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Augmented Reality in Surgical Planning: Enhancing Precision

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ABSTRACT

Augmented Reality (AR) is revolutionizing surgical planning by providing immersive and precise visualization of anatomical structures. By superimposing 3D medical images onto real-world environments, AR enables surgeons to interact with patient-specific anatomy in real time, enhancing preoperative planning, intraoperative navigation, and training. This paper examines the historical development, technological foundations, and current applications of AR in surgical environments, highlighting its role in improving spatial awareness, reducing procedural errors, and enhancing decision-making. Despite its transformative potential, the integration of AR faces several challenges, including technological limitations, geometric complexity, usability concerns, and ethical implications. Case studies demonstrate AR's effectiveness in complex procedures such as neurosurgery, maxillofacial reconstruction, and minimally invasive interventions. The study concludes by examining future trends and regulatory considerations essential for widespread adoption of AR in surgical practice. The paper emphasizes the need for surgeon-centered design, robust data integration, and the development of user-friendly AR authoring tools to optimize surgical outcomes and ensure ethical deployment.

Keywords: Augmented Reality, Surgical Planning, 3D Visualization, Medical Imaging, Intraoperative Guidance, Immersive Technology, Image-Guided Surgery.

INTRODUCTION

Surgery demands precise performance under pressure, greatly affecting patient outcomes. Medical imaging is crucial in surgical workflows, providing data for treatment planning and guidance. High-quality imaging data enables the construction of 3D models, enhancing surgical planning. 3D visualization offers anatomical context beyond conventional 2D slices, enabling better perception of the area of interest. While some preparations can occur offline, adjustments may be needed due to head alignment changes or occlusion during surgery. Augmented reality (AR) improves surgeons' understanding of spatial relationships by visualizing 3D models against real anatomy, creating a more immersive experience than classical methods. Medical imaging can be displayed in two-dimensional (surface) or three-dimensional (volumetric) formats. Conventional methods involve axial slices for 3D representation, while surface representations use color or opacity shading on meshes. AR overlays visualization results on real scenes, allowing natural head movements and focus on the surgical site without screen obstructions. Photonic trackers localize 3D models using infrared markers, maintaining the spatial relationship with the anatomy throughout the procedure. Early applications of AR in cranial tumor and scalp resurfacing surgeries show promising results. Displacing a large tumor alters scalp geometry, complicating surface adjustments. Traditional image processing can obstruct views and limit interaction with defects. The AR system enables operators to navigate volume and manage exposure effectively during surgery [1, 2].

Historical Background of Surgical Planning

Surgical planning for image-guided procedures involves multidisciplinary activities, including diagnostic image acquisition and clinical workflows reliant on medical imaging devices. CAD and CAM are crucial in preoperative planning, as they influence many preparation aspects. Typically, 2D medical images are inadequate for accurately defining anatomical structures due to interpatient variability. Consequently, diverse medical imaging generates numerous non-linear 3D datasets, necessitating the development of quick, reliable MRI registration algorithms for effective clinical use, since an in-depth understanding of 3D medical datasets is vital for interventions. 3D data enable volumetric visualization and clearer comprehension of anatomical relationships obscured in 2D images. This 3D data can be acquired through various techniques or reconstructed from traditional modalities. To accurately depict regions of interest (RoIs) and understand anatomical structures, rendering techniques must meet two critical requirements: alignment with the imaging device and real-time data integration. Many applications now utilize surface scanners that generate point sets instead of conventional volumetric representations, requiring an interpretation stage for geometrical information extraction and consistent surface description. As devices and their tools advance, more complicated workflows are developed. Some acquire 3D datasets that must be processed and integrated into interfaces visualizing anatomical knowledge at Fleur's three levels. These representations should align with imaging devices, as 3D visualization software controlling CAM tools needs to understand device poses to identify RoIs accurately. Technology has been established to support a real-time registration framework allowing various modalities to visualize and interact with the vicinity of interventional 3D images. This integrated approach enhances medical 3D images with high-definition RGB-Depth cameras. Recent studies explore the use of CAD tools by blending omni-directional imaging with literature and simple geometry partitioning or through sensor-detection of tools paired with machine learning. The application of AR in guiding image-driven interventions is re-emerging, focusing on optimizing AR display optics for the operating environment and outlining necessary guidelines [3, 4].

Technological Foundations of Augmented Reality

Realistic AR can be achieved on standard microscopes with stereo displays by augmenting 3D CT images on patients during surgery. Comparison with 2D 3D CT images is also possible. A volumetric rendering method enhances depth perception, while AR markers traditionally structure AR applications. An innovative method for marker-less imaging has been developed to address variations in position, rotation, and scale, enhancing practical AR applications. Integrating phonon drag techniques for 2D enclosure structures can stabilize sound states. The combination of 2D enclosure and a lateral sound switch aids in miniaturizing acoustic switches and addressing low-frequency sound manipulation challenges. Surface tension must be modeled in numerical simulations of osteotomy tracking, allowing for accessible AR generation. Free view-point volumetric rendering supports bimodal manipulation through a plug-and-play approach. Voxel-based data processing advantages require refinement. HMDs have become popular among specialists due to increased accessibility. Mono-HMDs typically offer a visual field of just 35-40 degrees in stereography, influencing the information a user can perceive. Immersive HMDs enhance the virtual 3D spatial perception, enabling better integration of real and virtual data through in situ visualization of surgical images for intuitive interaction. A general solution for visualizing 3D CT and MR images on immersive displays and graphs is provided. Rigid deformation engines align 3D models with anatomy variations in image volumes. Visual cues positively affect decision-making, aided by an AR-enabled airborne particle image velocimetry system featuring a novel calibration method and spatial reconstruction algorithm. Phantoscopy improves depth of field in surgical environments [5, 6].

Current Applications of Augmented Reality in Surgery

In recent years, visualization technologies have significantly improved our understanding of human anatomy. Imaging techniques can now provide 3D descriptions, enhancing both pre-operative and intra-operative visualization of anatomical structures. This evolution allows for better comprehension of complex surgical scenarios and improved planning strategies. Innovative technologies like augmented reality (AR) and mixed reality (MR) are being integrated into open surgery, using virtual models to enhance intra-operative visualization. These models can also be anchored to the surgical field in real-time through registration techniques. AR has been widely applied across various surgical fields, particularly in neurosurgery and otolaryngology. Mixed reality is also emerging in surgical applications. The last decade has seen a rise in intensive techniques for treating maxillofacial deformities, leading to more complex osteotomies and increased surgical time and complications. To address these issues, TMJ models and custom-fabricated plates have become common. However, these solutions necessitate a secondary intervention for proper plate positioning, requiring effective surgical workflows to reduce time. Research has explored the feasibility of AR systems in surgery, demonstrating their potential in maxillofacial procedures for planning, simulation, and intra-operative visualization of surgical anatomy [7, 8].

Benefits of Augmented Reality in Surgical Procedures

MR technology aids in pre-operative planning by modeling patient anatomy and strategizing surgical approaches, especially for complex hemilaminectomy. After a preoperative CT scan, 3D visualization was correlated with centric rings. An AR-based surgical simulator validated surgical knowledge, training, and planning for new medical procedures. Peritoneal bronchi, small structures deep in the lung parenchyma, are challenging to observe without dissection. Thoracoscopic techniques struggle with effective resection. A proposed technique employs deep convolutional neural networks (DCNN) for real-time 3D reconstruction of bronchi. AR capabilities extend to visualizing anatomical features in MR, unlike just overlaying 3D models from surgical planning software. An innovative AD-to-3D generation model creates simultaneous 3D layouts and texture maps based on musical performances. Neurosurgeons can better predict efficient trajectories through AR and 3D visualization, addressing difficulties in viewing complex 3D cortical structures. This method is user-friendly for new patients. Focused on preoperative rehearsal for mental exophytic parotid macroadenoma resection, an MR platform utilizing rapid prototyping and interaction techniques was developed. Master models of the macroadenoma, derived from CT images, facilitated online surgical rehearsals with adjustable perspectives. The augmented surgery simulation included haptic feedback for virtual tumor resections, influencing the surgical design through automatically generated motion blocks without requiring elaborate simulations [9, 10].

Challenges in Implementing Augmented Reality

The employment of augmented reality (AR) in surgical planning introduces a new set of challenges. AR technology is still a blooming industry regarding usability, affordability, and robustness; hence, its application in surgical planning can be supplemented by other more mature technologies to augment results and combat possible failures. However, it should be emphasized that many augmentations should still be achieved in conjunction with AR solutions. For some applications, deep learning methods may indeed provide results that would be hard to achieve by classical methods. Nevertheless, the classical image processing techniques are still as applicable methods in general as they have been before and should not be overlooked. Some clinical scenarios may also pose unique challenges that would limit the applicability of the proposed solutions. The geometric complexity comes to the forefront when assessing the maturity of medical augmentation technologies. For this reason, it is also the area where many proprietary "intelligent" planning tools exist. The difference is that these planning tools work with the limited input of 2D images and 3D point clouds or geometry files. The produced 3D computer-aided design (CAD) models are then sent for further examinations to the clinics or universities. Conversely, the proposed solutions outlined here could be practically applied in outpatient departments and education to check the applicability and expectability of surgery with more forgiving geometric conditions [11, 12].

Case Studies on Augmented Reality in Surgery

The experience of using augmented and mixed reality (AR) in treating abdominal cancer patients involved the utilization of Microsoft HoloLens glasses and innovative software. The study presents strategies to enhance visualization reliability of surgical targets and demonstrates how minimally invasive surgeries can be optimized during planning and in the operating room using AR. A modified algorithm for correcting the pose of the 3D models and HoloLens 2 allows for precise volumetric visualization of anatomical images. Issues like adjusting the transparency of the surgical site model and eliminating hidden organ faces were addressed. Several successful clinical cases utilizing AR and mixed reality technologies were highlighted. Surgical planning for cancer presents challenges as 3D data from CT or MR imaging often contains extraneous anatomical information, making visualization complex. Traditional screening techniques using multiple monitors can increase planning time significantly, complicating analysis. During surgery, a 3D model is displayed on one monitor alongside 2D slices on another, with varying screen distances affecting comfort. Addressing these inconveniences is crucial for improving surgical precision and efficiency [13, 14].

Future Trends in Augmented Reality for Surgical Planning

The development and practical implementation of augmented reality (AR) in surgery has advanced rapidly. All types of AR—such as all-VR viewing devices, mixed reality visors, and AR glasses—are now being employed in invasive operations. Projected images on screens or directly onto the patient can enhance the effectiveness of surgical workflows during minimally invasive procedures. Dedicated AR solutions are being created for specific operations, yet most studies are technical, often lacking a focus on the surgeon's perspective and workflows. This oversight means the full potential of AR in surgery remains underexplored. Surgery is complex, and AR technologies struggle to capture the intricacies of surgical workflows. Communication delays between instruments and settings changes can lead to adverse outcomes, highlighting the necessity of aligning AR development with surgical realities. Surgeons have diverse instrument preferences, ranging from traditional metal scalpels to disposable options and specially lit variants for visibility. Consequently, AR solutions, particularly those requiring penetrating light, must be tailored to each instrument type or model for effectiveness [15, 16].

Ethical Considerations in Augmented Reality Surgery

In recent decades, computer-based methods for creating 3D models from medical images have surged. Many are focused on exporting models, and some shareware software aids in medical data visualization. Despite having advanced tools for 3D model generation, the usefulness of these models is limited without effective tools for practical application in real environments. Current operating rooms often resemble a chaotic kitchen with excess data like DICOM files. For augmented reality (AR) surgery to be advantageous, appropriate tools are essential to facilitate cost-effective practical applications. Collectively chosen augmentations, aligned with surgical plans, frequently require multi-view perspectives as seen in arthroplasty or complex sternotomies. Existing AR solutions, rooted in outdated schemes, are overly complicated for straightforward use, making them poor substitutes for traditional tactile surgical techniques. Although some of these systems are entering the market, they are based on centuries-old knowledge, lacking maturity as technologies. Careful evaluation of these competing solutions is crucial. Ideally, perspective models from voxel datasets or triangulated meshes could be augmented for both planning and actual surgical use, without complicating the operating room's search space. Unfortunately, reaching this level of feasibility remains unachievable, and solutions must incorporate strategic generation tactics and simpler alternative solutions for effective implementation [17, 18].

Regulatory Landscape for Augmented Reality in Healthcare

Investment in augmented reality applications in the healthcare industry has been accelerating over the past few years. It is predicted that the augmented reality (AR) market will reach $48 billion in revenue in 2026 from $5 billion in 2021, a growth of over 800%. This rapid increase in the manufacturing and consumer acceptance of AR-capable hardware and the democratization of AR authoring tools have opened avenues for medical educators and physicians to publicly share 3D models, animations, and AR experiences of anatomy and pathology. However, in parallel, other industries have exposed users to unfiltered technicalities of AR environments, also called AR authoring tools. For example, manufacturing companies are adopting AR authoring tools that require a vast amount of technical background to create AR experiences. The severely limited availability of easy-to-use authoring tools in the medical field raises concerns about an inappropriate balance in the quality of AR hardware development and the quality of the AR authoring environment. As a consequence, the medical community risks using AR systems with poor content that could lead to an inaccurate recognition of the technology. For the effective medical advancement of AR, there is an urgent need to expose scientists and medical practitioners to the potential applications that a suitable technology could offer. Adjustment to Contents The set of criteria needed to create the magic of AR applications in the medical and healthcare industry may vary based on the specificity of focus (performa, usability, versatility, or accessibility). However, based on a participatory design approach to exploring user-generated concepts for three focal areas of AR application in the medical field, the most commonly shared criteria for successful implementation of AR presentations for each focal area could be extracted. Quantitative assessment of user-generated ideas provides a clearer overview of the prioritized desirable characteristics in AR services. “Exploration mode” applies to lightweight, low-effort experiences. “Trial mode” applies to passive, observational experiences on desktop computers. “Diagnosis mode” applies to interactive, participatory experiences on mobile and tablet devices. AR previews are expected to be beneficial means of user education to promote informed use of people-generated healthcare services in an uncertain and scary environment [19, 20].

Comparative Analysis with Traditional Surgical Techniques

In surgery, traditional methods use preoperative imaging with felt pen marks or markers on X-ray images to guide cutting, drilling, and screwing. This can lead to errors in implant positioning. Augmented reality (AR) offers accurate spatial models aligned directly to the patient, improving realism and safety. The proposed volumetric augmented reality (VAR) system combines data from preoperative CT or intraoperative X-ray images, locates patient-scanner-AR headset-object positions via 3D homography transformation, and is adjustable for different settings. Pilot studies show enhancements in perceived realism and surgical safety from the 3D models. Pre- and intraoperative images use a single holding frame with a 10° tracking error and a wide field of view. While volumetric visualization improves surgeon performance, faithful representation of rigid objects is challenged by AC lag. Stereoscopic spectacles also struggle with soft tissue interpretation and instrument guidance in dominant AR methods. The VAR setup maps volumetric models directly, compatible with any X-ray imaging, enhancing accuracy and tolerance. After validation, these methods could enhance understanding of 3D anatomy, intuitive manipulation, and motion tracking to prevent mixing fixed points. Integration of stereoscopic views increases spatial accuracy, while extended tracking volume from model and video cameras eliminates the need for light markers. This approach faces challenges related to subjective drawings and conflicting tracking models. Attention could shift towards 2D sprite images, benefiting contrast, though 2D tracking points face depth perception limitations. Volumetric visualization challenges include accurate 3D object fabrication. AR provides surgeons with superimposed views of the patient's image volume at comparable depths using head-mounted displays (HMDs). Guided AR systems co-register patient and object positions to pre-operative images, with view-dependent methods ensuring accurate overlays through HMD cameras [21, 22].

Interdisciplinary Collaboration in Augmented Reality Development

The interplay of expertise across interdisciplinary roles fosters development, impact, and accessibility, aiming to harness strengths for addressing technical, ethical, and educational issues in surgical environments. This analysis highlights a surgical intervention using mixed reality for visualizing crucial 3D patient CT scans. The focus is on system 2's deployment, emphasizing its technical and ethical challenges. Although augmented reality enhances immersive experiences in hospitals, it does not alter the surgeon's point of view. However, this technology brings forth issues regarding the transfer of know-how and dissemination of surgical templates. Currently, surgeons rely on conventional 2D screens, and efforts are being made to avoid occlusion through layers, spatiotemporal modeling, and improved patient interactions. Research indicates that alternative perspectives can yield better outcomes. The goal is to convert benign information like CT scans into manipulable 3D patient images, allowing quick access to critical information regarding cuts and depth of incision. However, caution must be exercised as biophysical phenomena might not be easily recognizable. Incorporating machine learning and simulation is necessary, uniting clinical expertise, engineering skills, and ethical considerations. Recognizing patient images as processes involving various stakeholders is crucial, as is addressing the unstructured nature of hospital data, technology's impersonality, and information overload [23, 24].

Patient Perspectives on Augmented Reality in Surgery

In the past decade, attempts have been made to familiarize patients with surgical planning through visualization programs, often based on 3D renderings with the introduction of VR devices. Viewing and jaunting through a meticulously rendered 3D simulation of the clinical data is immersive yet often insufficient in showcasing the surgical plan. A more intuitive understanding of the surgical plan can be achieved through phone-based AR applications capable of recognizing the patient using the suggestions made for patient-specific 3D printing. Here, a brief overview of clinical and technical feasibility studies providing the basis for future patient-specific AR applications is presented. The goal is to improve patient-surgeon communication beyond the 3D renderings offered by commercially available virtual surgical planning software. A free-to-download application based on AR technology was developed. It allows patients to visualize, in real time, the preoperative surgical planning created with software. The results of a pilot feasibility study for a pediatric case are presented, followed by a comprehensive analysis of surveys collected after extended in-clinic testing in four different surgical indications in children six years and older. The studies' results show that AR can be a valuable tool for preoperative planning in surgical cases suited for visualization. Feedback from patients suggests further improvements, mainly concerning stereoscopic and personalized data. This work highlights the importance of educating the surgical staff about new technology before attempting to implement it in the operating room. It focuses on AR tools employed in the operating room, including a server-client setup to broadcast images, damper synchronization software for camera resizing and movement control, and guidance annotation and review permission settings [25, 26].

Technical Specifications for Augmented Reality Systems

The AR systems in this work integrate into a preclinical workflow for CT-guided needle insertion and offer intuitive head-coupled navigation through a user-friendly interface. This interface meets modern expectations for faster and more adaptable design in professional and consumer settings. Addressing current challenges in 3D visualization in clinical practice, such as the accessibility of models and data, the work presents solutions that improve surgical workflow while maintaining efficiency. Preparation, data, and model handling can be managed in-house using free software, enhancing usability. The AR system simplifies the registration phase without the need for cumbersome tracking, facilitating its integration into preclinical workflows vital for its adoption in the OSR, a challenging environment for tech acceptance and usability. Interaction techniques for voxel-based methods have been limited by technology constraints and viewpoint issues. The novel techniques introduced allow intuitive navigation of volumetric CT scans with surface rendering, enabling better registration and planning for needle trajectories both preoperatively and intraoperatively. The system alleviates spatial understanding complexities, reducing mental load for operators, which is critical in surgical scenarios. The significant enhancements in usability, learnability, efficiency, and user satisfaction suggest multiple pathways for future advancements in AR technology and other visualization forms. Broader applications of XR technologies can leverage existing AR systems for orientation, location, interaction, and feedback in clinical workflows, particularly for remote and quality-control tasks. These systems link fixed and model viewing poses effectively. However, presenting medical image data with existing AR systems poses challenges due to domain similarities. Such tasks necessitate accurate and dynamic interaction techniques for managing intricate medical data, which have not yet been effectively integrated into XR systems. Solutions for these challenges, particularly in the consumer domain, can be explored using readily available gaming technology [27-29].

User Experience Design in Surgical Augmented Reality

Surgical augmented reality (AR) systems merge imaging modalities to position anatomical assets accurately. They enhance the surgical field with digital indicators, necessitating not only overlaying these indicators but also adjusting their identities based on anatomical properties. The AR container must align with surgical instruments and geometric transformations. Comparing augmented indicators with instruments and patient data using co-localized imaging improves surgical assistance usability. Updates in augmented content require co-registration with the surgical view. Indicators within the surgical display have the flexibility to change container volume, necessitating a robust estimation of device changes during engagement with surgical data. Localizing images during surgeries with various transformations poses challenges. Nonetheless, co-registering AR content with instruments allows for augmented observations outside the display, aiding in predicting plastic locations for AR devices and differentiating imaging modalities based on instrument data. The success of AR in applications like desktop and handheld systems requires significant pre-processing, including multi-temporal or multi-sensor data registration. These systems face limitations in operating rooms, where surgeons adeptly perform complex tasks under sub-optimal conditions and varying environments. For imaging-guided surgeries, AR needs to address imaging constraints to minimize hesitancy. The accessibility of original MR/CT scans and volumetric data in modern therapy suites enables the creation of a user-friendly interface for novice practitioners [30-33].

CONCLUSION

Augmented Reality presents a promising frontier in surgical planning, enabling enhanced precision, improved visualization, and efficient integration of preoperative and intraoperative workflows. By bridging the gap between 2D imaging and the 3D complexity of human anatomy, AR supports accurate navigation and informed decision-making during complex procedures. Its successful application in various surgical domains—ranging from neurosurgery to minimally invasive oncology—demonstrates its versatility and transformative potential. However, challenges such as the need for reliable data registration, device calibration, ethical use, and surgeon adaptability remain critical barriers. Future advancements must focus on surgeon-centric design, real-time data fusion, regulatory frameworks, and accessible AR development platforms. With strategic investment and cross-disciplinary collaboration, AR has the potential to redefine surgical precision and patient safety, marking a significant leap in the evolution of modern medicine.

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