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AUGMENTED AND VIRTUAL REALITY IN RADIOLOGY: A COMPARATIVE ANALYSIS OF CLINICAL APPLICATIONS AND OUTCOMES

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ABSTRACT

The accumulation of augmented reality (AR) and virtual reality (VR) in radiology is transforming procedural planning, medical imaging, and diagnostics. These state of art technologies offer immersive and interactive experiences, enhancing precision in interventional radiology, medical education, and surgical planning. AR aids with vascular intervention, tumor localization, and precise medicine by overlaying imaging data onto the patient's body in real-time. Virtual reality (VR) offers 3D holographic recreation of complicated anatomical structures to enhance medical training and diagnostic precision.

Despite of proficient benefits of AR and VR there are many drawbacks of their usage in radiology, for example hindrances in the smooth integration with current workflows, high installation costs, and hardware problems. As AR is best suited for real-time procedural guidance, in contrary VR is excellent for education and in-depth image analysis. AR/VR both could be efficient in reducing diagnostic errors, refining strategies for surgeries, and patient outcomes. For amplifying the usage of AR/VR in clinical applications there is need of development in AI integration, user-friendly designs, and cost-effective solutions. To authenticate long term benefits, large-scale clinical studies are essential, while efforts to enhance accessibility will play crucial role in determining the widespread adoption. Evolution in AR and VR has potential to redefine radiology, eventually bridging the gap between technology and patient-centered care. Both technologies can improve surgical techniques, decrease diagnostic mistakes, and enhance patient outcomes.

The research and development in AI integration, user-friendly designs, and affordable solutions can lead to the expansion of their clinical application. The efforts to improve accessibility can lead to wide recognition of these technologies, while vast clinical research is required to confirm their long-term advantages. As AR and VR develop further, they could revolutionize radiology by bringing technology and patient-centered treatment together.

KEYWORDS: Virtual Reality (VR), Radiology, Medical Imaging, Procedural Planning, Interventional Radiology, Surgical Planning

INTRODUCTION

Imaging the human body for medical diagnosis and treatment dates back for some time now and has become revolutionized since its origin. The role of radiology has rapidly evolved since Wilhelm Rontgen discovered x-rays in 1895, to include advanced imaging

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modalities, such as computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET).(1–4) These techniques revolutionized medical diagnostics by providing insight into interior structures without the need for invasive procedures, leading to greatly improved clinical decision-making.(5–7) The field has been substantially changed by technological advances, such as digital imaging that has displaced film-based approaches and artificial intelligence (AI), which now does some of the picture interpretation. With the incorporation of new technology into radiology, the focus is now on tools to help improve visualization, accuracy, and interaction, allowing for innovative solutions such as augmented reality (AR) and virtual reality (VR).(8–11) It all represents a sweeping shift, allowing clinicians to engage with imaging data in new ways.

AR and VR are exciting technologists, especially in radiology, as technology is shining new in health care.(10,12,13) **AR** presented the virtual elements (for example, interacting with 3D anatomical structures, or imaging data) upon the real world that brought to an improvement of user perception of its environment.(12,14–16) AR does that by integrating digital information with the physical environment supported by devices such as head-mounted displays (HMDs), smart glasses and mobile platforms.(17) **VR** on the other hand, submerge users in a fully virtual environment, isolating them from the real world. It offers unparalleled visualization of anatomical and pathological details by enabling the users to explore and manipulate 3D datasets.(18–21) Both AR and VR seem to great promise in radiology, by offering novel approaches to diagnostic imaging, medical education, and interventional procedures.(22–24)

AR and VR's applications in radiology have the capability to address key challenges in the field, for example enhancing spatial understanding of complex anatomy and also enhancing procedural precision.(25–28) In diagnostic imaging, AR provides real-time guidance for clinicians during interventions facilitates by superimposition of imaging data onto patients. In training and education, VR enables radiologists to practice interpreting images or performing virtual procedures without risk to patients by offering a safe and captivating environment.(25–27) In surgical planning, surgeons and radiologists collaborates using 3D visualizations of patient-specific anatomy using AR and VR, to improve preoperative planning and patient outcomes. As radiology becomes more twisted with precision medicine, AR and VR offer tools that can improve diagnostic accuracy, reduce procedure times, and enhance patient safety.(28–31) Therefore, understanding the comparative strengths and weaknesses of these technologies is important for maximizing their impact in clinical practice.(32–34)

Objectives

This narrative review explores and compares the applications of augmented reality and virtual reality in radiology. Both AR and VR offer transformative potential, but their specific advantages, limitations, and clinical outcomes remain areas of ongoing exploration. This comparison can provide valuable insights into their respective roles in advancing radiological practices and guide future integration into healthcare systems. This review discuss the current clinical applications of AR and VR in radiology, their impact diagnostic accuracy, procedural outcomes, and patient safety, their comparative advantages and limitations in clinical and educational contexts, Which technology demonstrates better cost-effectiveness and ease of implementation in radiological practice, future directions for these technologies in radiology, and their integration be optimized. This review aims to provide a comprehensive understanding of the role of AR and VR in radiology, offering evidence-based recommendations for their adoption and future research.

Overview of Augmented Reality (AR) in Radiology

Augmented reality (AR) technology superimposes digital data, such as real-time data, annotations, or 3D images, onto the user's physical surrounding to create interactive and user rich experience.(35,36) It combines the real and virtual worlds, allowing simultaneous interaction between them. In radiology, AR enhances visualization by projecting imaging data (e.g., CT, MRI, or ultrasound scans) onto the patient's body or a physical surface to facilitate better spatial understanding of anatomical structures and pathological changes.(37,38) For example, for accurate localization during interventions or surgeries, AR enables radiologists and clinicians to see a 3D display of a tumor overlaid on a patient's body.(31,38,39)

A proper AR system consists of different parts like cameras and sensors which compile information from the physical environment to match virtual and physical content. Processors are the other part which offers real-time digital overlay rendering and spatial data analysis.(35,36) Display devices which use mobile devices, smart glasses, or head-mounted displays (HMDs) to provide AR material to the user.(35,36) Software algorithms are also the most important part that compile imaging data, process sensor inputs, and ensure accurate virtual object alignment (registration) with the real world.(40)

AR-enabling technologies

AR applications in radiology require a number of devices and technologies, including head-mounted displays (HMDs) like Magic Leap and Microsoft HoloLens provide immersive augmented reality experiences, allowing users to interact with digital overlays without using their hands for other tasks.(41,42) Google Glass and other lightweight smart glasses can display simple augmented reality content, making them suitable for diagnostic or educational contexts. AR software-enabled smartphones and tablets offer portable and convenient solutions for tasks like surgical planning and picture review.(41,43) Optical or electromagnetic tracking methods ensure accurate alignment of virtual objects with the patient's anatomy.(41–43)

Uses in Clinical Settings

1. ***Interventional Radiology***

To guide minimally invasive procedures, imaging technologies such as fluoroscopy, CT, or ultrasound are being used frequently in interventional radiology (IR).(43,44) AR adds a new dimension by providing real-time, three-dimensional overlays of imaging data directly onto the patient's body, significantly improving accuracy and efficiency. During biopsies, AR can help radiologists precisely locate and target lesions by projecting 3D imaging data onto the patient.(44) This increases diagnostic yield while cutting down on procedure time. AR also helps in catheter placement as during vascular interventions, it enables real-time visualization of blood vessels, guiding catheter navigation with greater precision. AR can assist in tumor ablation because in procedures like radiofrequency ablation, AR helps radiologists visualize the tumor's boundaries and adjacent critical structures, minimizing damage to healthy tissue.(9,45)

AR-guided procedures decrease reliance on fluoroscopy which reduces radiation exposure for both patients and clinicians ultimately improving procedural accuracy.(46)

2. ***Surgical Planning***

AR is being utilized in radiology more and more to help surgeons with pre-surgery planning and intraoperative guidance, especially in cases involving complex anatomy.(39,47) AR aids in preoperative visualization as it enables the creation of patient-specific 3D models

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of organs, tumors, and vascular structures, allowing surgeons to study the anatomy in detail before the operation. AR, for instance, can be used to project the vascular anatomy of the liver during surgery, assisting in the planning of resections while maintaining healthy tissue.(47) It is also helpful for intraoperative guidance as AR systems can overlay imaging data onto the surgical field, so it guide incisions and instrument placement during surgery.(40,48) This is especially helpful in minimally invasive procedures where there is little opportunity for direct visualization. In Orthopedic surgeries AR increases the surgical precision while providing aid in bone alignment and implant placement, reducing the requirement for preoperative CT scans.(12,48) Better patient outcomes, shorter procedure times, and a lower risk of complications have all been linked to AR-driven surgical planning.(49)

3. ***Education and Training***

Augmented reality has turned up to be a significant tool with regards of medical education and training, particularly in radiology, where understanding of intricate anatomical structures and imaging data is crucial.(17,25) Teaching anatomy by using augmented reality applications, students can view 3D models of somatic structures superimposed on cadavers or real mannequins. Such methods increase the chances of enhancing spatial memory and comprehension.(50) Radiological interpretation augmented reality platforms offer trainees immersive environments with real-time feedback and annotations, in which they can practice interpreting imaging studies.(27,50) Procedural simulations through AR-based simulators enabled radiologists to rehearse secure and lifelike training settings like catheter insertions and needle biopsies, by image-guided procedures.(27,35,51) Unlike traditional simulators, AR enables trainees to interact with real-world objects while visualizing virtual overlays, bridging the gap between theory and practice. Training programs and educational institutions have reported that AR has improved procedural skills, learner engagement, and comprehension of complex concepts. (27,35,51,52)

Advantages of AR in Radiology

1. ***Enhanced Precision in Interventional Radiology***

As compared to conventional imaging methods augmented Reality (AR) has brought revolution to interventional radiology by amplifying the accuracy of procedures.(43) For instance CT or ultrasound, they provide 2D representations of 3D structures, which make clinicians to interpret the spatial relationships of anatomical features by mind mapping.(43,45) On the other hand AR removes this complication of mind mapping by directly superimposing 3D imaging data onto the patient's body. This allows internal structures to be seen in real-time.(15,45) AR provides real time guidance which makes it easier to precisely navigate tools during procedures like tumor ablations, catheter insertions, and biopsies. The possibility of harming healthy tissue declines with AR, as during liver tumor ablation AR projects the tumor's borders and nearby essential structures which give an accurate tumor location.(9,44) AR offers decreased radiation exposure by providing extremely accurate spatial localization which reduces the need for fluoroscopy, which eventually lowers radiation exposure for both patients and medical professionals. The idea that AR-guided interventions improve patient outcomes is supported by many researches.(9,50,53) As it decreases procedure time and increases accuracy of outcome data eventually leading to enhanced efficiency.(46)

2. ***Improved Understanding of Complex Anatomical Structures***

Among the prime advantages of AR in radiology the most significant is that it improves the visualization of intricate anatomical relationships.(54,55) As in radiology the understanding of the spatial arrangement of structures depends on the precise diagnosis and treatment planning. Conversion of 2D imaging data into interactive 3D models helps surgeons and radiologists to better understand complex anatomical patterns.(25,55,56) For instance, in cardiac imaging AR helps with preoperative planning via offering a detailed view of the heart's chambers and vessels, to deal with conditions like congenital heart defects. AR enables personalized treatment plans by allowing physicians to use each patient's unique imaging data to develop customized anatomical models.(54,56) AR fosters better communication among multidisciplinary teams by projecting imaging data in 3D space, as collectively all members can interact with and interpret the data.(25,55)

Limitations of AR

1. ***Challenges in Hardware Integration***

Instead of the extreme potential of AR, there are a lot of technical obstacles in this area, particularly when it's about integrating and implementing hardware systems in clinical settings.(44,57) Cost and complexity could be a challenge as advanced AR devices like head-mounted displays (HMDs) and tracking systems are expensive and require specialized training, limiting their widespread adoption in resource-constrained environments. AR could be less useful for prolonged operations and surgeries.(44,57) It's because of its heavy or unwieldy headsets, which can make user uncomfortable if wore for extended periods of time. Seamless integration of AR systems with already-existing imaging devices, like CT or MRI scanners is crucial. In spite of that, it is still difficult to ensure compatibility across various platforms and devices.(58)

2. ***Dependence on Accurate Alignment of Virtual and Real-World Data***

The clinical utility of AR in radiology is severely limited by its reliance on accurate spatial alignment (registration) between virtual overlays and the real world; any misalignment raises the possibility of diagnosis or treatment errors. Attaining the exact alignment between virtual object and real world anatomy can be technically difficult, mainly in dynamic environments, where patient movement or physiological changes (like breathing) can cause errors in registration.(44,57) AR systems need to process and render data in real time, to guarantee effortless and precise overlays of image. Latency problems can result from data processing delays which make virtual objects, lag or not line up with real-world structures. AR dependence on high-quality imaging data, as the quality of the input data from imaging modalities determines how effective AR is. Poor image resolution or artifacts can degrade AR performance and reduce its reliability.(44,57)

Virtual Reality (VR) in Radiology

Virtual Reality (VR) immerses users in a fully synthetic, computer-generated environment designed to replicate real-world or abstract scenarios.(59,60) VR totally replaces the user's environment with a virtual space, in contrast to Augmented Reality (AR), which superimposes virtual elements onto the real world.(36,60) Virtual reality (VR) tracks the user's head, hand, and body movements to create an engaging experience, which provides real-time visual, aural, and occasionally tactile responses. This interaction is enabled by advanced hardware and software integration. In radiology, virtual reality (VR) is helping to improve procedural planning by offering an interactive environment for analysis, interpretation and instruction. This enables users to manipulate 3D medical imaging data (such as MRI or CT scans) using handheld controllers or motion-sensing technologies.(41,61,62) Virtual reality (VR) is being used to visualize intricate anatomical structures, interpret diagnostic imaging, and simulate radiological workflow which will also help in making better decisions.(41,62,63)

VR-Enabling Technologies

Developments in hardware and software have fuelled the broad use of virtual reality in radiology: Head-Mounted Displays (HMDs)**,** these gadgets allow submerging oneself in virtual worlds for instance, the Oculus Rift, HTC Vive, and Meta Quest. Such HMDs provide high resolution images which give radiologists a more detailed and interesting experience with a broad field of view.(41,57,61,62,64) In order to manipulate data more precisely radiologist use motion tracking technologies like Leap Motion and haptic gloves, which allow them to interact with 3D reconstructions through gestures.(65,66) Computing power is important to support flawless processing of medical imaging data and to create interactive VR environment, therefore modern GPUs and real-time rendering software (e.g., Unity, Unreal Engine) are used.(20,67) In order to enable radiologists to directly import and visualize imaging datasets in virtual space, VR platforms can integrate with Picture Archiving and Communication Systems (PACS).(58)

Uses in Clinical Settings

1. ***Diagnostic Imaging***

By reshaping conventional 2D imaging sections into interactive 3D reconstructions, virtual reality (VR) has boosted radiologists' comprehension and analysis of imaging data. Intricate anatomical areas, like the brain, spine, or vasculature, radiologists can explore 3D models of these structures, which gives them a more thorough grasp of spatial relationships.(57,68) This is particularly useful when diagnosing intricate conditions like tumor mapping or congenital anomalies. VR increase diagnostic accuracy because radiologists can examine imaging data with the help of virtual reality (VR) from different angles, this decreases the chances of interpretative errors that usually occurs in plane 2D imaging view.(1,69,70) Virtual reality (VR) can provide a comprehensive view of patient’s health, as it combine information from different imaging modalities (such as CT, MRI, and PET) into a single virtual model.(1,25,56)

2. ***Radiology Workstations***

Virtual reality has converted traditional radiology workstations into enticing environments, which allows more sophisticated and effective image analysis. VR enable

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radiologists to "walk into" the imaging data, allowing them to examine lesions, fractures, or vascular anomalies within 3D space.(1,56,68,71) Radiologists, surgeons, and other medical professionals can collaborate through VR-based workstations. So, multiple users can interact with the same dataset at once. VR platform increases the speed and precision of diagnosis while interpreting complex data, relatively because of ease of use that lessens the mental stress.(72)

3. ***Education and Simulation***

Use of virtual reality in education and training has become popular these days, as it provides realistic and hand-on learning environment to medical professionals. VR-based platforms that mimic real-life radiological work flow, by using it students can get practical skills in a risk free environment.(71,73,74) Students can practice analyzing multi-slice CT scans or performing needle biopsies under imaging guidance. By engrossing users in a 3D model of anatomical structures virtual reality (VR) improves the learning of intricate ideas like organ systems or the course of disease.(52,69,71,75) Difficult clinical situations, like spotting minute fractures or determining uncommon diseases are mimicked in virtual reality simulations, providing users the opportunity to practice making decisions under pressure. By using virtual reality (VR) practicing radiologists can keep abreast of developing technologies and methodologies, to stay up-to-date with current industry developments.(2,35,52)

Advantages of VR in Radiology

1. ***Immersive Visualization for Complex Diagnostic Tasks***

VR allows radiologists to interact with complex anatomical and pathological features in a fully immersive 3D environment. VR applications, for example, increase diagnosis accuracy and treatment planning by allowing for in-depth inspection of tumors, fractures, and vascular anomalies from numerous perspectives.(68,70) By merging CT, MRI, and PET scans into a unified 3D model, virtual reality (VR) devices might help radiologists discover minor anomalies and better grasp spatial relationships.(1,4,76) Virtual reality's immersive visualization is particularly beneficial for complex preoperative planning. Radiologists and surgeons can virtually practice procedures to identify potential issues and enhance techniques.(46) Virtual reality systems encourage interdisciplinary teamwork by allowing radiologists and other medical specialists to collaborate in real-time. VR is a valuable tool for case discussions and decision-making since it allows numerous users to interact with the same dataset at the same time.(59,61,64)

2. ***Improved Educational Opportunities in Medical Education***

Virtual reality creates realistic clinical environments, providing medical students with practical experience. In a virtual environment, trainees can perform diagnostic and interventional procedures while honing their abilities without jeopardizing patient safety. Virtual reality (VR) can help practitioners and students understand complex relationships and structures in human anatomy, such as the organization of tissues, organs, and arteries.(52,73,74) VR-based training packages are effective for teaching technical skills such as interpreting images and guided needle placement. Virtual reality systems promote customized learning by adjusting scenarios according to the learner's proficiency level.(2,27,52,77) That boosts confidence and memory retention. VR can also become source of consistent development in professional, educational, and technological fields.(58)

Limitations of VR

1. ***High Costs and Resource Requirements***

Advanced VR systems, such as high-resolution headsets (e.g., Oculus Rift, HTC Vive) and haptic feedback devices, often come with high acquisition and maintenance costs. This may prevent smaller healthcare facilities with tighter budgets from using VR. To successfully integrate VR in radiology, a strong computational infrastructure is needed, including strong GPUs, substantial data storage options, and smooth interaction with current imaging systems like PACS.(44,57) Not all institutions may be able to afford this level of infrastructure. Training of staff members is important in order to use VR systems efficiently and also cost money which increases the total budget.

2. ***Isolation of Users from the Clinical Environment***

Virtual reality (VR) separates users from the actual clinical setting, even though it immerses them in a virtual environment. It can lead to reduction in situational awareness, most probably in cases when VR is utilized for teamwork or patient interactions.(44,57) As opposed to AR, which superimposes data on the actual world, VR replaces it entirely. This lack of real-time interaction between patient, medical equipment, and coworkers as AR could be a potential drawback.(72) VR use could impair user performance and prevent broad

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adoption in clinical workflows. Because long-term exposure to VR may result in motion sickness, visual fatigue, or discomfort.(72)

Table 1: Comparison of Augmented Reality (AR) and Virtual Reality (VR) in Radiology

Feature	Augmented Reality (AR)	Virtual Reality (VR)
Definition	Overlays digital elements onto the real world	Fully immersive digital environment
Key Devices	AR glasses, smartphones, tablets	VR headsets, motion controllers
Applications	Surgery guidance, education, real-time imaging	Radiology training, simulation, treatment planning
Advantages	Enhances real-world interaction, real-time updates	Fully immersive experience, detailed visualization
Limitations	Can be expensive, requires precise alignment	High cost, may cause motion sickness

Comparative Analysis of AR and VR in Radiology

1. ***User Experience***

Augmented reality (AR) enables radiologists to work with tools in the real world by the fusion of real and virtual-world elements, while superimposing digital data, like imaging data, on the patient or equipment. This leads to improves situational awareness, particularly in surgical guidance and interventional radiology.(26,78) On the contrary VR, transport users into an artificial environment offering them a fully immersive experience. Even though VR makes it possible to concentrate more intently on imaging data or surgical simulations, but it separates users from their immediate physical environment. This leads VR to make it less appropriate for tasks that call for multitasking or direct patient interaction.(13,73)

Procedures like catheter placements, biopsies, and intraoperative imaging that call for real-time decision-making and direct patient interaction are better suited for AR. In stressful dynamic clinical settings AR is a useful tool as it can superimpose digital data on actual objects.(26,79) On the other hand immersive qualities of VR make it ideal for non-clinical uses for instance education, training, and intricate diagnostic testing. Radiologists can study complex 3D anatomical models in virtual reality (VR) without interruptions, something that might not be possible in a busy clinical setting.(27,80)

2. ***Diagnostic and Clinical Outcomes***

Augmented reality (AR) enhances diagnostic accuracy by directly overlaying imaging data onto patients, enabling real-time correlation between imaging results and physical anatomy. For example, by offering real-time visual feedback, AR has enhanced the accuracy during vascular interventions and tumor ablation.(81,82) VR's immersive 3D visualization of imaging data has made better diagnostic comprehension possible. For example, while using VR, radiologists interact with volumetric data from CT or MRI scans, which aid them to identify unnoticeable peculiarities and complex pathologies that might have been missed in 2D imaging.(4,9) A study showed that AR-guided liver tumor destruction therapy has higher localization accuracy and lower procedure times as compared to conventional ultrasound-guided techniques.(23,27,83) On the other hand it has been demonstrated that VR-based training programs enhances radiologist's and surgeon's procedural accuracy and skill retention when it comes to surgical planning for intricate craniofacial reconstructions.(58)

3. ***Workflow Integration***

AR adopts perfectly with current radiology workflows as it augments rather than replaces in-person interactions. With AR-enabled smart glasses radiologists do not need to leave the procedure room or go to a different workstation to view imaging data.(84,85) What makes AR easier to adopt is its user friendly interface and compatibility with existing imaging data (e.g., ultrasound, CT, and MRI) without significant interruption. On the opposite side, specialized hardware (such as headsets like the Oculus Rift or HTC Vive) and sophisticated processing power are required for VR in order to render 3D images in real time.(1,39,84) VR demands serious infrastructure improvements, such as powerful GPUs, specialized areas, and strong software integration, might be required to implement VR workstations. Workflow disruption is easier in VR as users' needs transition between virtual and real-world tasks, which lowers capacity in hectic clinical settings.(39,84,85)

4. ***Cost-Benefit Analysis***

Although AR gadgets like smart glasses and head-mounted displays are reasonably priced, integrating them with imaging modalities might necessitate further funding. However, by increasing productivity and lowering complications, AR's improved precision and shortened procedure times can more than make up for these upfront expenses. The high costs of VR hardware and infrastructure are a significant barrier to widespread adoption. (17,36,73,86,87) Additionally, VR requires ongoing expenditures for maintenance, user education, and software upgrades. Smaller radiology departments may find their budgets strained by these costs. AR provides observable clinical advantages, like better patient outcomes and lower procedural risks, which over time may offset its upfront expenses.(68,88,89) AR, for instance, can reduce radiation exposure and shorten procedure times, which can result in long-term savings. The main long-term advantage of VR is its potential to transform radiology research and education. Virtual reality (VR) has the potential to greatly improve medical professionals' skill sets by offering immersive and interactive training experiences, which will ultimately yield better patient care.(72)

Table 2: Applications of AR and VR in Different Radiological Modalities

Radiological Modality	**AR Applications**	**VR Applications**
CT Scan	3D visualization for surgical planning	Virtual simulations for training
MRI	Real-time image enhancement	Full 3D MRI-based training
Ultrasound	Live AR overlays for better guidance	VR training for sonographers
X-ray	AR-assisted diagnosis	Interactive learning modules

Challenges and Limitations

1. ***Technical Challenges***

Both AR and VR technologies rely significantly on specialized hardware, which still has a number of usability and reliability issues despite being extremely sophisticated. Smart glasses, head-mounted displays (HMDs), and other wearable technology must consistently connect to imaging systems and real-time data inputs in order to function in augmented reality. Problems like poor resolution, battery life restrictions, or device malfunctions can affect how well overlays work or how well you can interact with virtual data. Furthermore, the weight, size, or complexity of the operation of these devices may make them impractical, especially in hectic clinical settings. The efficacy of AR glasses decreases if they are used for prolonged time, as they may cause discomfort during lengthy procedures. Using VR can cause various problems that can hinder immersive experiences include motion sickness due to lack of synchronization between head movements and virtual environments or discontinuation in 3D images display. Furthermore, the prerequisites of VR systems like high class setup and calibration before use particularly in clinical settings make it difficult to operate.

One of the main challenges of augmented reality is making sure that virtual information accurately aligns with the real world. While fundamentals of AR is the real-time fusion of physical and anatomical data obtained from the different imaging sources (such as CT, MRI, and ultrasound), minor misalignments can occur due to inaccurate overlays or differences between the two, which could cause mistakes in procedure instructions or diagnosis. So the accuracy of AR overlays becomes even more crucial in high-stakes settings like interventional radiology, where misalignment could lead to complications. In VR the quality of the input imaging data has an immediate impact on how accurately 3D reconstructions in VR work. The virtual model can produce inaccurate depictions of the patient's anatomy by exaggerating any flaws or artifacts in the original scans. For example, errors in a 3D model of a brain tumor could make it more difficult to plan surgery or use it for teaching. Making sure that virtual reality models faithfully capture anatomical details in the real world is therefore a crucial challenge.

2. ***Clinical Implementation Barriers***

Extensive training of radiologists and support staff is crucial, which is one of the major obstacles to integrating AR and VR technologies into clinical practice. Learning AR and VR requires a lot of time and effort because of its complicated software and hardware. The radiologists have to work simultaneously with virtual overlay and physical instruments, so disruption can occur in workflow if they are not aware of AR usage. Users of virtual reality (VR) have to by train them not only to interact with virtual environment but also learn to interpret 3D data, which is different from conventional 2D imaging. So, additional time, money, and devoted teachers are needed to implement VR training into current settings.

Furthermore these settings need frequent updates according to updating hardware and software features which can also make incorporation of these setting even more challenging.

Acceptance of AR and VR technologies could be an obstacle because of reluctance of conventional radiology, particularly by the healthcare workers with established practices as they have to adopt the new technologies, especially if their benefits are not immediately apparent or measurable. Users can show more hesitation to adopt AR and VR in environments where conventional methods (2D imaging) have history of success. Furthermore, if AR and VR are integrated in already existing clinical settings it would disturb the workflow and can create doubtfulness among radiologist and technicians. Also, integration of AR and VR demands extra time and efforts for setup, training, and operation. This could be a barrier particularly in busy hospital environment or imaging centers where immediate clinical benefits are required.

3. ***Ethical and Legal Concerns***

While using AR in radiology the main ethical issue that rises is patient privacy. As real-time imaging data is superimposed onto the patient bodies, AR has to handle patient's private information like scan, tests and surgical plans. If AR is unable to surely encrypt and protect the data, data breaches can occur. For instance, unauthorized people can access confidential patient data if AR system is composed poorly. Additionally, while using AR in interventional radiology personal data is shared across may need to be shared across numerous devices (e.g., AR glasses, patient monitoring systems, and imaging machines). In order to reduce these ethical and legal concerns adherence to patient privacy laws is needed, such as the General Data Protection Regulation (GDPR) in Europe or the Health Insurance Portability and Accountability Act (HIPAA) in the United States.

Ethical and legal issues have more importance in terms of data security and VR stimulations, particularly with data being used for training and education. In order to create 3D models for surgical planning or diagnostic training VR use real patient data this imposes risk to data atomization and protection and if this data is not managed appropriately it may result in legal and regulatory infraction. Moreover, in VR accuracy to stimulated scenarios in clinical settings can be a concerning question. Inadequate data security measures may expose the integrity of the training data, which could affect the realism and effectiveness of VR-based educational tools. For example, a VR surgical simulation's 3D data could mislead medical trainees and have an impact on their learning outcomes and subsequent clinical judgments if it is tampered with or compromised.

Future Directions

1. ***Innovations in AR and VR Technologies***

For further shaping the future of augmented reality and virtual reality in radiology the rapid advancements in hardware and software will play a prime role. With new tools like lightweight, more ergonomic glasses and headsets AR and VR systems are becoming easier to use and more accessible in clinical settings. For example, in order to enable AR for more precise and efficient real-time guidance during interventions like surgeries, biopsies, and catheter placements the creation of AR glasses with enhanced field of view (FoV) and augmented vision capabilities is required. In order to enhance captivating experience of radiologists with VR, developments in haptic feedback devices and multi-sensory simulations in the virtual reality space are anticipated, to make it easier for radiologists to interact with 3D anatomical models. High-resolution imaging VR platforms can enable better visualization of somatic structures which could eventually lead to more accurate diagnosis. There is probability that the new generation of AR/VR will allow the integration of images from other modalities like functional MRI or PET scans. That will provide more detailed pictures to for diagnostics eventually leading to better treatment planning and diagnostics accuracy.

One powerful tool that can advance AR and VR applications in radiology is artificial Intelligence (AI), which can increase diagnostic precision leads to automate data analysis, and enhance the viewing experience of medical images by incorporating AI-driven algorithms, such as deep learning models. In virtual reality simulations, for medical training and planning, AI may be used, in order to segment anatomical structures in 3D models, which could allow accurate and customized virtual environment leading to improve radiologists' training results. Moreover, in AR artificial intelligence AI can assist system in improving image alignment, tracking, and object recognition in real time. These AI algorithms in AR glasses and headsets could help in automatically adjusting virtual overlays with patient’s anatomy based on continuous tracking and updates from imaging systems. This integration of AI has the potential to improve procedure precision, decrease human error, and boost workflow efficiency in radiology departments.

2. ***Expanding Clinical Applications***

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With development of technologies AR and VR influence in radiology is continuously increasing, such as telemedicine and remote diagnostics. With growth in telemedicine, radiologists can use augmented reality AR to remotely give instruction for procedures in real-time from a distance. AR system can help local doctor or technicians in making decision by projecting real-time anatomical illustrations onto the patient body typically during an ultrasound or biopsy. Also remote assessment of a medical team by a senior radiologist is also possible due to this technology. On the other hand, VR also have ability of remote assessment with the representing data in 3D immersive environment enabling radiologists to analysis data and diagnose without being available on site. VR have potential for quicker diagnosis, by enabling remote modification and examination of data from CT scans or MRI particularly in places where imaging specialists are not available. VR also have potential for clinical trials with centralized VR system to connect professionals from remote areas for communal diagnostic discussions and analyze imaging data from a range of sources.

3. ***Enhancing Accessibility***

The high cost of the necessary hardware and software is one of the main obstacles to the broad use of AR and VR in radiology, especially in environments with limited resources. But as AR and VR technologies advance, there is an increasing chance to cut costs with software-as-a-service (SaaS) models, cloud-based VR platforms, and more reasonably priced hardware possibilities. This could make it easier for institutions in low- and middle-income countries (LMICs) to enter the market. To improve the accessibility and cost issue, the designing of mobile-based augmented reality applications able to run on both smartphones and tablets, this alternative would be beneficial for radiologists, teachers, and other medical personnel in areas with limited resources. Another important strategy to bring AR and VR in the areas where access to high-end imaging equipment is confined is to incite cooperation between government agencies, tech firms, and public health groups in order to sponsor the adoption of these technologies. Furthermore, if efforts of integrating AR and VR into telemedicine gets recognition it will help radiologists to use advance tool without requiring expensive infrastructure. This initiative could expand the scope and influence of radiology services in underprivileged areas that could guarantee fair access to medical care and enhance patient outcomes.

4. ***Research Gaps and Opportunities***

There are much more areas is available for research in radiology AR and VR, like research on combining these tools with new technologies like molecular imaging or AI-powered image identification which can create more advance instrumentation and diagnostic technique. There is limited research on application of AR/VR in radiology and their impact on efficiency, quality of care, and patient. More research including what AR and VR can achieve, routine radiology workflows particularly in busy hospital environments, remains an area to be explored. Another avenue of AR and VR that is possible in radiology — but not talked about enough — is the address of mental health needs stemming from medical imaging use, such as when radiology professionals are under stress during busy shifts performing high-stakes procedures, or patients are experiencing anxiety during imaging sessions. Virtual reality can provide patients with peaceful, immersive environments while undergoing diagnostic imaging, which may help ease the psychological burden of imaging procedures.

Limited large-scale clinical studies have been performed to compare the efficacy of AR and VR in real radiology laboratories, one of the primary literature gaps. Most of the current evidence is limited to controlled trials, simulations, or small samples that may not capture the complexities of everyday clinical care. Well powered comparative studies that assess AR and VR effects on workflow efficiency, patient outcome, and diagnostic accuracy in a variety of clinical settings are needed. Longitudinal studies are also needed to evaluate longer-term impacts of AR and VR on innovative radiology teaching (such as skill retention and decision-making capabilities). Digging deeper into the potential cost savings associated with AR and VR technologies could provide more measurable data to bolster decision-making at healthcare organizations. This form of research would facilitate extensive adoption of AR/VR technologies to radiology clinics and departments all over the world.

Conclusion

As AR and VR technologies continue to develop, they will shape the future of radiography. Given the advances of hardware, the integration of AI, and the push for novel clinical applications, AR and VR have the potential to render radiography a more accurate, accessible, and efficient field. However, the prevention of high costs, technical hurdles, clinical barriers, and research gaps can make it a widely used process. This approach explored the potential role of both Augmented Reality (AR) and Virtual Reality (VR) in the field of radiology. These technologies have shown potential applicability in many therapeutic scenarios, such as diagnostic imaging and interventional therapies. Augmented Reality (AR) has been demonstrated to be useful in interventional radiology, either by providing the ability to see imaging data overlaid onto the area of interest in real-time guidance of treatments, such as during biopsies, catheter insertion, and tumor ablation, demonstrating its potential in surgical planning, providing 3D visualizations of patient-specific anatomy, as in education aiming to enhance medical professionals learning experiences via interactive and immersive anatomical and procedural simulations. Virtual Reality (VR), conversely, is a specialized tool for provided three-dimensional immersive renderings of complex anatomy that allow the radiologists to explore diagnostic images from different perspectives. VR also finds applications in radiology workstations for advanced image analysis and interpretation and in medical education by simulating real-world clinical situations for training purposes. Although these clinical and instructional advantages are significant, they also face challenges due to technology limitations, capital costs, and clinical deployment. A comparison developing on AR and VR confirms that both have unique roles within the clinical setting. While VR is an immersive environment and good for diagnostic interpretation and training, AR's real-time linkage to the real world make it more appropriate for surgical guidance and interventional procedures. However, it is important to take into account the need for further refinement of these current technologies to fully leverage their potential advantages to clinical workflows and patient care.

The incorporation of AR and VR in radiology is vital to enhance patient outcomes and diagnostic precision. These technologies can significantly change how radiologists diagnose or treat. These tools provide visualization of anatomical features and disease disorders that are often difficult to visualize using traditional imaging techniques, which can enhance diagnostic accuracy. AR minimizes the risk of surgical complications by providing real-time anatomical overlays and through this they can also provide better patient outcomes which are important for needle insertion, tumor ablation, and other such operations. While VR, provides immersive learning environment to assist radiologists and surgeons in performing difficult procedures more efficiently, resulting in better patient care which can also help patients, to better comprehend their condition, reduce anxiety, and increase adherence to treatment programs. The use of AR and VR in clinical practice simplifies radiology operations by enhancing cooperation among healthcare teams and speeding up decision-making processes. The capacity to access imaging data while collaborating remotely and navigating difficult cases with greater ease adds to a more efficient healthcare system in general.

Although AR and VR technologies are promising Technologies in radiography but future research or clinical adoption efforts should target various domains such as large scale clinical studies, to evaluate long-term effects of AR and VR on diagnosis accuracy, treatment outcomes and patient safety. Such research on its cost-effectiveness and accessibility is also needed to convince stakeholders that integrating these innovations into clinical practice would be economically beneficial. User-carried design and workflow integration, to build systems that don't disrupt medical function but enhance them. There is also research required on training and education — for instance, to sharpen diagnostic and procedural skills. Laws and regulations, especially concerning patient privacy, data security, and regulatory compliance, should be targeted. Vendors must work closely with CIOs to ensure that these technologies serve the needs of radiologists and healthcare providers.

Integrating Augmented Reality (AR) and Virtual Reality (VR) technologies into radiology can revolutionize the practice through enhanced diagnostic abilities, procedure performance, and medical training. With the adoption of these advanced technologies, the role of radiologists could be to deliver accurate and timely care through positive patient outcomes. But affordability, hardware integration, and clinical acceptance will be a key to their widespread adoption. Future research should be geared toward developing these technologies, with large-scale trials that show their therapeutic value and promotion of these technologies to health care workers worldwide. As they continue to get better, AR and VR are likely to be an integral part of the future of radiology.

Authors Contribution

Hafsa Bhatti: Conceptualization, study design, manuscript drafting, reviewing, editing, supervision, final approval, accountability

Muhammad Moeed Azwar Bhatti: Drafting, study design, manuscript writing, proofreading, critical revisions, final approval, accountability

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Dr. Mubashir Javed: Drafting writing significant sections of the manuscript, critical revisions, consistency check, final approval, accountability.

Dr. Shehryar Ali: Drafting writing significant sections of the manuscript, critical revisions, consistency check, final approval, accountability.

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Khadija: Conclusion writing, proofreading, manuscript preparation, critical revisions, final approval, accountability.

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References

1. - MN. Assessing the Impact of Virtual Reality Integration in PET-CT Scans: A New Frontier in Radiology. International Journal For Multidisciplinary Research [Internet]. 2024 Sep 6 [cited 2025 Mar 4];6(5). Available from: https://www.ijfmr.com/research-paper.php?id=27212
2. Gunn T, Jones L, Bridge P, Rowntree P, Nissen L. The use of virtual reality simulation to improve technical skill in the undergraduate medical imaging student. Interactive Learning Environments. 2018 Jul 4;26(5):613–20.
3. Allen DR, Cattari N, Cambranis Romero JN, Peters TM, Chen ECS. Towards virtual displays in the interventional radiology suite: a feasibility study. 2023 Apr 3;42.
4. Douglas DB, Venets D, Wilke C, Gibson D, Liotta L, Petricoin E, et al. Augmented Reality and Virtual Reality: Initial Successes in Diagnostic Radiology. State of the Art Virtual Reality and Augmented Reality Knowhow. 2018 May 23;
5. Bridge P, Gunn T, Kastanis L, Pack D, Rowntree P, Starkey D, et al. The development and evaluation of a medical imaging training immersive environment. J Med Radiat Sci [Internet]. 2014 [cited 2025 Mar 4];61(3):159–65. Available from: https://onlinelibrary.wiley.com/doi/10.1002/jmrs.60
6. Adeoye Idowu Afolabi, Adebimpe Bolatito Ige, Afees Olanrewaju Akinade, Peter Adeyemo Adepoju. Virtual reality and augmented reality: A comprehensive review of transformative

potential in various sectors. Magna Scientia Advanced Research and Reviews [Internet]. 2023 Apr 30 [cited 2025 Mar 4];7(2):107–22. Available from: https://magnascientiapub.com/journals/msarr/node/1059

7. Jacquemyn X, Bamps K, Moermans R, Dubois C, Rega F, Verbrugghe P, et al. Augmented and virtual reality imaging for collaborative planning of structural cardiovascular interventions: a proof-of-concept and validation study. Journal of Medical Imaging [Internet]. 2024 Oct 8 [cited 2025 Mar 4];11(06). Available from: https://www.spiedigitallibrary.org/journals/journal-of-medical-imaging/volume-11/issue-06/062606/Augmented-and-virtual-reality-imaging-for-collaborative-planning-of-structural/10.1117/1.JMI.11.6.062606.full
8. Cieri RL, Turner ML, Carney RM, Falkingham PL, Kirk AM, Wang T, et al. Virtual and augmented reality: New tools for visualizing, analyzing, and communicating complex morphology. J Morphol. 2021 Dec 1;282(12):1785–800.
9. von Ende E, Ryan S, Crain MA, Makary MS. Artificial Intelligence, Augmented Reality, and Virtual Reality Advances and Applications in Interventional Radiology. Diagnostics. 2023 Mar 1;13(5).
10. Singh DK, Kumar P, Arora P, Sharma M. A bibliometric Analysis of Virtual Reality and Augmented Reality Applications in Healthcare. International Conference on Artificial Intelligence for Innovations in Healthcare Industries, ICAIIHI 2023. 2023;
11. Le H, Nguyen M, Yan WQ. A Web-Based Augmented Reality Approach to Instantly View and Display 4D Medical Images. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). 2020;12047 LNCS:691–704.
12. Stauffer T, Lohmeyer Q, Melamed S, Uhde A, Hostettler R, Wetzel S, et al. Evaluation of augmented reality training for a navigation device used for CT-guided needle placement. Int J Comput Assist Radiol Surg. 2024 Dec 1;
13. Takata T, Kondo H, Yamamoto M, Shiraishi K, Kobayashi T, Furui S, et al. Immersive Radiation Experience for Interventional Radiology with Virtual Reality Radiation Dose Visualization Using Fast Monte Carlo Dose Estimation. Interventional Radiology. 2020;5(2):58–66.

14. Talbot J, Meyer J, Watts R, Grasset R. An augmented reality application for patient positioning and monitoring in radiotherapy. IFMBE Proc. 2009;25(1):620–3.
15. Takata T, Nakabayashi S, Kondo H, Yamamoto M, Furui S, Shiraishi K, et al. Mixed Reality Visualization of Radiation Dose for Health Professionals and Patients in Interventional Radiology. J Med Syst. 2021 Apr 1;45(4).
16. Singh B, Kaunert C. AR and VR in Health Expansions and Medical Education. 2024 Nov 22 [cited 2025 Mar 4];15–36. Available from: https://services.igi-global.com/resolvedoi/resolve.aspx?doi=10.4018/979-8-3693-4252-7.ch002
17. Xu X, Mangina E, Campbell AG. HMD-Based Virtual and Augmented Reality in Medical Education: A Systematic Review. Front Virtual Real. 2021 Jul 6;2.
18. Shetty S, Bhat S, Al Bayatti S, Al Kawas S, Talaat W, El-Kishawi M, et al. The Scope of Virtual Reality Simulators in Radiology Education: Systematic Literature Review. JMIR Med Educ. 2024;10.
19. Serrano Vergel R, Morillo Tena P, Casas Yrurzum S, Cruz-Neira C. A Comparative Evaluation of a Virtual Reality Table and a HoloLens-Based Augmented Reality System for Anatomy Training. IEEE Trans Hum Mach Syst. 2020 Aug 1;50(4):337–48.
20. Selvan C, Vidhya K, Kumar RS, Veningston K. Comparative overview of augmented reality, virtual reality, and mixed reality. Applications of Virtual and Augmented Reality for Health and Wellbeing. 2024 Apr 4;1–16.
21. Schaake R, Leopold I, Sandberg A, Zenk B, Shafer L, Yu D, et al. Virtual Reality for the Management of Pain and Anxiety for IR Procedures: A Prospective, Randomized, Pilot Study on Digital Sedation. Journal of Vascular and Interventional Radiology. 2024 Jun 1;35(6):825–33.
22. Sauer F, Schoepf UJ, Khamene A, Vogt S, Das M, Silverman SG. Augmented reality system for CT-guided interventions: system description and initial phantom trials. Medical Imaging 2003: Visualization, Image-Guided Procedures, and Display. 2003 May 30;5029:384.
23. Saruwatari MS, Nguyen TN, Talari HF, Matisoff AJ, Sharma K V., Donoho KG, et al. Assessing the Effect of Augmented Reality on Procedural Outcomes During Ultrasound-Guided Vascular Access. Ultrasound Med Biol. 2023 Nov 1;49(11):2346–53.

24. Saravanan YG, Shankar JD, Ganapathy N. AR-MED: ILLUMINATING HEALTHCARE'S PATH WITH AUGMENTED REALITY. Futuristic Trends in Medical Sciences Volume 3 Book 21. 2024 Mar 5;28–39.

25. Salimi S, Asgari Z, Mohammadnejad A, Teimazi A, Bakhtiari M. Efficacy of virtual reality and augmented reality in anatomy education: A systematic review and meta-analysis. Anat Sci Educ [Internet]. 2024 Dec 19 [cited 2025 Mar 4];17(9):1668–85. Available from: https://anatomypubs.onlinelibrary.wiley.com/doi/10.1002/ase.2501

26. Salim A, Indra I, Nugraha U, Abdulghani T, Anwar S. Augmented Reality and Virtual Reality Applications: Enhancing User Experience Across Industries. Global International Journal of Innovative Research. 2024 Jul 31;2(4):840–9.

27. Saliba T, Pather S. The use of virtual reality and augmented reality in ultrasound education, a narrative review of the literature. Journal of Clinical Ultrasound [Internet]. 2025 Feb 20 [cited 2025 Mar 4];53(2):315–24. Available from: https://onlinelibrary.wiley.com/doi/10.1002/jcu.23840

28. Rohmer K, Becker M, Georgiades M, March C, Melekh B, Sperka P, et al. Acceptance and feasibility of an augmented reality-based navigation system with optical tracking for percutaneous procedures in interventional radiology - a simulation-based phantom study. RoFo Fortschritte auf dem Gebiet der Rontgenstrahlen und der Bildgebenden Verfahren. 2024;

29. S. K. S, J. A. J, Pajila B, R. SS, Kumari R. Exploring the Applications of Augmented Reality and Virtual Reality in Medicine. 2024 Jul 22;212–22.

30. Rowe SP, Schneider R, Krueger S, Pryde V, Chu LC, Fishman EK. Augmented Reality with Cinematic Rendered 3-Dimensional Images from Volumetric Computed Tomography Data. J Comput Assist Tomogr. 2023 Jan 1;47(1):67–70.

31. Rodríguez-Pérez JA. Augmented reality as an accessory technology in surgery. Gamification and Augmented Reality. 2023 Dec 26;1:27.

32. Paul P, Fleig O, Jannin P. Augmented virtuality based on stereoscopic reconstruction in multimodal image-guided neurosurgery: Methods and performance evaluation. IEEE Trans Med Imaging. 2005 Nov;24(11):1500–11.

33. Nogueira GN, Silva NCP, Vidal W da SR, Raymundo IA, Paglioli LH, Souza ME de, et al. Virtual Reality and Augmented Reality as Support for Neurosurgery. JBNC - JORNAL BRASILEIRO DE NEUROCIRURGIA. 2024;35(2):49–55.
34. Nagamata S, Nagamata S, Sekine N. Simulation Using Augmented Reality to Teach Body Angle Positioning for Radiography. Radiology and Medical Diagnostic Imaging. 2020 Aug 14;1–5.
35. Barteit S, Lanfermann L, Bärnighausen T, Neuhann F, Beiersmann C. Augmented, mixed, and virtual reality-based head-mounted devices for medical education: Systematic review. JMIR Serious Games. 2021 Jul 1;9(3).
36. Weiss TL, Bailenson JN, Bullock K, Greenleaf W. Reality, from virtual to augmented. Digital Health: Exploring Use and Integration of Wearables. 2021 Jan 1;275–303.
37. Rancati A, Angrigiani C, Nava MB, Catanuto G, Rocco N, Ventrice F, et al. Augmented reality for breast imaging. Minerva Chir. 2018 Jun 1;73(3):341–4.
38. Douglas DB, Wilke CA, Gibson JD, Boone JM, Wintermark M. Augmented reality: Advances in diagnostic imaging. Multimodal Technologies and Interaction. 2017 Dec 1;1(4).
39. Andersen D, Lin C, Popescu V, Munoz ER, Eugenia Cabrera M, Mullis B, et al. Augmented visual instruction for surgical practice and training. 2018 IEEE Workshop on Augmented and Virtual Realities for Good, VAR4Good 2018. 2018 Dec 13;
40. Tu M, Jung H, Moghadam A, Raythatha J, Hsu J, Kim J. Exploring the Performance of Geometry-Based Markerless Registration in a Simulated Surgical Environment: A Comparative Study of Registration Algorithms in Medical Augmented Reality. Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS. 2023;
41. Harreld MR, Valentino DJ, Duckwiler GR, Lufkin RB, Karplus WJ. <title>Virtual reality in radiology: virtual intervention</title>. Medical Imaging 1995: Image Display. 1995 Apr 27;2431:388–96.
42. Christie M. “Augmented reality and radiology: Visual enhancement or monopolised mirage.” BJR|Open. 2024 Dec 12;
43. Baker J, Antypas A, Aggarwal P, Elliott C, Baxter R, Singh S, et al. Augmented Reality in Interventional Radiology: Transforming Training Paradigms. Cureus. 2024 Feb 26;

44. Elsakka A, Park BJ, Marinelli B, Swinburne NC, Schefflein J. Virtual and Augmented Reality in Interventional Radiology: Current Applications, Challenges, and Future Directions. Tech Vasc Interv Radiol. 2023 Sep 1;26(3).

45. Finos K, Datta S, Sedrakyan A, Milsom JW, Pua BB. Mixed reality in interventional radiology: a focus on first clinical use of XR90 augmented reality-based visualization and navigation platform. Expert Rev Med Devices. 2024;21(8):679–88.

46. Online Master's in Engineering | CWRU [Internet]. [cited 2025 Mar 16]. Available from: https://online-engineering.case.edu/

47. Zhao X, Zhao H, Zheng W, Gohritz A, Shen Y, Xu W. Clinical evaluation of augmented reality-based 3D navigation system for brachial plexus tumor surgery. World J Surg Oncol. 2024 Dec 1;22(1).

48. Jiang J, Zhang J, Sun J, Wu D, Xu S. User's image perception improved strategy and application of augmented reality systems in smart medical care: A review. International Journal of Medical Robotics and Computer Assisted Surgery. 2023 Jun 1;19(3).

49. Marquette University Bulletin | Marquette University [Internet]. [cited 2025 Mar 16]. Available from: https://bulletin.marquette.edu/

50. Gelmini AYP, Duarte ML, da Silva MO, Guimarães Junior JB, Dos Santos LR. Augmented reality in interventional radiology education: a systematic review of randomized controlled trials. Sao Paulo Medical Journal. 2022;140(4):604–14.

51. Liao SC, Shao SC, Gao SY, Lai ECC. Augmented reality enhances medical education and improves efficiency. Med Educ. 2024 May 1;58(5):586–7.

52. Bin Kamarudin MF, Zary N. Augmented Reality, Virtual Reality and Mixed Reality in Medical Education: A Comparative Web of Science Scoping Review. 2019 Apr 29 [cited 2025 Mar 4]; Available from: http://www.preprints.org/manuscript/201904.0323/v1

53. Lima TV, Simões RFP, Heinrich M, Kreienbühl T, Wetzel R, Roos JE. Usefulness of augmented reality in radiological protection education and training for interventional radiologists. British Journal of Radiology. 2023 Apr 1;96(1145).

54. Mondal SB, Achilefu S. Virtual and Augmented Reality Technologies in Molecular and Anatomical Imaging. Molecular Imaging: Principles and Practice. 2021 Jan 1;1591–612.

55. Moro C, Štromberga Z, Raikos A, Stirling A. The effectiveness of virtual and augmented reality in health sciences and medical anatomy. Anat Sci Educ. 2017 Nov 1;10(6):549–59.

56. Banerjee S, Pham T, Eastaway A, Auffermann WF, Quigley EP. The Use of Virtual Reality in Teaching Three-Dimensional Anatomy and Pathology on CT. J Digit Imaging. 2023 Jun 1;36(3):1279–84.
57. Agarwal R, Tatrari P, Jain S. Augmented and virtual realities: A comprehensive survey, current advancements, and future technologies for immersive technologies in industry and beyond. Challenges in Information, Communication and Computing Technology [Internet]. 2024 Nov 19 [cited 2025 Mar 4];661–5. Available from: https://www.taylorfrancis.com/books/9781003559092/chapters/10.1201/9781003559092-114
58. PHD TOPIC [Internet]. [cited 2025 Mar 16]. Available from: https://phdtopic.com/
59. Kassutto SM, Baston C, Clancy C. Virtual, Augmented, and Alternate Reality in Medical Education: Socially Distanced but Fully Immersed. ATS Sch. 2021 Dec 1;2(4):651–64.
60. Müller-Wittig W. Virtual Reality in Medicine. Springer Handbook of Medical Technology [Internet]. 2011 [cited 2025 Mar 4];1167–86. Available from: http://link.springer.com/10.1007/978-3-540-74658-4_63
61. Mustafa AR, Moloudi F, Balasalle E, Lang M, Uppot RN. Virtual reading room for diagnostic radiology. Curr Probl Diagn Radiol. 2024 Mar 1;53(2):230–4.
62. Means K, Kleiman K, Ogdon D, Woodard S. A Review of Virtual Reality in Radiology. Curr Probl Diagn Radiol. 2024 Jan 1;53(1):17–21.
63. Bin S, Masood S, Jung Y. Virtual and augmented reality in medicine. Biomedical Information Technology. 2019 Jan 1;673–86.
64. Anderson J, Raghavan R. Virtual reality in interventional radiology. Minimally Invasive Therapy and Allied Technologies. 1997;6(2):111–6.
65. Javaid M, Haleem A, Singh RP, Khan S. Understanding roles of virtual reality in radiology. Internet of Things and Cyber-Physical Systems. 2022 Jan 1;2:91–8.
66. Elsayed M, Kadom N, Ghobadi C, Strauss B, Al Dandan O, Aggarwal A, et al. Virtual and augmented reality: potential applications in radiology. Acta radiol. 2020 Sep 1;61(9):1258–65.
67. González Izard S, Juanes Méndez JA, Ruisoto Palomera P, García-Peñalvo FJ. Applications of Virtual and Augmented Reality in Biomedical Imaging. J Med Syst. 2019 Apr 1;43(4).

68. Venson JE, Berni J, Maia CS, Da Silva AM, D'Ornelas M, Maciel A. Medical imaging VR: Can immersive 3D aid in diagnosis? Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST. 2016 Nov 2;02-04-November-2016:349–50.
69. Gunn T, Cert G, Practice A, Rowntree P, Starkey D, Sfhea F, et al. The use of virtual reality computed tomography simulation within a medical imaging and a radiation therapy undergraduate programme. J Med Radiat Sci [Internet]. 2021 Mar 1 [cited 2025 Mar 4];68(1):28–36. Available from: https://onlinelibrary.wiley.com/doi/10.1002/jmrs.436
70. Lastrucci A, Giansanti D. Radiological Crossroads: Navigating the Intersection of Virtual Reality and Digital Radiology through a Comprehensive Narrative Review of Reviews. Robotics. 2024 May 1;13(5).
71. Deutschmann H, Steininger P, Nairz O, Kopp P, Merz F, Wurstbauer K, et al. "Augmented reality" in conventional simulation by projection of 3-D structures into 2-D images: A comparison with virtual methods. Strahlentherapie und Onkologie. 2008 Feb;184(2):93–9.
72. Home - College of Design and Engineering [Internet]. [cited 2025 Mar 16]. Available from: https://cde.nus.edu.sg/
73. Uçar ED. Exploring the Potential of Augmented Reality (AR) and Virtual Reality (VR) in Developing Immersive Experiences for Education, Entertainment, and Training: Innovations, Applications, and Future Prospects. Human Computer Interaction [Internet]. 2024 Nov 26 [cited 2025 Mar 4];8(1):47. Available from: https://globalresearchandinnovationpublications.com/HCI/article/view/94
74. Iqbal AI, Aamir A, Hammad A, Hafsa H, Basit A, Oduoye MO, et al. Immersive Technologies in Healthcare: An In-Depth Exploration of Virtual Reality and Augmented Reality in Enhancing Patient Care, Medical Education, and Training Paradigms. J Prim Care Community Health. 2024 Jan 1;15.
75. Park HM, Kim ES, Kwon DM, Cho PK, Kim SH, Lee KB, et al. Assessment of the viability of integrating virtual reality programs in practical tests for the Korean Radiological Technologists Licensing Examination: a survey study. J Educ Eval Health Prof. 2023;20.
76. Izard SG, Juanes Méndez JA, Ruisoto P, García-Peñalvo FJ. NextMed: How to enhance 3D radiological images with Augmented and Virtual Reality. ACM International Conference Proceeding Series. 2018 Oct 24;397–404.

77. Uppot RN, Laguna B, McCarthy CJ, De Novi G, Phelps A, Siegel E, et al. Implementing virtual and augmented reality tools for radiology education and training, communication, and clinical care. Radiology. 2019;291(3):570–80.
78. Anderson J, Chui CK, Cai Y, Wang Y, Li Z, Ma X, et al. Virtual reality training in interventional radiology: The Johns Hopkins and Kent Ridge digital laboratory experience. Semin Intervent Radiol. 2002;19(2):179–85.
79. Pooja Ladkhedkar, Vaishnavi Yadav. Use of Augmented reality and virtual reality in cardiac rehabilitation. J Pharm Negat Results. 2022 Oct 17;2957–9.
80. Pires F, Costa C, Dias P. On the Use of Virtual Reality for Medical Imaging Visualization. J Digit Imaging. 2021 Aug 1;34(4):1034–48.
81. Farrell K, MacDougall D. An Overview of Clinical Applications of Virtual and Augmented Reality. Canadian Journal of Health Technologies. 2023 Mar 20;3(3).
82. Matthew UO. Healthcare applications of Augmented Reality (AR) and Virtual Reality (VR) simulation in clinical education. Journal of Clinical Images and Medical Case Reports [Internet]. 2024 Jun 26 [cited 2025 Mar 4];5(6). Available from: https://jcimcr.org/articles/JCIMCR-V5-3141.html
83. Liao SC, Shao SC, Gao SY, Lai ECC. Augmented reality visualization for ultrasound-guided interventions: a pilot randomized crossover trial to assess trainee performance and cognitive load. BMC Med Educ. 2024 Dec 1;24(1):1058.
84. Knodel MM, Lemke B, Lampe M, Hoffer M, Gillmann C, Uder M, et al. Virtual reality in advanced medical immersive imaging: a workflow for introducing virtual reality as a supporting tool in medical imaging. Comput Vis Sci. 2018 Mar 1;18(6):203–12.
85. Gamba IAD, Hartery A. The Virtual Reality Radiology Workstation: Current Technology and Future Applications. Canadian Association of Radiologists Journal. 2024 Aug 1;75(3):479–87.
86. Xin M, Lei Z, Volkau I, Weili Z, Aziz A, Ang MH, et al. A virtual reality simulator for remote interventional radiology: Concept and prototype design. IEEE Trans Biomed Eng. 2006 Aug;53(8):1696–700.
87. Vashishth TK, Sharma V, Sharma KK, Kumar B, Chaudhary S, Panwar R. Virtual reality (VR) and augmented reality (AR) transforming medical applications. AI and IoT-Based Technologies for Precision Medicine. 2023 Oct 18;324–48.

88. Alghamdi A. Simulation system for radiology education integration of physical and virtual realities: Overview and software considerations. Journal of Health Specialties. 2015;3(3):144.

89. Wirth M, Gradl S, Sembdner J, Kuhrt S, Eskofier BM. Evaluation of interaction techniques for a virtual reality reading room in diagnostic radiology. UIST 2018 - Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology. 2018 Oct 11;867–76.