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Immersive Technologies in Medicine

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ABSTRACT

In a world where technology is continually reshaping the way we approach medical treatment, training, and education, immersive technologies are becoming integral to the advancement of healthcare. Immersive technologies are gaining popularity in healthcare settings, as new technological breakthroughs enable diagnosis and therapy. With the help of these technologies, practitioners can visualize human structures better than ever before, enabling them to be highly accurate in various types of surgeries. This paper focuses on the implementation and integration of immersive technologies into existing medical practices.

KEYWORDS: *virtual reality, VR, augmented reality, AR, mixed reality, MR, extended reality, XR, immersive technologies, medicine, healthcare immersive medicine.*

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INTRODUCTION

Virtual reality (VR) and augmented reality (AR) are rapidly gaining traction in healthcare, offering transformative opportunities for patient care, medical education, and therapeutic interventions. Personalized VR and AR devices have been available in the market for several years and continue to evolve and improve. As its name suggests, VR 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 3D virtual space. 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 [1].

Scholars from various fields identified different ways and application domains to use immersive technology to train medical and healthcare professionals (including students). VR and AR technologies significantly enhance patient experiences and medical training, providing immersive and interactive environments for learning and practice. They hold considerable promise in revolutionizing medical practices [2]. MR merges the real and virtual worlds, allowing digital and physical elements to interact. In healthcare, MR facilitates immersive experiences for surgical planning, medical training, and patient education. Figure 1 shows a representation of immersive technology [3].

WHAT ARE IMMERSIVE TECHNOLOGIES?

The first step in understanding how to use immersive technologies is to learn the differences between various forms. In their simplest form, immersive technologies consist in adding virtual objects to the real world. There are four types of digital realities leading to different types of immersive technologies [4,5]:

- *Augmented reality* (AR)- designed to add digital elements over real-world views with limited interaction.
- *Virtual reality* (VR)- immersive experiences helping to isolate users from the real world, usually via a headset device and headphones designed for such activities.
- *Mixed reality* (MR)- combining AR and VR elements so that digital objects can interact with

the real world means businesses can design elements anchored within a real environment.

- *Extended reality* (XR)- covering all types of technologies that enhance our senses, including the three types previously mentioned.

These devices also enable new user interactions including spatially tracked 3D controllers, voice inputs, gaze tracking, and hand gesture controls.

Extended reality (XR) is the overarching term used to describe employing technology to blend real life and the digital world. It includes all the machine-human interfaces beyond the physical realm (reality) such as augmented reality (AR), mixed reality (MR), assisted reality (aR), and virtual reality (VR), as illustrated in Figure 2 [6]. Figure 3 shows the XR spectrum [7]. Immersive technologies reside along a continuous scale ranging between the completely real and the completely virtual world. At one end, the real environment refers to the actual physical space, objects, and people that exist in the tangible world around us. At the other end, the virtual environment represents a completely computer-generated and immersive digital space, distinct from the physical reality. The space in the middle is called mixed reality, which is a blend of the real and virtual environments, where digital and physical elements coexist and interact in real time. A range of devices makes up XR, and these are used by consumers and in many industries for entertainment, safety, training, or productivity purposes.

1. *VIRTUAL REALITY:* Virtual reality (VR) is XR at its most extreme. It completely immerses the user in a digital world, often using a computer-generated environment with scenes and objects that appear to be real. The term "virtual reality" essentially means "near-reality." Virtual reality is the key technology for experiencing sensations of sight, hearing, and touch of the past, present, and future. VR is a fully immersive technology where users wear a head-mounted display and experience a simulated world of imagery and sounds. VR enables active learning. The terms, "virtual reality" and "cyberspace" are often used interchangeably. A cyberspace may be regarded as a networked virtual reality. A person using virtual reality can look around an artificial world, move around it, and interact with virtual features or items. This effect is commonly created by virtual reality headsets. Head-mounted displays immerse the user in a virtual environment. Virtual reality is a simulated experience that can be similar to or different from the real world. It is a computer-generated, 3D environment that completely immerses the senses of sight, sound, and touch. The complete immersion of the senses overwhelms users engrossing them in the action. Virtual reality technology includes multiple components divided into two main groups: hardware and software components [8].

- *Hardware Components:* The hardware components include a computer workstation, sensory displays, a tracking system, wearable devices, and input devices. Sensory displays are used to display the simulated virtual worlds to the user. The most common type is the head-mounted displays (HMDs), which is used in combination with tracking systems. A head-mounted display is shown in Figure 4 [9]. Users interact with the simulated environment through some wearable devices. VR depends on special responses such as raising hands, turning the head, or swinging the body. A wearable device is important in making these effects realistic. Special input devices are required to interact with the virtual world. These include the 3D mouse, the wired glove, motion controllers, and optical tracking sensors. These devices are used to stimulate our senses together to create the illusion of reality.

- *Software Components:* Besides the hardware, the underlying software plays an important role. It is responsible for the managing of I/O devices and time-critical applications. The software components are 3D modeling software, 2D graphics software, digital sound editing software, and VR simulation software. VR technology has been designed to ensure visual comfort and ergonomic usage.

2. *AUGMENTED REALITY:* Augmented reality (AR) is a technology that combines real-world environments with computer-generated generated information such as images, text, videos, animations, and sound. It can record and analyze the environment in real-time. In augmented reality, the user typically experiences the real world through a device such as a smartphone, tablet, smart glasses, or head-mounted display. For example, AR allows consumers to visualize a product in more detail before they purchase it. This feature enhances consumer interaction and helps them never to repurchase the wrong item. The key objective of AR is to bring computer-generated objects into the real world and allows the user only to see them. In other words, we use AR to track the position and orientation of the user's head to enhance/augment their perception of the world. Augmented reality falls into two categories: 2D information overlays and 3D presentations, like those used with games. AR

blends the virtual and real worlds by overlaying digital objects and information onto the users' view of the physical world.

To obtain a sufficiently accurate representation of reality, AR needs the following five components [10]:

- *Sensors:* AR needs suitable sensors in the environment and possibly on a user, including fine-grained geolocation and image recognition. These are activating elements that trigger the display of virtual information.
- *Image augmentation:* This requires techniques such as image processing and face recognition.
- *Head-mounted Display*: HMDs are used to view the augmented world where the virtual computer-generated information is properly aligned with the real world. Display technologies are of two types: video display and optical see-through display.
- *User Interface:* This includes technologies for input modalities that include gaze tracking, touch, and gesture. AR is a user interface technology in which a camera-recorded view of the real world is augmented with computer-generated content such as graphics, animations, and 2D or 3D models.
- *Information infrastructure:* AR requires significant computing and communications infrastructure undergirding all these technologies. The infrastructure determines what real-world components to augment, with what, and when.

3. *MIXED REALITY:* Mixed reality (MR) is a term used to describe the merging of a real-world environment and a computer-generated one. Physical and virtual objects may co-exist in mixed reality environments and interact in real time. This is an extension of AR that allows real and virtual elements to interact in an environment. MR liberates us from screen-bound experiences by offering instinctual interactions with data in our living spaces and with our friends. Online explorers, in hundreds of millions around the world, have experienced mixed reality through their handheld devices. Mixed reality is a blend of physical and digital worlds, unlocking natural and intuitive 3D human, computer, and environmental interactions, as shown in Figure 5 [11] and Figure 6 [12]. This new reality is based on advancements in computer vision, graphical processing, display technologies, input systems, and cloud computing. Mixed reality has been used in applications across fields including design, education, entertainment, military training, healthcare, product content management, and human-in-the-loop operation of robots [13].
4. *ASSISTED REALITY:* Like mixed reality, assisted reality (aR) is an extension of augmented reality, with a few notable differences to both. One of these differences is that aR is primarily hands-free through the wearing of a headset, whereas AR usually requires the holding of a device such as a mobile phone. While MR is a digital-first, real-world second reality, aR is a real-world first system. It combines software and a head-mounted display. It is best experienced using smart glasses or other wearable technology. The aR market is growing rapidly and promises to be the next great leap to boost workers' productivity. A worker wearing an aR device is shown in Figure 7 [14].
5. *EXTENDED REALITY:* The term "extended reality" (XR) has recently gained favor as an umbrella term that encompasses all of AR, VR, and MR. The primary user inputs for XR devices are described as follows. Voice interfaces are now ubiquitous thanks to mobile devices and standalone smart speakers. Apple's Siri, Amazon's Alexa, Google's Assistant, and Microsoft's Cortana are all voice-driven software interfaces that are continuously gaining new capabilities. Many XR devices enable user control with handheld controllers, which have capabilities beyond button press inputs. Both voice-driven interfaces and human-computer interactions have been developed specifically for XR devices, including gaze and gesture controls [15]. Figure 8 compares conventional computing with extended reality [15].

IMMERSIVE MEDICINE

Medical knowledge is changing rapidly and it doubles every 6–8 years, with new medical procedures appearing every day. The rapid change in medical knowledge calls for innovative learning tools for medical practice and education. Immersive technology seems to be one of them. Immersive technology blurs the line between the real and virtual worlds, allowing users to feel fully immersed in the experience. Virtual reality (VR), augmented reality (AR), mixed reality (MR), and extended reality (XR) are examples of immersive technologies that have the potential to improve medical practice and education. Mixed reality (MR) technologies such as virtual and augmented reality (VR/AR) are well established in medical practice, enhancing diagnostics, treatment, and education. Immersive technologies are increasingly used in several fields of medical education. In medical education, these technologies provide realistic clinical simulations, improving skills and knowledge retention. Several reasons have supported the use of immersive technologies in medical education; adult learning theories promote their use for the training and evaluation of medical students, as they provide a repeatable, and learner-friendly environment [16].

AR-based technology is revolutionizing various aspects of healthcare and offering unprecedented opportunities for medical imaging and visualization, anatomy education, and telemedicine. 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. Relaxation and meditation in various VR applications have become increasingly widespread for treating patients at home or in hospitals. Figure 9 shows virtual and augmented reality applications in healthcare [1], while Figure 10 shows how VR hardware and software are utilized to reach diagnosis [1].

APPLICATIONS OF IMMERSIVE MEDICINE

Immersive technologies have become game-changing tools in healthcare services, offering an improved patient experience, better medical training, and innovative therapeutic interventions. They have been proved to be effective in many specialties including surgery, emergency medicine, radiology, obstetrics, dentistry, and many more. AR, VR, and MR are becoming dynamic allies in healthcare through applications in surgery, training, and patient care. Common areas of applications include the following [1,2,17]:

- *Medical Education:* For decades, junior doctors have primarily learned surgical skills through direct experience in the operating room under the supervision of seasoned surgeons. Traditional training methods have become insufficient for mastering advanced surgical techniques, leading to the integration of VR into surgical education. VR simulations provide a highly realistic and interactive learning environment, surpassing traditional methods such as animal models, films, or electronic-learning. VR has transformed immersive learning by making educational instruction more engaging and motivating. AR further enhances medical education by offering interactive simulations and remote learning opportunities. 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. While VR-based training offers promising supplementary methods, it cannot replace traditional learning techniques for healthcare providers.
- *Surgery:* Immersive systems have proven valuable in surgery, a field that relies heavily on manual skills. VR simulators allow surgeons to practice complex procedures and emergency scenarios in a safe environment, reducing risks to patients and enhancing manual skills under high-stress conditions. In surgery, immersive tools enhance procedural precision with detailed anatomical visualizations. During surgery, AR allows surgeons to enhance their view of the surgical field with digital images, particularly highlighting tumors, and anatomical structures. The use of VR in surgery has become increasingly popular. VR is particularly useful for training in laparoscopic and robot-assisted surgery.
- *Pain Management:* The use of virtual reality for pain relief and stress reduction during medical procedures is becoming an increasingly popular method. The introduction of VR technology in 1998 marked a significant advancement in pain management, demonstrating its efficacy in reducing burn-related pain and managing pain in various conditions. VR is transforming pain management by offering a non-pharmacological approach to alleviate both acute and chronic pain. Engaging individuals in immersive virtual environments, VR diminishes pain perception and discomfort, leading to decreased reliance on pharmaceuticals. 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.
- *Rehabilitation:* In rehabilitation, VR, AR, and MR are used as assistive rehabilitation tools for patients who suffer from stroke and severe burns. Immersive technology-based rehabilitation allows patients to obtain a more intensive learning and rehabilitation experience by immersing themselves in an enriched practice environment specifically designed for rehabilitation purposes. In stroke rehabilitation, VR has been shown to increase patient motivation and engagement, enhancing adherence to treatment and improving outcomes.
- *Radiology:* VR in radiology offers users an immersive 3D experience through wearable technology. Efforts are currently underway to develop a VR radiology reading room equipped with a fully digital picture archiving and communication system workstation. This technology aims to enhance the accessibility of medical imaging, allowing radiologists to utilize their personalized reading room wherever they are.

- *Mental Health:* Virtual reality has shown promising applications in mental health. Research indicates that virtual reality exposure therapy is as effective as traditional exposure therapy for treating specific phobias, often preferred by patients due to controlled, repeatable environments that help reduce anxiety. VR is effective in treating post-traumatic stress disorder. It is also used in the therapy of children with autism spectrum disorder and attention deficit hyperactivity disorder. Immersive technologies can be easily accepted by children for easing anxiety.
- *Telemedicine:* AR can be particularly beneficial for telemedicine, remote assistance, and patient evaluation. AR shows benefits during remote post-surgical wound assessment.
- *Anatomy:* VR can improve student engagement and understanding of complex anatomy, making it a valuable addition to educational programs, especially when access to physical specimens is limited.

BENEFITS

VR and AR technologies significantly enhance patient experiences and medical training, providing immersive and interactive environments for learning and practice. There are numerous advantages to using VR or AR over traditional therapies. By increasing patient adherence to treatment and improving the quality of care, AR also alleviates the overall burden on the healthcare system. Other benefits include the following [1,18]:

- *Improved Accuracy*: Immersive technologies enhance the precision of medical procedures, reducing the margin of error.
- *Mindfulness Practice:* Using VR with depressed patients can lessen the severity of their depression and self-degradation while enhancing their overall satisfaction. By minimizing real-world distractions and enhancing the sense of presence, VR can facilitate mindfulness practice.
- *Training:* Immersive technology supports learning-by-doing, bridges the theory-practice gap, and improves skills acquisition and transfer. Immersive technology-based training can provide medical professionals with a rich, interactive, engaging, and safe learning experience while emphasizing skills transferability into the clinical setting. Current VR systems have proven to be effective in training nurses to interact with patients and perform various procedures. While VR cannot replace all types of training, such as hands-on procedures requiring tactile feedback, it is effective for procedural algorithm learning.
- *Global Healthcare:* The potential impact on global healthcare practices is monumental. From improving accessibility to specialized medical expertise through AR-driven telemedicine to revolutionizing surgical procedures with VR simulations, these technologies can bridge healthcare gaps around the world.

CHALLENGES

In spite of their potential, challenges remain regarding the implementation and integration of immersive technologies into existing medical practices. 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. Other challenges include [1]:

- *Ethical Concerns*: In vulnerable patient groups, such as those who are critically ill, there are ethical concerns surrounding the use of VR/AR technologies. 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." VR/AR should always enhance, rather than replace, the human elements of healthcare, ensuring that advancements are both ethically sound and aligned with patient-centered care.
- *Integration:* 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.
- *Compatibility:* Compatibility issues between VR headsets and electronic health record (EHR) systems can hinder adoption. For example, VR headsets that are not compatible with hospital EHR infrastructure may be useless.
- *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. Interestingly, cybersickness may be more pronounced in AR than in VR. AR/VR-related side effects appear to differ across various age and gender groups.
- *Regulations:* Recent updates by the US Food and Drug Administration (FDA) have paved the way for more widespread use of 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.

FUTURE OF IMMERSIVE MEDICINE

Modern medicine is rapidly evolving with the introduction of immersive technologies (VA/AR). Immersive technologies have rapidly emerged as transformative tools in patient care and medical training. These technologies provide advanced capabilities for creating immersive, interactive, three-dimensional environments, unlocking new possibilities for their application in medical practice. Their proven efficacy in managing pain, reducing stress, enhancing rehabilitation, and improving clinical education makes them valuable assets in the medical field. Understanding the needs of medical professionals and patients will be critical to maximizing the impact of these technologies in clinical settings.

Immersive technologies enable realistic simulations, making educational and therapeutic programs potentially more immersive, interactive, and effective. They are transforming medical education by creating interactive and safe learning environments that simulate real clinical scenarios, allowing students and professionals to develop skills without risk to patients. They can enhance learning and improve productivity in medical domain training. 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. The integration of VR and AR in healthcare and medical training presents numerous opportunities for advancing patient care and education.

CONCLUSION

Immersive technology is a term that describes VR, AR, and MR technology as a whole. As immersive technologies continue to advance in the medical sector, their integration into healthcare holds great promise for advancing both therapeutic interventions and professional training. These technologies are rapidly gaining traction in healthcare, offering transformative opportunities for patient care, medical education, and therapeutic interventions. They not only enhance the motivation of trainers but also provide more effective training and education in the field. VR is becoming increasingly popular in healthcare settings for diagnostic and therapeutic purposes. It is increasingly recognized as a valuable tool in undergraduate medical education. It offers immersive, interactive environments that support experiential learning and skill development. MR technologies are well established in medical practice, enhancing diagnostics, treatment, and education.

AR, VR, and MR each continue to reshape healthcare in unique ways, with the promise of improving training methods, enhancing the patient experience and contributing to more effective medical practices. Physicians, patients, and caregivers can enlist AR/VR to help them prepare for, or perform, certain treatments or procedures. More information about immersive medicine can be found in the books [19-24].

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Figure 1 A representation of immersive technology [3].

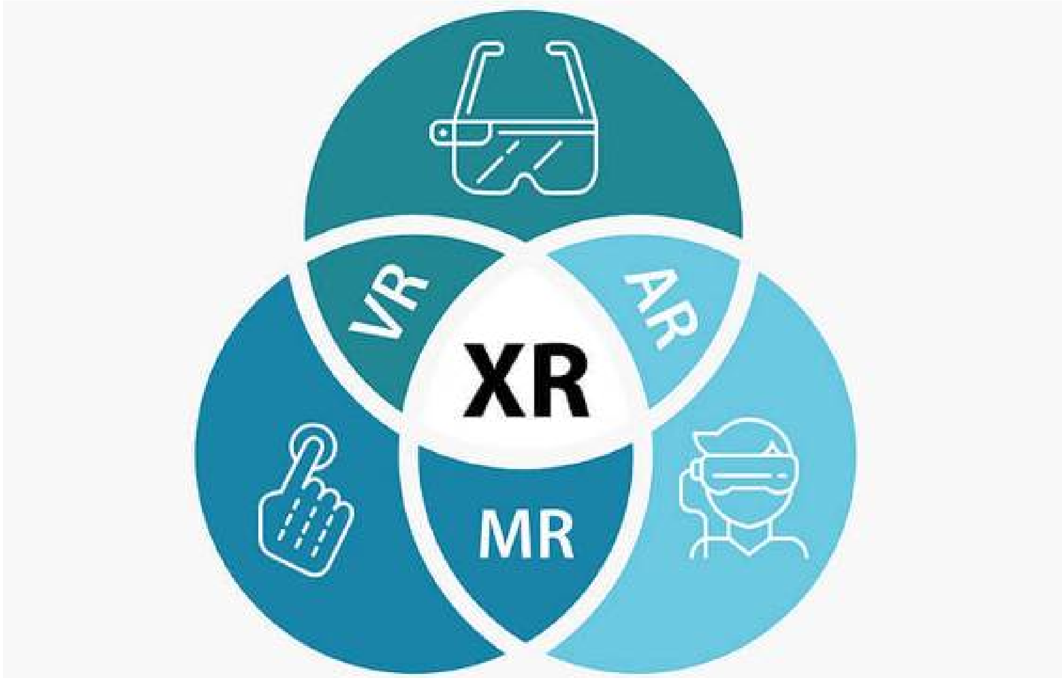

Figure 2 Extended reality (XR) includes AR, MR, and VR [6].

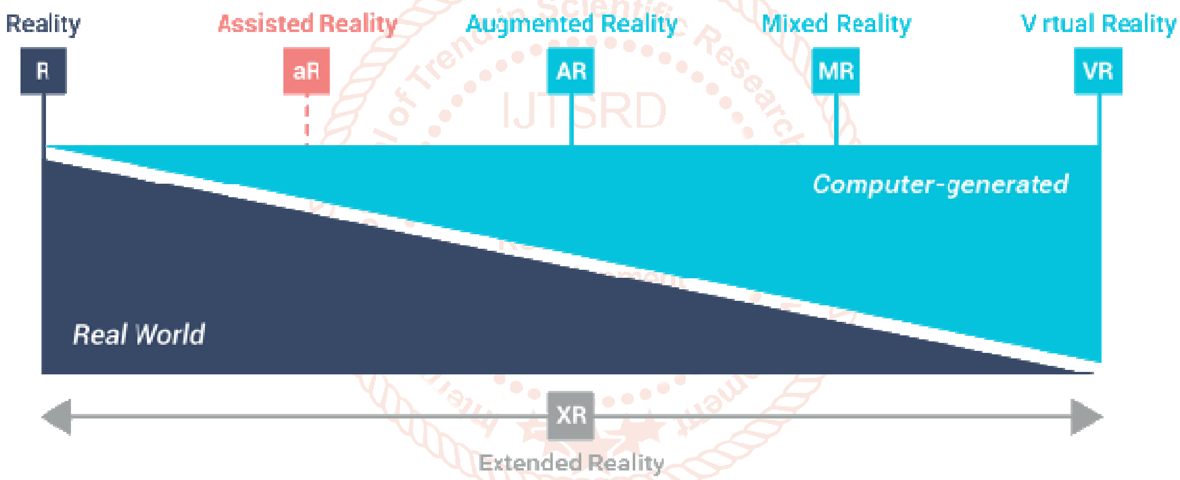

Figure 3 The XR spectrum [7].

Figure 4 A head-mounted display [9].

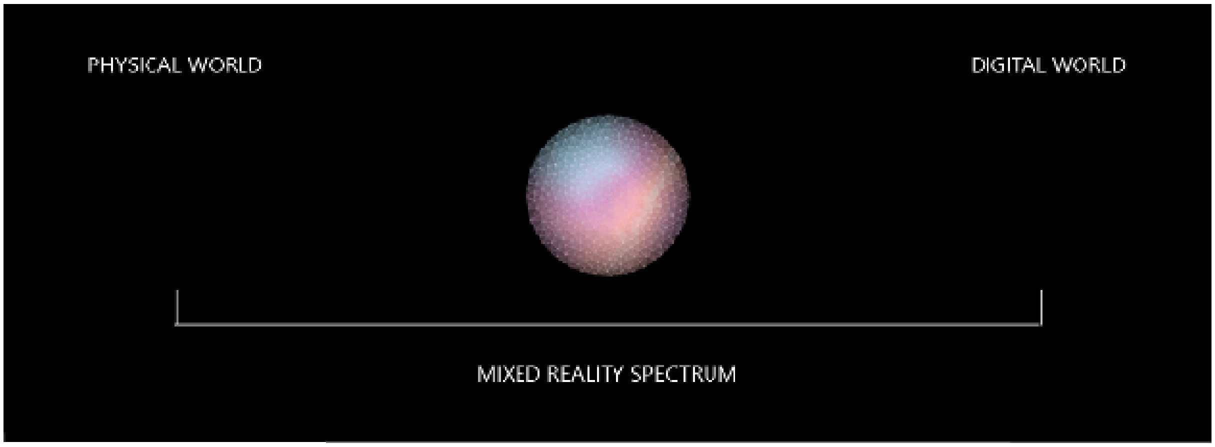

Figure 5 Mixed reality is a blend of physical and digital worlds [11].

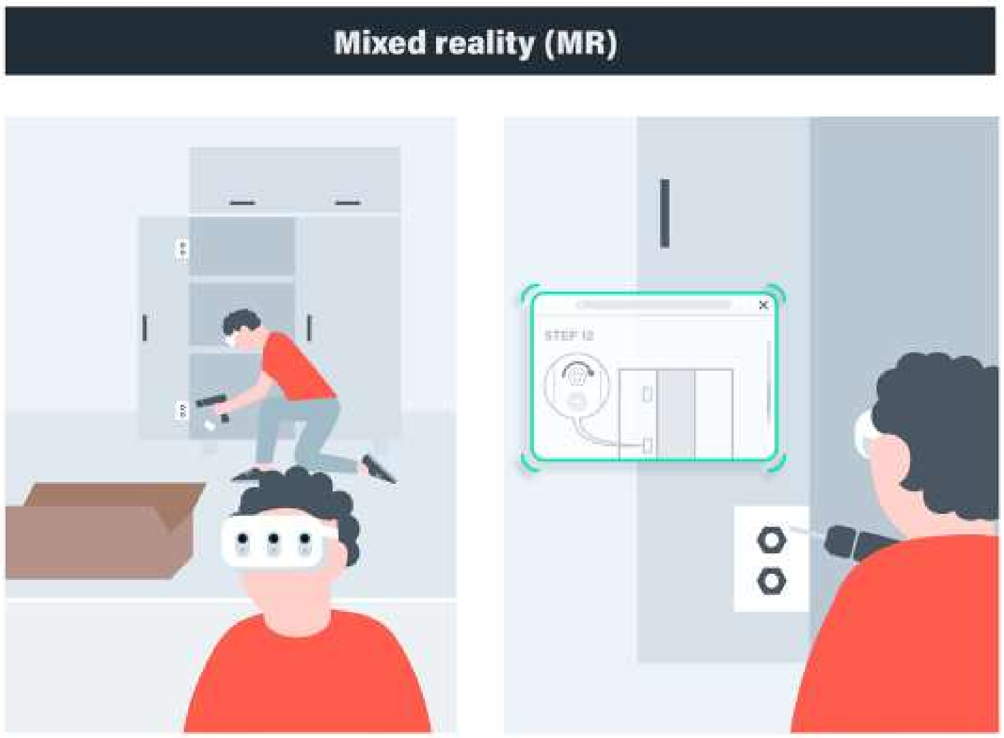

Figure 6 Mixed reality [12].

Figure 7 A worker wearing an assisted reality device [14].

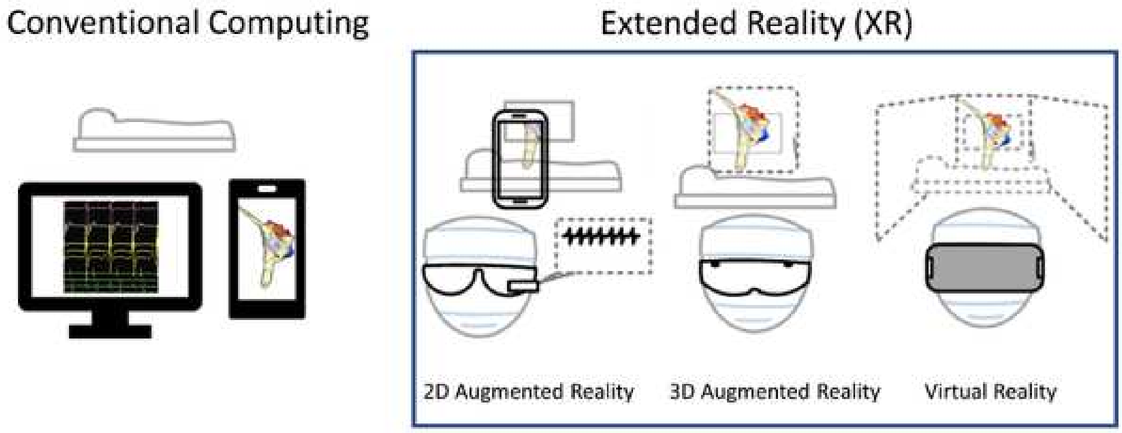

Figure 8 Comparing conventional computing with extended reality [15].

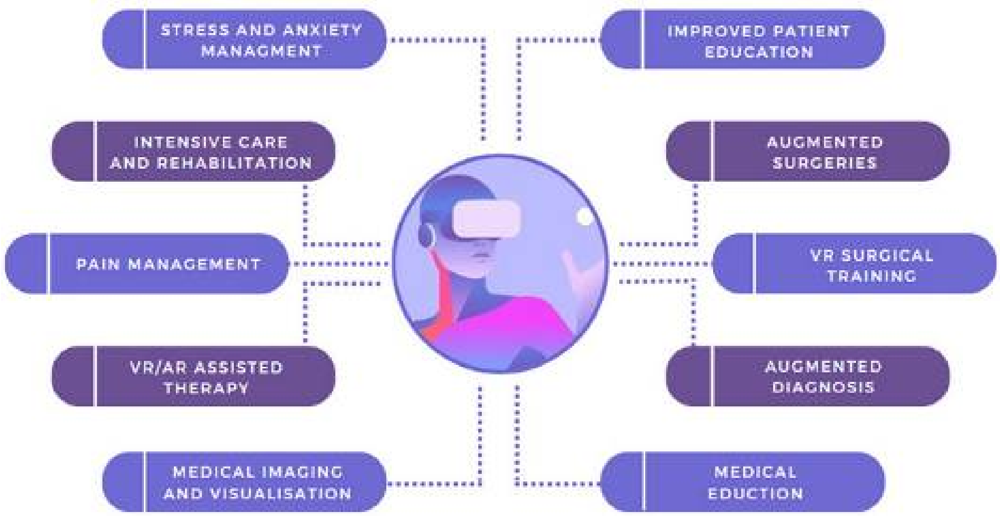

Figure 9 Virtual and augmented reality applications in healthcare [1].

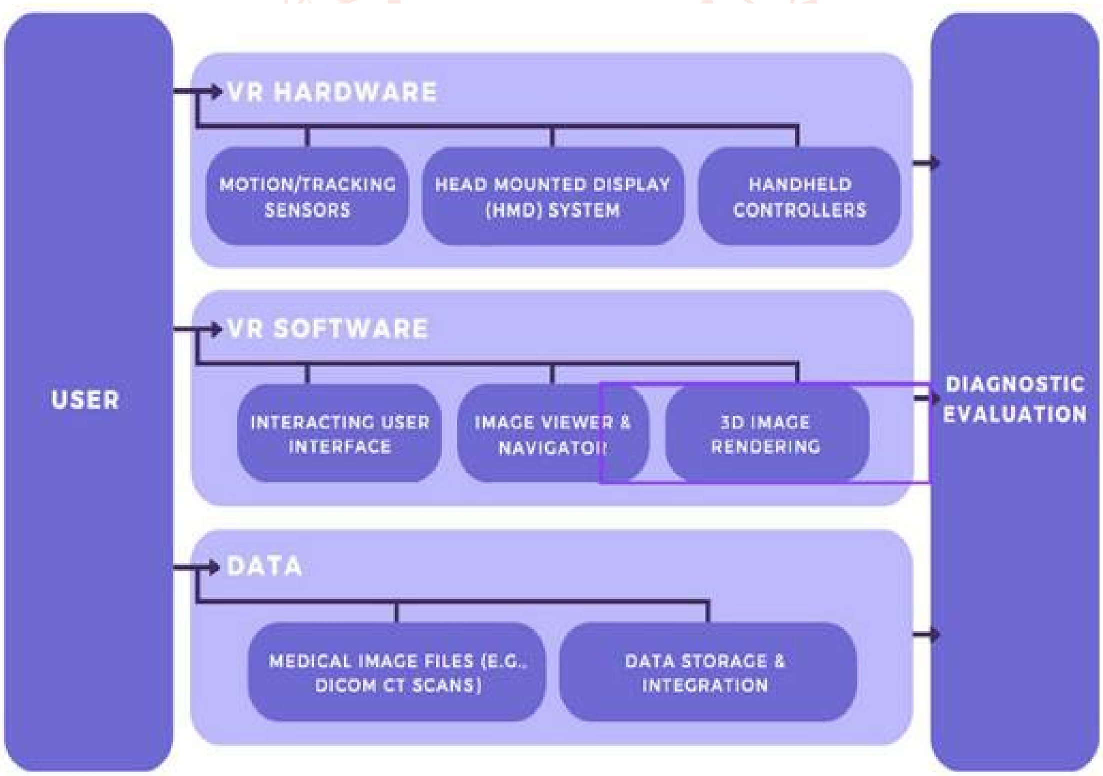

Figure 10 How VR hardware and software are utilized to reach diagnosis [1].