgical accuracy to democratizing medical education (20). Similarly, Kyaw et al. found evidence indicating that VR, when compared to traditional education or other forms of digital education (online or offline), improves post-intervention knowledge and skill outcomes among health professionals (21). In line with this, Baashar et al. reported that AR significantly increases performance speed, satisfaction, and confidence, although it is less effective in improving knowledge and skill (22).

However, it is also essential to acknowledge that not all findings are uniformly positive. Several important studies have presented opposing results regarding AR and VR technologies. For example, a meta-analysis by Yeung et al. assessed the effectiveness of AR in medical training (23). This analysis included 13 studies with 654 participants, comparing AR to other educational methods, such as conventional teaching and non-AR techniques, in terms of skills, knowledge, confidence, performance time, and satisfaction. Results showed that AR improved performance time ($I^2=99.9\%$; $P<0.001$), confidence ($I^2=97.7\%$; $P=0.02$), and satisfaction ($I^2=99.8\%$; $P=0.006$), but had no significant effect on knowledge or skill levels compared to control conditions (I^2 — knowledge: 99.4%; skill: 97.5%). This meta-analysis suggests that although AR and VR are promising technologies for the future, they are not yet fully effective as training tools.

Moreover, Barteit et al. included 27 studies comprising 956 participants (24). The participants represented all types of healthcare professionals, particularly medical students (N=573, 59.9%) and residents (N=289, 30.2%). Most of these studies showed that AR and VR achieved results that were at least non-inferior to conventional teaching and training. Furthermore, in the study by Tene et al., which analyzed 28 studies, the majority reported positive or increased effects from the use of immersive technologies (25). However, statistical analysis did not reveal a significant association with improvements in medical education and training compared to traditional educational methods, highlighting the need for further research with larger sample sizes.

The value of anatomy courses lies in the fact that they provide a three-dimensional view of human anatomy, including tactile learning experiences. These courses enable students to expand on the knowledge gained from lectures and textbooks, providing a comprehensive perspective on anatomical structures and their interrelationships throughout the body. Nevertheless, this form of training is costly, and to date, there is no objective empirical evidence on the effectiveness of traditional laboratory courses for training anatomy.

In this regard, augmented reality technology could serve as an additional training method for anatomy education, depending on its implementation. Its strengths lie in its visualization capabilities, including 3D depiction of anatomical images. Other sensory experiences, such as tactile feedback, could also be incorporated. Augmented reality enables the real-time manipulation of these visualizations, providing immediate feedback to students and offering some of the benefits of traditional anatomy courses at a potentially lower cost (19).

Similarly, virtual reality combines a fictitious environment that is similar or identical to the real world and enhances information through visual or other sensory stimuli. Training supported by virtual and augmented reality technology enables collaborative learning, providing a sense of immediacy and resulting in multiple benefits for the training process (26). These learning environments offer many possibilities, with the goal of fostering meaningful learning—a necessary condition for transferring knowledge to learners. Toward the end of this paper, we focus on health professionals in clinical practice.

In conclusion, the growing interest in virtual reality systems will contribute to the advancement of education in the health sciences, particularly in clinical practice. As technology advances, 3D modeling can be applied to a wide range of technological systems.

Conclusion

The growing interest in augmented reality and virtual reality technologies will contribute to the advancement of education in the health sciences, particularly in clinical practice. As technology progresses, 3D modeling can be integrated into a wide range of technological systems. These training environments offer numerous possibilities, aiming to foster meaningful learning—a necessary condition for the effective transfer of knowledge to trainees. However, further studies are needed to clarify the benefits of these technologies in the training of medical students.

What Is Already Known on This Topic:
Traditional anatomy education relies heavily on cadavers, which are expensive and raise ethical and logistical issues.

What This Study Adds:
This review demonstrates how virtual reality and augmented reality can serve as effective supplements or alternatives to cadaver-based teaching.

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