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REVIEW

Role of eXtended Reality use in medical imaging interpretation for pre-surgical planning and intraoperative augmentation

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ABSTRACT. **Purpose:** eXtended Reality (XR) technology, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), is a growing field in healthcare. Each modality offers unique benefits and drawbacks for medical education, simulation, and clinical care. We review current studies to understand how XR technology uses medical imaging to enhance surgical diagnostics, planning, and performance. We also highlight current limitations and future directions.

Approach: We reviewed the literature on immersive XR technologies for surgical planning and intraoperative augmentation, excluding studies on telemedicine and 2D video–based training. We cited publications highlighting XR's advantages and limitations in these categories.

Results: A review of 556 papers on XR for medical imaging in surgery yielded 155 relevant papers reviewed utilizing the aid of chatGPT. XR technology may improve procedural times, reduce errors, and enhance surgical workflows. It aids in preoperative planning, surgical navigation, and real-time data integration, improving surgeon ergonomics and enabling remote collaboration. However, adoption faces challenges such as high costs, infrastructure needs, and regulatory hurdles. Despite these, XR shows significant potential in advancing surgical care.

Conclusions: Immersive technologies in healthcare enhance visualization and understanding of medical conditions, promising better patient outcomes and innovative treatments but face adoption challenges such as cost, technological constraints, and regulatory hurdles. Addressing these requires strategic collaborations and improvements in image quality, hardware, integration, and training.

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1 Introduction

Immersive technology, encompassed by the term eXtended Reality (XR), is a rising innovation finding different areas of implementation across a variety of disciplines. XR's growth in healthcare is second only to that in gaming, followed closely by its use in education and training.[1] XR technology includes several immersive modalities including virtual reality (VR), augmented reality (AR), and mixed reality (MR). VR refers to 3D immersion into a completely digital space. AR involves superimposing virtual content and information into the physical world. MR allows for the superimposition of virtual objects into the user's tangible environment in a more seamless and integrated way than AR, allowing for limitless interaction and blending of the physical and virtual worlds within a singular space.[2] Each of these technologies offers unique ways of allowing people to experience and interact with the physical and digital world around them. The various immersive modalities have both advantages and disadvantages in how they can be utilized in the healthcare setting. For example, MR utilization with existing physical simulation equipment may be better for procedural training than VR, which currently lacks the haptic feedback necessary for fine motor skills. VR, on the other hand, may offer advantages in patient care settings, for example, by alleviating patient pain by providing a completely immersive setting.

The field of immersive technology is currently in a state of expansive growth as technological hardware becomes more ubiquitous, and software innovation is leading to enhanced usability of immersive products and applications. Currently, in medicine, specific use cases have arisen for XR applications in medical training, including assisting in diagnostic, therapeutic, and procedural techniques. Companies are finding new ways of utilizing medical imaging for surgical diagnostics, preoperative planning, and intraoperative surgical augmentation.[3] The two medical disciplines poised to receive significant benefits in the near future from these technology applications are radiology and surgery.

Immersive surgical simulation and intraoperative utilization of immersive technologies are two commonly studied areas within the field of XR in healthcare. Numerous studies have been designed to assess the impact XR may provide to augment current training standards and improve surgical outcomes. Most studies have been single-institutional in nature, include only a small number of participants, and perform subjective versus objective analyses. However, despite these study limitations, they show significant promise in the ability of immersive technology to augment medical imaging analysis to improve surgical training, customize preoperative planning, and translate these efficiencies into surgical practice. The purpose of this article is to provide a framework for the utilization of XR in medical imaging interpretation for surgery and procedures. To do so, we provide a high-level overview of studies analyzing the use of VR, AR, and MR in medical imaging assessment as well as 3D augmentation techniques for preoperative and pre-procedural planning and intraoperative augmentation.

2 Methods

To provide a comprehensive analysis of the use of XR for medical imaging and surgery, we reviewed the literature for manuscripts citing the use of immersive XR technologies (VR, AR, and MR) for surgical planning as well as intraoperative augmentation using medical imaging data. Publications were screened by a process of converting portable document format (PDF) forms into rich text format using the artificial intelligence PDF plugin on ChatGPT followed by summarization of the manuscript assessing for XR applications for surgical planning and intraoperative augmentation of surgical procedures. The summaries were then manually assessed for relevance, and relevant content was reviewed and incorporated into the literature, specifically citing data that supported advantages and/or limitations to the use of XR for medical image interpretation to enhance surgical planning as well as intraoperative use. We then identified several categories of advantages and limitations within the healthcare delivery system in which immersive technologies have been shown to impact medical imaging analysis as it relates to surgical patients (Fig. 1). We highlight these advantages and limitations of XR technology for medical imaging analysis during preoperative planning stages as well as intraoperative augmentation of surgical procedures.

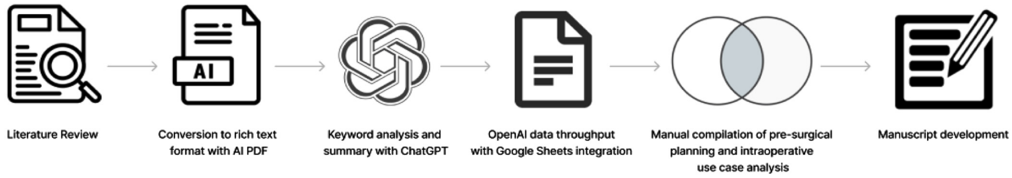

Fig. 1 Workflow for a novel method for a systematic review of the literature utilizing ChatGPT and OpenAI resources for data throughput analysis and compilation of supporting and contradicting data elements. This data was then manually reviewed and compiled based on the healthcare use case analysis.

3 Results

The use of immersive technology has been most utilized and studied in surgical applications, especially in its use for medical imaging analysis and 3D conceptualization and interactivity for surgical planning and intraoperative augmentation. A total of 329 papers were manually reviewed for the use of XR in surgery as well as 227 papers for the use of XR in medical imaging. Of these, we manually selected 85 papers focusing on VR applications, 48 publications focused on AR, and 32 papers that focused on MR applications and had relevance to the use of XR for the interpretation of medical imaging in surgery. We identified papers focusing on preoperative planning versus surgical augmentation and extracted data that supported the advantages as well as limitations of this technology for each. We then discuss anticipated future directions as the use cases for this technology have rapidly expanded over the last decade. A total of 59 papers were able to be analyzed by this process and included in the analysis.

3.1 Immersive Technology and 3D Image Analysis for Surgical Planning

A key aspect of immersive reality for procedural application lies in its capacity to provide a simulated environment to review patient-specific elements of a surgical case, allowing for improved surgical planning and preparation. Although most applicable to the trainee, this also helps experienced surgeons/proceduralists in designing and practicing patient-specific procedures, focusing on patient anatomy and personalized details. Table 1 outlines the advantages shown from using immersive technology for surgical planning.

To date, 3D printing has been utilized as a pre-surgical planning method for patient-specific disease and recently has even been assigned billing research codes within the US healthcare system.[4] Rather than providing a physical 3D model for planning purposes, immersion technology can provide the same level of 3D planning but within a digital environment, although no codes currently exist to cover the cost of this technology.[5,6] Virtual 3D models can enhance the anatomical knowledge of the surgeon in real time.[7] Also, 3D models and XR planning have both been assessed[8] and shown to reduce procedural times, decrease blood loss, and improve the quality of cancer surgeries.[9] Surgeons favored the VR models over viewing of images on

Table 1 Advantages of immersive technology and 3D imaging in surgical planning.

Advantages of 3D images for surgical planning
Patient-specific
Allows for “practice” prior to surgery
Improve anatomy details
Reduce procedure times
Decrease blood loss
Reduce workflow errors
Higher surgeon confidence

computer screens.[10] Similarly, when patient-specific rehearsal (PsR) for complex endovascular cases was performed using XR planning, an overall reduction in procedural time, radiation exposure, contrast volume utilization, and potential errors in procedural workflow was found compared with the non-immersive planning control group.[11] Furthermore, procedural planning studies found the use of immersive preparation for procedural planning as both feasible and realistic while also improving confidence, improving surgical planning, and receiving a higher rating of satisfaction compared with traditional methods.[12,13]

Other studies have assessed XR surgical planning for complex surgical conditions that require reconstructive elements, such as congenital cardiac conditions where the tissue must be reshaped to improve function. This contrasts with cancer operations where tissue may just be removed. These authors provide evidence that XR can help in performing a more precise and tailored surgical approach, especially for complex surgical cases with a limited safety net, and can reduce the dependence on alternative planning methods, such as cadaveric dissections.[12] They also highlight the use of XR to provide remote collaboration for complex surgical diseases, both at a multidisciplinary level, as well as at a multi-institutional level, providing a framework for reviewing and planning patient-specific surgical cases while democratizing surgical planning skills through remote mentorship.[14] These studies suggest XR may be an efficient, immersive technology that can provide new insights and methods for complex surgical planning techniques, especially as it relates to patient-specific anatomy and a step-wise procedural workflow to reduce operative times and improve patient outcomes.

3.2 Use of Medical Imaging and Immersive Technology to Augment the Operating Room (OR)

Immersive technologies are poised to play a significant role in the operating room in the future. We have previously highlighted how XR can improve surgical diagnostics and understanding of patient-specific pathology, as well as in preoperative surgical planning techniques. These improvements in clinical assessment and procedural readiness already provide a framework for improving the execution of the surgical operation. However, immersive technologies may also be extended into the operating room environment, augmenting the surgical operation itself in an attempt to improve the procedural workflow, facilitate disease localization and completeness of resection (i.e., not leaving cancer behind), and provide improved methods of implementing clinical data to facilitate a smoother, faster, more efficient operation (Table 2).

3.2.1 *Anatomic mapping and navigation*

Augmented and MR modalities of immersive technology allow for the digital augmentation of a surgery or procedure. Perhaps the most recognized utilization of immersive technology in the operating room is the superimposition of medical imaging data onto the patient, providing

Table 2 Advantages of immersive technology to augment the operating room.

Advantages of immersive technology to augment the OR	
Aanatomic mapping	Superimposition of 3D images on the patient in an AR/format
	Improved incision and port placement
	Improved guidance on boundaries for resection
Augmentation of the OR field	Provide supplementary information (vital signs) in the field of view
	Improved instrument navigation
Ergonomic improvement	Limits movement to view other data, by showing it in the AR field
	Postural feedback to reduce physical strain
Remote mentoring	Enhance global access to state-of-the-art techniques and care
	Improve procedural efficiency through remote training

augmented surgical navigation and disease localization. Patient-specific imaging data can help in pinpointing important anatomic structures and identifying areas of disease versus healthy tissues,[9] optimizing the surgical operation by enabling faster and more accurate anatomic identification.[15,16] This has been used prior to the start of a surgical operation to align the location of surgical incisions,[17] to inform appropriate instrument placement for minimally invasive procedures,[18] and to provide an optimal surgical setup for implant placement.[19,20] It can also be used to provide guidance on surgical and ablative resection boundaries[21] as well as prevent damage to adjacent structures. Studies have been completed crossing multiple surgical disciplines including neurosurgery,[18] orthopedic surgery,[17] thoracic surgery,[15] and vascular surgery.[16] Commercial companies have already entered this space hoping to aid interventional radiologic and surgical procedures.[22]

3.2.2 *Augmentation of the operative field*

As the surgeon navigates the complexities of the human anatomy during a procedure, patient data can be implemented into the surgeon's field of vision, offering a blend of the live surgical view with supplementary information (see Fig. 2).[23] This can range from displaying vital signs such as heart rate and blood pressure readings, incorporating images, videos, or external technology for procedural reference,[24] information related to procedural efficiency,[25] or to review patient data such as labs or imaging.[26,27] These types of data are available in the operating room already, but the ability for the surgeons to interact with this data is limited due to the sterile environment and reliance on operating room staff and anesthesia. XR allows for a more integrated access to information during the procedure. Furthermore, XR can assist with instrument navigation, indicating the optimal path for surgical instruments and potentially reducing the risk of inadvertent damage to critical structures, especially for cancer operations[28] as well as minimally invasive and percutaneous operations. By seamlessly integrating this wealth of real-time data into the surgical view, immersive technology can not only bolster the surgeon's spatial awareness and precision but can also expedite decision-making and improve overall surgical outcomes.[15]

Fig. 2 VR (top left) of a heart anatomy training module. AR (top right) showing a visual overlay of the positioning of surgical instruments for vascular access during an extracoporeal membrane oxygenation (ECMO) cannula insertion. MR (bottom) showing a step-by-step guide to performing a central catheter line insertion procedure. This shows how the various immersive modalities have differences in the level of immersion provided as well as the haptic feedback that can be afforded by the technology. Each technology has advantages and disadvantages as to how it can be applied to both pre-surgical planning and surgical augmentation in the operating room.

3.2.3 *Ergonomic improvement*

A critically important feature of XR's ability to provide clinical information and patient data to the surgeon's immediate point-of-view, without distracting away from the surgical operation, is its impact on ergonomics. Iqbal et al.[29] demonstrated the integration of holographic operating data from a surgical robot to the surgeon using AR, enhancing the surgeons' ability to see the operative field and have added information present, without having to go to an alternate screen. By having the ability to optimize how and where information is presented, the surgeon can improve their personal ergonomics during the operation, limiting unnecessary and strainful movements.[30] This both helps to facilitate the speed and smoothness of the operation as well as the longevity of the surgeon in the physically challenging environment of the operating room.[31] Postural feedback mechanisms may also be provided in the future with the addition of positional monitors to help provide information to the surgeon to optimize their posture and decrease mechanical stress and positional strain.[32]

3.2.4 *Remote surgical mentoring/collaboration*

We have previously highlighted the advantages immersive technologies provide for remote collaboration in both diagnostics, training, and planning methods. The same applies during the surgical operation as XR allows for surgeons at all levels of training and anywhere in the world to provide remote guidance and instruction in an immersive format.[33,34] One study even evaluated using immersive technology to overlay a virtual physician's hands into the surgical operative environment to facilitate instruction and teaching as a method of enhancing global access to state-of-the-art care.[35] Remote telementoring even has military applications as the US Military has used it for surgical augmentation through their system for telementoring with an augmented reality system.[36] As has been stated previously, remote surgical collaboration using immersive technologies may provide democratization of surgical skills and expand procedural proficiency and competency among surgical peers.[37] This can be applied at a local, regional, national, and even international level.

In summary, immersive technology stands poised to improve surgical operations and interventional procedures, offering multifaceted enhancements to the proceduralist's experience. Visual overlays utilizing medical imaging data grant surgeons and others an augmented perspective of the operative field. By seamlessly integrating patient data and medical imaging into the surgeon's line of sight, real-time decision-making becomes more informed, reducing the need to divert attention to external monitors or charts. Ergonomically, XR addresses challenges faced by surgeons by offering postural feedback, reducing physical strain, and facilitating more natural interactions with the surgical environment. In addition, immersive technology breaks down geographical barriers through remote telementoring, allowing novice or inexperienced surgeons to receive guidance from experienced mentors in real time. Immersive technology, through its various modalities, lays a foundational framework to provide augmented surgical care strategies in the future.

3.3 Benefits of Immersive Technology for Healthcare Delivery

We are seeing an expansion in how medical imaging is utilized to improve medical imaging analysis for surgical preparation and augmentation of the intraoperative environment. Here, we highlight the advantages XR provides over traditional methods in augmenting healthcare delivery and how these advantages can be utilized for medical imaging evaluation and application in the surgical context.

3.3.1 *Cost/Affordability*

This is a common theme in the use of XR technologies within both preoperative and operative use cases. Despite the initial costs required for hardware and software, with the rapid scalability and enhanced methods of communications and sharing of patient data with immersive technologies, there are various methods that can be utilized to provide cost savings to healthcare systems, especially with repeatable and scalable environments and the ability to provide remote collaboration.[38–40] One study has demonstrated the benefits of immersive VR in training scrub nurses on technically challenging knee surgeries, resulting in significant improvement in real-world skills for everyone in the operating room team.[41] Others have shown that VR can be used to reduce costs associated with designing operating rooms and other healthcare environments by allowing "interactive virtual prototyping" of novel spaces.[42]

3.3.2 *Accessibility*

Cloud computing has hastened the speed at which we can share and utilize digital resources and current information transfer technology now allows for both live and recorded shared XR experiences. This not only allows for locoregional collaborations using XR at a multidisciplinary level but allows users to connect from remote locations anywhere in the world rather than requiring presence at a physical facility. Previous studies have cited the ability to coordinate complex surgical cases and discuss them at both an institutional and multidisciplinary level, as well as at a global level, sharing knowledge and clinical expertise at an intercontinental scale.[26,27] This allows for the democratization of radiological and surgical skill sets through shared medical imaging interpretation as well as surgical planning and operative collaboration.[12]

3.3.3 *Telementoring and remote collaboration*

Immersive technology provides the capacity for remote collaboration which, when applied in the training environment, allows for telementoring and remote coaching/teaching. When comparing immersive collaboration with traditional, in-person methods, studies have shown no changes in communication application and performance while citing the numerous benefits provided by the virtual environment.[43] Immersive telementoring has been used in the clinical operative setting between faculty physicians through remote collaboration, providing the quick sharing of surgical skills and expanding procedural proficiency and competency among surgical peers.[12]

3.3.4 *Multidisciplinary Planning and Communication*

Because of its accessibility, XR provides a method to conduct multidisciplinary, interdisciplinary, and peer-to-peer communication, allowing multiple users from various specialties, levels of expertise, or regionality to communicate, learn, plan, and execute patient care within the same 3D environment. Ghaderi et al.[44] piloted a VR-based multidisciplinary orthopedic trauma meeting and demonstrated feasibility, excellent data visualization, and effective decision making. Remote collaboration enables faster and easier methods of interprofessional and multidisciplinary communication, providing an enhanced level of flexibility while breaking down logistical barriers.[45] As healthcare delivery continues to become more digitized, XR will play an increasingly important role in fostering digital methods of communication for accessible and expedited patient care.[46]

3.3.5 *Telemedicine and patient education*

Patients often have difficulty understanding and analyzing medical imaging, leading it to be a poor resource for explaining and describing disease pathology and proposed treatment interventions. Approaches of providing 3D visualizations of imaging findings to explain human anatomy and proposed treatment/procedural strategies have been shown to alleviate anxiety from the patient and promote informed decision-making while also providing an excellent educational environment for both the patient and medical trainees.[47]

3.3.6 *3D interactivity*

XR's primary advantage over traditional medical imaging interpretation lies in its capacity to allow image interpretation in a 3D environment with a high level of interactable experiences for user navigation.[48] Surgical cases with complex, aberrant anatomy, such as congenital cardiac disease, that require significant knowledge of the disease and the ability to imagine complex 3D structures, benefit from significant advancements in enhanced data interpretation and interactivity with 3D modeling.[49,50] This not only provides a more accurate analysis of patient-specific anatomy and physiology[51] but also provides visual elements that aid localization and can be combined with other localizing technologies.[52]

3.3.7 *Enhanced visualization and localization*

The 3D environment allows for the augmentation of surgical operations with the use of 3D, patient-specific medical imaging models and the superimposition of these models onto the operative field for surgical guidance and navigation.[9] Immersive technologies allow for improved planning for surgical procedures as well as augmentation of the operation by being able to better visualize internal anatomy in relation to the physical location of the patient. This allows for localization of the pathology and the appropriate setup (incision, instrument placement, etc.) to facilitate the surgical operation and ensure operative efficiency and success.[15] Further, AR systems are well-suited for visualizing thin medical devices (e.g., catheters) that require high-precision tracking. Techniques have been developed that overlay devices onto a user's field of view, leaving the device functionally unchanged while accurately and responsively relaying its position.[53]

3.3.8 *Realism/reliability/accuracy*

Immersive technology can also be used to improve medical image analysis by immersing the user in realistic 3D models of patient-specific imaging including computed tomography and magnetic resonance imaging.[54,55] This interactive visualization can lead to a better understanding of the anatomical and pathological features of patient-specific diseases crucial for accurate diagnosis and treatment planning.[56] The interactive, immersive, and realistic environment enables healthcare professionals to visualize and interact with complex, patient-specific anatomy, leading to a deeper understanding of pathology, diagnosis, prognosis, and therapeutics.[57,58]

3.3.9 *Complex (or low volume) scenarios*

Immersive simulation offers a digital arena in which rare and/or complex training scenarios can be rapidly deployed and shared in the XR environment while minimizing expenditures related to setup and execution. Complex surgical cases can be stored and reviewed collaboratively across disciplines or across institutions to share knowledge and know-how in managing rare or complex disease states.[26,27]

In summary, immersive technologies are heralding a new era in healthcare by offering advantages over traditional clinical care methods (Table 3). These technologies merge the digital and physical worlds, granting healthcare professionals enriched visualization, real-time data access, and interactive clinical and training environments to improve patient care delivery.

Table 3 Benefits of XR in healthcare delivery overall.

Benefits of XR in healthcare delivery	
Costs	Remote collaboration
	Reduced training costs for staff
	Virtual prototyping for hospital design
Accessibility	Multidisciplinary discussions for remote providers
	Remote telementoring and coaching for providers
	Improved patient experience and understanding
Reliability	Improved accuracy in understanding anatomy
	Improved training for rare scenarios

Table 4 Summary of the limitations in the use of XR technology for pre-surgical planning and augmentation of the surgical operating room.

Key limitations of XR
Startup costs
Complex infrastructure requirements
Hardware limitations
Software limitations
Resistance to change
Regulatory approval challenges
Paucity of data/validation

Immersive technologies offer the potential to elevate the standard of clinical care, drive improved outcomes, enhance training, and offer a more personalized and informed patient experience.

3.4 Limitations of Immersive Technology for Medical Imaging and Surgery

The use of immersive technologies in healthcare is promising. However, adoption and implementation face several limitations (Table 4). The integration of immersive technologies is limited by cost, hospital infrastructure, technological limitations, resistance to change, a paucity of data and validation, and regulatory approval challenges within the complex healthcare system. While ample evidence exists suggesting benefits, these limitations and barriers must be overcome through strategic partnerships with industry, national and world health institutions, healthcare delivery networks, and hospital systems to enhance immersive applications and provide the necessary data to validate and integrate this promising technology.[24,58,59]

4 Conclusions on the Use of XR for Medical Imaging Analysis for Surgery

Immersive technologies have showcased considerable potential in the domain of healthcare. Their integration into medical imaging and surgery promises to revolutionize these fields by offering enhanced visualization, interactive engagement, and a more comprehensive understanding of medical conditions and procedures. These technologies can lead to improved patient outcomes, more accurate diagnoses, and innovative treatment methodologies through pre-surgical planning methods and intraoperative augmentation of the surgeon's operative environment. The immersive nature of these tools provides healthcare professionals with an unparalleled opportunity for training, planning, skill refinement, and improving surgical care.

It must also be acknowledged that the adoption and implementation of immersive technologies are not without challenges. Factors such as cost, infrastructure, technological constraints, and resistance to change act as significant barriers. In addition, there is a notable lack of data and validation supporting the widespread adoption of these technologies, compounded by regulatory approval challenges that exist within the multifaceted healthcare system. Future directions for the use of XR technology in medical imaging interpretation, preoperative planning, and surgical augmentation must address several key barriers. Technical challenges include improving image quality, reducing latency, and enhancing hardware comfort and battery life. Integration issues involve ensuring compatibility with existing medical systems and minimizing workflow disruptions. Regulatory and safety concerns necessitate rigorous testing and compliance with patient privacy regulations and patient outcomes data. Economic barriers, such as high initial costs and ongoing maintenance expenses, must be mitigated. Comprehensive training programs are essential to overcome resistance to change among medical professionals. In addition, more clinical studies are needed to validate XR's effectiveness and standardize outcome measurements. Ethical considerations, including patient consent and equitable access, must also be addressed to ensure the successful adoption of XR in medical practice.

For these technologies to reach their full potential and become an integral part of healthcare delivery, it is imperative to address these limitations through the forging of strategic collaborations with industry stakeholders, global health institutions, healthcare networks, and hospital systems. Such partnerships are crucial to further the development, provide necessary validation data, and ultimately integrate this promising technology seamlessly into the healthcare landscape.

Disclosures

The authors declare that there are no financial interests, commercial affiliations, or other potential conflicts of interest that could have influenced the objectivity of this research or the writing of this paper.

Code and Data Availability

All data in support of the findings of this paper are available within the article or as supplementary material.

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