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REVIEW ARTICLE

# Development of Holoeyes Holographic Image-Guided Surgery and Telemedicine System: Clinical Benefits of Extended Reality (Virtual Reality, Augmented Reality, Mixed Reality), The Metaverse, and Artificial Intelligence in Surgery with a Systematic Review

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ABSTRACT:
Image-guided surgery using XR (extended reality: VR/AR/MR) technology has the potential to revolutionize the field of surgery by improving surgical accuracy, reducing procedure time, and enhancing communication and collaboration among the surgical team. We have developed a web-based system, Holoeyes, integrating XR, AI, and metaverse technology to facilitate holographic image-guided surgery. Holoeyes extracts organ shape data from CT or MRI scans and renders them with positional information to obtain X, Y, and Z coordinates. These coordinates are then converted into polygonal information for use in XR technology. The medical device, Holoeyes MD, was developed to create XR applications for surgical planning and navigation. It provides an immersive experience for the surgical team, improving both accuracy and efficiency. The integration of the metaverse in surgery allows for spatial conferencing and review of training, and the avatars replicate the hand and eye movements of the actual surgical procedure. Our Holoeyes system has already been utilized in numerous institutions for pre-and post-operative conferences, surgical planning, and surgical records, with multiple people wearing the headset and sharing information about the pathology, extent of resection, and layers of dissection from all directions. We conducted a systematic review of the literature to investigate the effectiveness of Holoeyes, focusing on the use of XR and the metaverse in surgery. We believe that Holoeyes has the potential to become an indispensable tool in the field of surgery, and we encourage further research and development in this field.
**Keywords:** Extended Reality (XR), Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), Artificial Intelligence (AI), metaverse, Holoeyes, OsiriX

## Introduction

Spatial awareness is an essential ability for surgeons in preoperative diagnosis, surgical planning, accurate surgical techniques, technical training, and education. Although two-dimensional (2D) images from computed tomography (CT) or magnetic resonance imaging (MRI) can be analyzed and reconstructed into three-dimensional (3D) models, most hospitals still display these images on a small, flat computer screen. Moreover, as long as the images are presented within the limited area of this display, spatial recognition of the actual depth of the organs and lesions, and their spatial positional relationships over a wide area, is insufficient. Although diagnostic imaging by CT and MRI has established diagnostic science using 2D screens, 3D spatial information, and spatial approach methods in the surgical process are also important. We hypothesized that extracting shape data of each organ from the 3D space coordinates provided by CT and MRI, processing this into polygon data, and mapping it onto real-space 3D coordinates, could provide a more natural and spatial understanding of a patient's pathology. In recent years, the use of virtual reality (VR), augmented reality (AR), mixed reality (MR), these are collectively called extended reality (XR), and have been widely used in the fields of entertainment, games, and medicine[1-27]. We applied this XR technology to 3D data of medical images such as CT and MRI[1-3]. On a 2D screen displaying a patient's CT or MRI image data, regions of interest, such as organs, tumors, and lesions, are continuously extracted from each planar slice. This extraction is achieved using various algorithms, including deep learning powered artificial intelligence (AI). The extracted data is then rendered with slice thickness and position information to obtain 3D X, Y, and Z coordinates. This information was converted into polygonal information using polygon mesh, and exported to polygon formats called "STL" and "OBJ". Polygonization of organ shapes from medical images is widely used in 3D printers and CAD systems, and many commercially available medical image analysis software and free (some paid) applications such as OsiriX (Pixmeo SARL Geneve Swiss)[28] are already widely used. OsiriX is widely used by surgeons worldwide and is marketed as a medical device in the United States (FDA Class II), Europe (CE Class IIa), and Japan (PMDA Class II). We believe that if the polygon data of organs can be immediately viewed and manipulated in a sterile surgical field, it will be useful for surgical guidance, navigation, simulation, training, training, and education. For this purpose, we thought that a system that uses XR technology to present polygon data of organs and avatars of surgeons in the metaverse space would be useful. However, creating an XR application for each case requires advanced programming techniques and code writing, which is not easy for surgeons to do in a clinical setting. Therefore, we developed a web service that automatically converts polygon data of organs into XR apps on the cloud, and developed "Holoeyes MD" (Holoeyes Inc. Tokyo Japan)[29], which is now commercially available after approval as a medical device in Japan. The system can create an XR application for each case in about 10 minutes and can be used immediately after installation on commercially available VR head-mounted displays for holographic image-guided surgery[1-3]. The system is already being used at many institutions for pre-and post-operative conferences, surgical planning, and surgical records, with multiple people wearing the headset and moving around while sharing information about the pathology, extent of resection, and layers of dissection from all directions[4-27]. This holographic image-guided surgery using XR technology has the potential to revolutionize the field of surgery by improving surgical accuracy, reducing procedure time, and enhancing communication and collaboration among the surgical team. In this paper, we describe the development of Holoeyes MD, a software approved as a medical device in Japan, and present our clinical experience with holographic image-guided surgery.

## Methods:

In developing the Holoeyes system, we initially extracted shape data of each organ from the 3D spatial data acquired from CT and MRI scans using AI technology. We used various algorithms, including deep learning using AI, to continuously extract organs, tumors, and lesions as regions of interest at the boundaries of each region in each planar slice of the patient's CT or MRI image data. The extracted data was then rendered using the slice thickness and position information to obtain the X, Y, and Z coordinates. The X, Y, and Z coordinates were then converted into polygonal information using polygon mesh and exported to general-purpose polygon formats such as STL and OBJ.

Polygonization of organ shapes from medical images was performed using specific commercially available medical image analysis software like OsiriX and standard Digital Imaging and Communications in Medicine (DICOM) image workstations. This polygonal data was presented in accordance with the 3D coordinates of the real space, thereby enabling spatial recognition of the actual depth of the organs and their spatial positional relationships over a wide area using XR technology.

To promptly visualize and manipulate polygon data of organs in a sterile surgical field, we created a web service that automatically transforms polygon data of organs into XR apps on the cloud. We then developed "Holoeyes MD" (Holoeyes Inc. Tokyo Japan), which is now commercially available after approval as a medical device in Japan. The Holoeyes system can generate an XR application for each case in approximately 10 minutes and can be utilized immediately after installation on commercially available VR head-mounted displays (for instance, Meta Quest) or MR goggles (such as HoloLens and Magic Leap). (Figure 1).

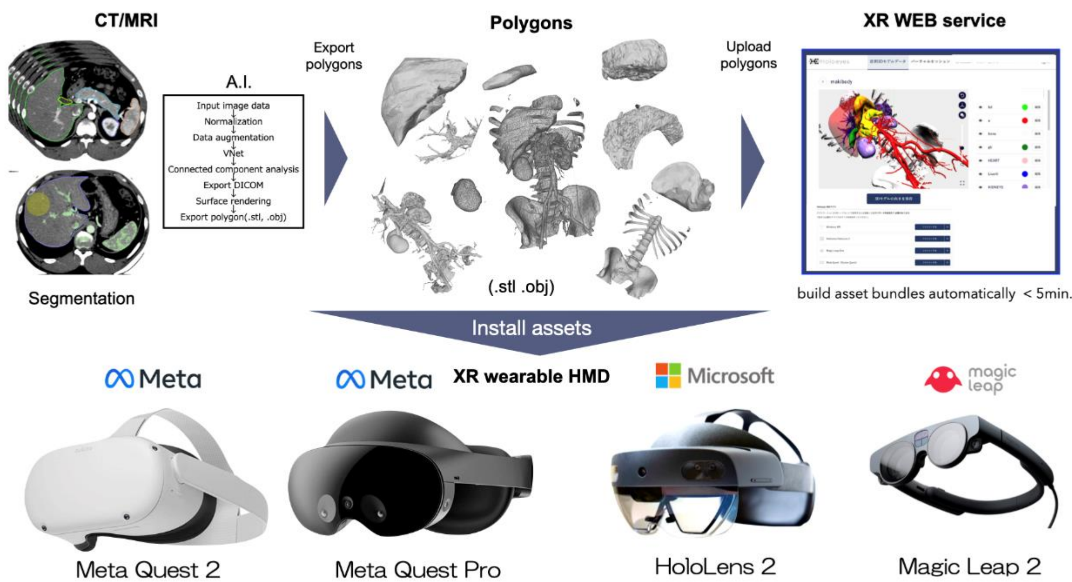


**Fig 1:** The workflow of Holoeyes system that enables surgeons to generate XR apps automatically and install on wearable XR devices in less than 10 minutes from 3D reconstruction of medical images via the Holoeyes cloud.

The following is a step-by-step workflow for converting medical images to an XR application using Holoeyes Cloud (Table 1):

1. Data acquisition: Obtain medical imaging data, such as CT or MRI scans (including volume data) of the patient. Prior to use, obtain the patient's consent.
2. Segmentation: Using medical image analysis software, extract the regions of interest of the patient's anatomical structures through manual or automated segmentation, such as by AI.
3. 3D polygon modeling: Export each extracted region of interest to a polygon file in STL or OBJ format, which is supported by Holoeyes system.
4. Import the 3D polygon model: Upload the STL or OBJ file to the Holoeyes website. Here, the user can change the color and transparency of each organ model. In less than 10 minutes, the Holoeyes cloud will automatically generate assets for the individual XR application and list them on the cloud server.
5. 3D Visualization: Install the Holoeyes system application on a compatible XR headset (such as MetaQuest, HoloLens, MagicLeap) or other device, and install the generated assets for the XR app. This allows for the display of the patient's anatomy in a 3D immersive environment for stereo-spatial visualization using the 3D polygon model.

**Step-by-step workflow of converting medical images to XR application by Holoeyes Cloud**

1. **Data acquisition**: Obtain medical imaging data (CT or MRI scans, including volume data) of the patient. The user need to obtain the patient's consent for data use.

2. **Segmentation**: Using medical image analysis software, extract regions of interest of the patient's anatomical structures through manual or automated segmentation, e.g., by AI.

3. **3D polygon modeling**: Export each extracted region of interest to a polygon file. Holoeyes MD supports STL and OBJ formats.

4. **Import the 3D polygon model**: Upload the STL or OBJ file to the Holoeyes website. The color and transparency of each organ model can be changed. In less than 10 minutes, Holoeyes will automatically generate the assets for the individual XR application in the Holoeyes cloud and list them on the cloud server.

5. **3D Visualization**: Install the Holoeyes MD application on your XR headset (MetaQuest, HoloLens, MagicLeap, etc.) or other compatible device, install the generated assets for the XR app, and display the patient's anatomy in a 3D immersive environment for stereo-spatial visualization using the 3D polygon model.

It should be noted that the above workflows may vary depending on the specific version of the Holoeyes MD application and user configuration. Also, technology continues to evolve, and new features may be added or existing features may be improved.

**Table 1:** Step-by-step workflow of converting medical images to XR application by Holoeyes cloud.

Holoeyes system encompasses the following features (Table 2):

- Interaction and manipulation: Users can interact with the 3D model employing gestures or controllers, allowing them to manipulate the model's position, rotation, and scale. This interaction helps to better understand anatomical structures and plan surgical interventions.
- Collaboration: With the optional Holoeyes VS virtual session feature, users can conduct conferences in the metaverse space with multiple avatars situated in remote locations. They can share 3D polygon models with others to facilitate discussion, learning, and better decision-making.
- Documentation: Users can add text, lines, and other annotations to the 3D polygon model in a spatially flexible manner. Controller, fingers, eye direction, and body position can also be spatially recorded at the same time. Later, these movements can be reproduced spatially as an avatar.
- Spatial Recording: Voice commentary and remote conversations can be simultaneously recorded in chronological order and saved as annotations and additional information for future reference. The database can be managed in the cloud as an archive of surgical records and conferences.
- Mobile education: With the optional HoloeyesEd feature, the above recordings can be delivered to an XR-HMD or mobile device (such as an iPhone, iPad, or Android) and viewed in VR and AR.

We conducted a literature review on the practical usage of the Holoeyes system in clinical scenarios, basing our analysis on a questionnaire provided to surgeons who actively use the system, along with published English-language articles[-27]. Details on the calculation, inclusion/exclusion criteria, study design and protocol, and data collection methods are elaborated in the referenced articles.

**List of features of Holoeyes MD application**

**Interaction and manipulation**:
Interact with the 3D model using gestures or controllers to manipulate the model's position, rotation, and scale. This interaction helps to better understand anatomical structures and plan surgical interventions.

**Collaboration**:
With the optional Holoeyes VS virtual session feature, users can hold conferences in the metaverse space with multiple avatars in remote locations. Share 3D polygon models with others to facilitate discussion, learning, and better decision-making.

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Add text, lines, etc., along with the 3D polygon model in a spatially flexible manner. Controller, fingers, eye direction, and body position can also be spatially recorded at the same time. Later, these movements can be reproduced spatially as an avatar.

**Spatial Recording**:
Voice commentary and remote conversations can be simultaneously recorded in chronological order and saved as annotations and additional information for future reference. The database can be managed in the cloud as an archive of surgical records and conferences.

**Mobile education**:
With the optional HoloeyesEdu feature, the above recordings can be delivered to an XR-HMD or mobile device (iPhone, iPad, Android) and viewed as VR and AR.

It should be noted that the above workflows may vary depending on the specific version of the Holoeyes MD application and user configuration. Also, technology continues to evolve, and new features may be added or existing features may be improved.

**Table 2:** List of features of Holoeyes system application

**Results:**

A detailed examination of the cited literature suggests that most surgeons have found the use of the Holoeyes system useful for accurate visualization of the surgical site and for surgical planning, navigation, and education, however, a precise numerical assessment of accuracy and effectiveness rates is yet to be accomplished[4-27]. Using HoloLens2, the holographic images offered an immersive experience for the surgeon (Figure 2) and the surgical team, enhanced communication and collaboration during surgery (Figure 3).

**Fig 2:** The use of Holoeyes system in an operating theater allows for precise visualization and navigation of the surgical anatomy, improving the accuracy and efficiency of the procedure.

**Fig 3:** Using HoloLens2 to share holographic images provides an immersive experience for the surgical team and enhances communication and collaboration during surgery.

The metaverse presented through these holographic images, holds significant potential benefits for surgical planning and navigation. By visualizing patient-specific anatomy in 3D and allowing for virtual rehearsal of surgical procedures, the metaverse can contribute to improved surgical outcomes and reduced risks (Figure 4).

**Fig 4:** By visualizing patient-specific anatomy in 3D for surgical simulation and allowing for virtual rehearsal of surgical procedures, it could contribute to improving surgical outcomes and reducing risks.

Additionally, Holoeyes system was used for preoperative planning and patient education, providing a better understanding of the surgical plan and possible outcomes. To foster collaboration and enhance surgical precision, we incorporated an optional feature to Holoeyes that enables multiple surgeons to appear as avatars at the same time in a virtual space, using XR technology to spatially present medical images. Postoperative reviews and discussions with surgical team members were also facilitated by the system. This allows for spatial conferencing and review of training. The avatars mimic the hand and eye movements of the actual surgical procedure, which are recorded as spatial coordinates with audio commentary, and saved as a data archive. Other surgeons can then revisit the procedure in a spatial context at a later time (Figure 5).

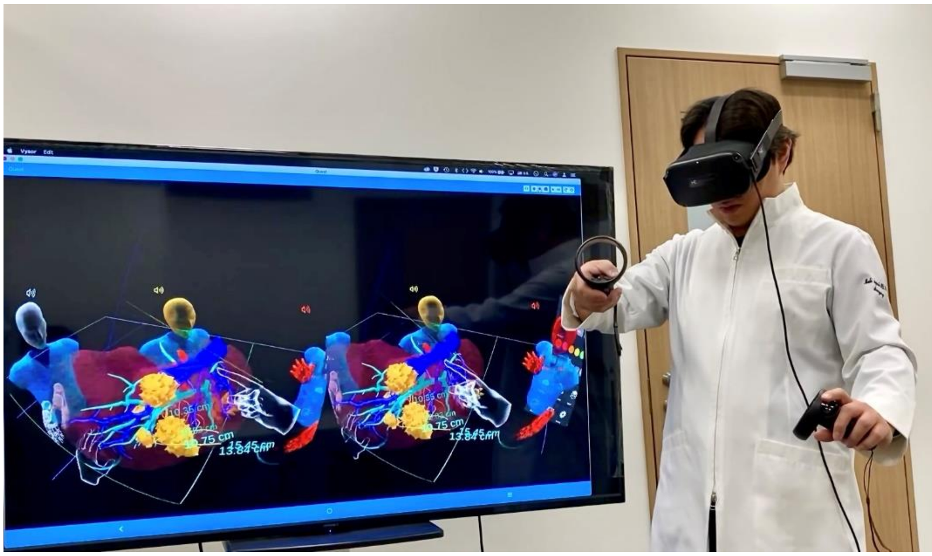

**Fig 5:** Holoeyes Vietual Session (VS) is used in the metaverse for spatial conferencing and training review, allowing multiple surgeons to appear as avatars in the same virtual space at the same time.

We evaluated the effectiveness of XR and the metaverse in surgery utilizing the Holoeyes system. Five databases (PubMed, Cochrane Library, Web of Science, Science Direct, and Google Scholar) were searched from January 1, 2015, through April 30, 2023, This resulted in the inclusion of 27 pertinent published reports following an exhaustive review process (Table 3).

| Paper Number (References) | Author | Year | Department of surgery | Application | Brief Summary |
|---|---|---|---|---|---|
| 1 | Sugimoto M. | 2021 | overall | overall | Cloud XR and 5G networks for holographic medical image-guided surgery and telemedicine |
| 2 | Sugimoto M. | 2020 | overall | overall | XR in precision surgery, 3D printing, holography, AI, radiomics, online VR telemedicine |
| 3 | Sugimoto M. | 2015 | overall | overall | Augmented tangibility surgical navigation using 3D hologram zSpace, OsiriX, bio-texture organ modeling |
| 4 | Aoki T. et al. | 2020 | hepatobiliary | hepatectomy | Holography-guided percutaneous puncture for IR fluorescence-guided laparoscopic hepatectomy using HoloLens |
| 5 | Saito Y. et al. | 2020 | hepatobiliary | hepatectomy | Intraoperative 3D hologram support with MR techniques in liver surgery |
| 6 | Saito Y. et al. | 2021 | hepatobiliary | hepatectomy | Simulation and navigation in hepatectomy |
| 7 | Saito Y. et al. | 2022 | hepatobiliary | hepatectomy | Intraoperative support with 3D holographic cholangiography in hepatobiliary surgery |
| 8 | Kitagawa M. et al. | 2020 | hepatobiliary | laparoscopic cholecystectomy | MR holographic cholangiography for image-guided laparoscopic cholecystectomy |
| 9 | Kitagawa M. et al. | 2022 | hepatobiliary | laparoscopic cholecystectomy | Intraoperative holography navigation using a HoloLensr during laparoscopic cholecystectomy |
| 10 | Morimoto T. et al. | 2022 | orthopedic | spine surgery | Digital transformation on medical education and rehabilitation in spine surgery |
| 11 | Morimoto T. et al. | 2022 | orthopedic | spine surgery | Status quo and future directions of XR technology in spine medicine |
| 12 | Aoyama R. et al. | 2022 | orthopedic | spine surgery | Novel techniques using MR systems in the treatment of spinal cord tumors |
| 13 | Aoyama R. et al. | 2021 | orthopedic | spine surgery | AR device for preoperative marking of spine surgery to improve accuracy of level identification |
| 14 | Aoyama R. et al. | 2021 | orthopedic | spine surgery | AR in spinal decompression surgery using CT/MRI fusion image |
| 15 | Sakai D. et al. | 2020 | orthopedic | spine surgery | Real-world experience using XR in spinal surgery |
| 16 | Koyachi M. et al. | 2023 | dental | mandibular reconstruction | MR and CAD/CAM technology for mandibular reconstruction |
| 17 | Sugahara K. et al. | 2023 | dental | le Fort I osteotomy | MR and CAD/CAM technology for treatment of maxillary non-union after Le Fort I osteotomy |
| 18 | Koyachi M. et al. | 2021 | dental | le Fort I osteotomy | Accuracy of Le Fort I osteotomy with combined CAD/CAM technology and MR |
| 19 | Sugahara K. et al. | 2020 | dental | maxillary tumor resection | MR and 3D printed models for resection of maxillary tumor |
| 20 | Sato Y. et al. | 2020 | digestive | thoracoscopic esophagectomy | Holographic image-guided thoracoscopic surgery for esophageal cancer patients with abnormal artery |
| 21 | Tokunaga T. et al. | 2022 | digestive | transanal rectal resection | Reports the use of intraoperative holographic image-guided surgery in a transanal approach for rectal cancer |
| 22 | Ryu S. et al. | 2022 | digestive | laparoscopic colorectomy | Intraoperative holographic guidance using XR technology during laparoscopic colorectal cancer surgery |
| 23 | Hosoya K. et al. | 2022 | otorhinolaryngeal | sinus anatomy education | Demonstrates the use of VR to teach sinus anatomy |
| 24 | Yamazaki A. et al. | 2021 | otorhinolaryngeal | temporal bone surgery | XR for immersive, experiential anatomy education and for surgical planning in temporal bone surgery |
| 25 | Ito K. et al. | 2021 | otorhinolaryngeal | trauma simulation at hybrid ER | Describes a trauma patient care simulation using XR technology in the hybrid emergency room system |
| 26 | Tachibana K. et al. | 2022 | cardiac | coronary artery bypass | VR simulation for minimally invasive coronary artery bypass grafting |
| 27 | Yoshida S. et al. | 2019 | urologic | partial nephrectomy | Report on the use of MR CT-based surgical planning for partial nephrectomy using a HoloLens |

**Table 3:** A summary table of the studies included in the present systematic literature review of XR and the metaverse in surgery using Holoeyes is presented. Five databases (PubMed, Cochrane Library, Web of Science, Science Direct, and Google Scholar) were searched from January 1, 2015, to April 30, 2023, resulting in the inclusion of 27 relevant published reports after a thorough review process.

There were 3 articles [1-3] regarding overall image-guided surgery using XR and the metaverse, and by department of surgery, the most common were 6 hepatobiliary[4-9], and 6 orthopedic[10-15], followed by 4 dental[16-19], 3 digestive[20-22], 2 otorhinolaryngeal[23-24], 1 emergency[25], 1 cardiac[26], and 1 urologic surgery [27].

The surgical applications were hepatectomy[4-7], laparoscopic cholecystectomy [8-9], spine surgery [10-15], maxillofacial surgery[16-19], esophagectomy [20], colorectal resection [21-22], otorhinolaryngology surgery[23-24], cardiac surgery[26], and urologic surgery [27], as well as in medical education and trauma patient care [25].

Here, we summarize various clinical use cases. This review provides a current and comprehensive examination of the Holoeyes technology and their applications in surgery.

In liver surgery using HoloLens and MR techniques, surgeons have been able to visualize 3D holograms of the liver during laparoscopic liver resection and hepatectomy by holography-guided percutaneous puncture and intraoperative 3D hologram support. These holograms aid in navigation and enhance surgical outcomes[4].

In hepatobiliary surgery, 3D holographic cholangiography and MR holographic cholangiography facilitate image-guided laparoscopic cholecystectomy. Intraoperative holography navigation using HoloLens has enhanced the surgeon's situational awareness and surgical precision[5-9].

In spine surgery, XR technology has significantly impacted medical education, rehabilitation, and treatment planning. It provides an immersive, experiential anatomy education and has enabled the development of novel techniques for treating spinal cord tumors[10-13].

AR devices have improved the accuracy of preoperative marking in spine surgery and spinal decompression surgery[14]. By merging CT/MRI images, surgeons can better identify the levels for intervention and minimize complications[15].

In maxillofacial surgery, MR and CAD/CAM technology have been employed for mandibular reconstruction, treatment of maxillary non-union after Le Fort I osteotomy, and resection of maxillary tumors. The combination of CAD/CAM and MR technologies has improved the accuracy of Le Fort I osteotomies[16-19].

Holographic image-guided thoracoscopic surgery has been used for esophageal cancer patients with abnormal arteries[20]. Intraoperative holographic guidance using XR technology during laparoscopic colorectal cancer surgery has improved surgical outcomes[21-22].

In sinus anatomy education, VR has been employed to create immersive and interactive learning experiences for students[23]. Similarly, XR technology has been utilized for surgical planning in temporal bone surgery[24].

XR technology has been used in trauma patient care simulations, improving patient outcomes in hybrid emergency room systems[25]. It has also been applied in VR simulations for minimally invasive coronary artery bypass grafting, enhancing surgical skill development and patient safety[26].

MR CT-based surgical planning for partial nephrectomy using HoloLens has streamlined the process, leading to more precise and effective surgeries[27].

These clinical use cases highlight the transformative power of Holoeyes technologies in various medical fields. The continued development and integration of Holoeyes technology will undoubtedly revolutionize patient care and medical education, providing safer and more effective treatments for a wide range of conditions.

**Discussion:**

These results suggest that holographic image-guided surgery employing XR technology holds significant potential as a valuable tool within the surgical field.

The experiences with Holoeyes system suggest that holographic image-guided surgery using XR technology enhances communication and collaboration among the surgical team, offering an immersive experience for the surgical team, which can enhance communication and collaboration during the surgery. The precise navigation and visualization provided by the Holoeyes system can enhance surgical precision and efficiency, resulting in better patient outcomes.

In the use of XR technology in medical capability, it is frequently used for training in the field of surgery and anatomy, and training using XR-HMDs is highly motivating and engaging, the XR-HMD intervention is effective, has no negative impact on patients, and can alleviate financial, ethical, and supervisory constraints. This is an excellent benefit in medical education.

The Holoeyes system is already being utilized at numerous institutions for pre-and post-operative conferences, surgical planning, and surgical records, with multiple individuals donning the headset and moving around while sharing information about the pathology, extent of resection, and layers of dissection from all directions[1-27].

**Surgery Employing XR and AI**

Medical image analysis, particularly in the realm of CT and MRI technologies, is undergoing significant transformation thanks to the advent of AI, more specifically, deep learning and machine learning. These AI subfields are critical to the development of core applications such as image reconstruction and enhancement, data augmentation, anomaly detection, and the segmentation of specific lesions.

Deep learning, a specific subset of machine learning, utilizes neural networks with multiple layers (hence 'deep') to model and understand complex patterns in datasets. In medical imaging, deep learning techniques can significantly enhance image reconstruction and data augmentation. They can process large amounts of imaging data, identify intricate patterns, and generate more detailed and accurate visuals. This potentially elevates the diagnostic capabilities of physicians.

Machine learning, a broader field, uses algorithms to parse data, learn from it, and then subsequently make determinations or predictions about something in the world. Its techniques are particularly effective in anomaly detection within medical images. By learning from a large number of normal and abnormal cases, these algorithms can effectively detect anomalies in new patients' data.

Another pivotal area is lesion segmentation. Deep learning models, particularly convolutional neural networks, have shown remarkable performance in identifying and segmenting lesions in medical images, which aids in the formulation of more precise treatment plans.

In sum, if these AI-driven tools are fully leveraged, they could offer considerable advantages to the medical field. However, it is crucial to understand the capabilities and limitations of these technologies for their optimal application in clinical settings. The anticipation is high for further research and development in this exciting and promising field.

In Japan, several AI-based medical applications have been developed and commercialized to improve diagnostics and patient care. Some examples include:

Ziosoft: Ziosoft, a Japanese company, offers an advanced visualization and analysis software for medical imaging. Their solution provides 3D, 4D, and 5D imaging for CT, MRI, and other modalities, enabling enhanced visualization and quantification of anatomical structures.

Fujifilm: Fujifilm's AI platform is designed to support diagnostic imaging by leveraging deep learning technologies. The platform aids in detecting suspicious lesions in medical images, reducing reading time, and improving diagnostic accuracy.

Canon Medical Systems: Canon's Advanced Intelligent Engine is an AI-based image reconstruction technology for CT and MRI scans. It uses deep learning algorithms to produce high-quality images with improved resolution and reduced noise.

These examples demonstrate the growing use of AI-based medical applications in Japan, aiming to enhance diagnostic accuracy, visualization, and patient care across various medical specialties.

**The Metaverse in Surgery**

The integration of the metaverse in surgery, facilitated by XR technologies, has the potential to revolutionize the way healthcare is delivered, providing numerous benefits across various aspects of the medical field. One of the key applications of the metaverse in surgery is its role in surgical education and training. By providing realistic virtual environments that simulate real-world clinical scenarios, the metaverse allows medical students and professionals to hone their skills in a safe and controlled setting. The immersive nature of these environments enhances the learning experience, potentially resulting in better-prepared practitioners and improved patient outcomes.

In the realm of telemedicine, the metaverse provides a platform for remote consultations, diagnostics, and treatment planning, connecting medical professionals and patients across distances. This not only expands access to healthcare services for patients in remote or underserved areas but also facilitates collaboration among healthcare providers, ultimately leading to more comprehensive and effective care.

Surgical planning and navigation also stand to benefit greatly from the metaverse. By visualizing patient-specific anatomy in 3D and allowing for virtual rehearsal of surgical procedures, the metaverse can contribute to improved surgical outcomes and reduced risks. Furthermore, XR technologies can enhance surgical navigation by overlaying digital information onto the surgeon's field of view, providing real-time data and guidance during the procedure.

However, the implementation of the metaverse in medicine also poses several challenges. Ensuring data privacy and security is paramount, as the sensitive nature of medical information demands strict safeguards against unauthorized access or misuse. Additionally, the integration of the metaverse into existing healthcare systems requires significant investment in both infrastructure and training for medical professionals.

Moreover, concerns surrounding the digital divide and equitable access to these cutting-edge technologies must be addressed. Ensuring that the benefits of the metaverse in medicine are available to all, regardless of socioeconomic status or geographical location, is essential to prevent further widening of healthcare disparities.

**Challenges of XR-Guided Surgery**

Holographic image-guided surgery with XR technology by Holoeyes system has the potential to improve the accuracy and efficiency of surgery, but there are several challenges.

First, there are technical limitations. High-quality holographic images require advanced computational power to generate and update in real-time, and some XR devices vary in image resolution, response time, viewing angle, device weight, and wearing comfort, all of which could be further improved. Attention must also be paid to the privacy and data security of patient data, the Holoeyes system can manage patient polygon data and personal information in an untethered manner. It is important to ensure strict data protection policies and cybersecurity measures, especially during data transfers from inside the hospital to outside the hospital. Insurance coverage and regulatory issues must also be considered. Novel technologies must undergo a testing and approval process in conjunction with regulatory authorities to ensure that they are suitable for use in the medical field. This is one reason why it takes considerable amount of time for technologies to become widely available.

In order to address technological limitations, it is crucial to enhance image resolution and response time through rigorous research and development efforts. Furthermore, both hardware and software components must be optimized to deliver superior computational capabilities and high-speed internet connectivity. With respect to the education and training of healthcare professionals, the development of effective training programs and curricula is essential for facilitating the dissemination of technology. Additionally, expert-led workshops and seminars conducted by experienced healthcare professionals can aid in the acquisition of technological proficiency.

In order to tackle cost-related challenges, the prices of devices should be lowered through research and development of innovative technologies and the optimization of manufacturing processes. Moreover, it is imperative for governments and non-profit organizations to provide financial support to facilitate deployment this technology in developing countries and resource-limited healthcare facilities. Concerning privacy and data security, stringent data protection policies must be established, and the management of patient medical and imaging data must be meticulously executed. Additionally, cybersecurity measures should be reinforced to ensure the security of the implemented technology. To address regulatory and legal concerns, technology developers and regulatory bodies must collaborate to expedite the testing and approval processes. Furthermore, international cooperation and information exchange are required to foster the development of technologies that comply with the regulatory standards and legal frameworks of each country.

**Conclusions:**

This study provides an objective and evidence-based assessment of Holoeyes, an XR-based system, by incorporating scientific literature and the opinions of surgeons in clinical practice. The findings highlight the potential in Holoeyes Holographic Image-Guided Surgery in revolutionizing the field of surgery. The findings demonstrate the significant clinical advantages of Holoeyes and the integration of XR, the metaverse, and AI in surgery. Holoeyes enhances surgical visualization, planning, navigation, and education by converting medical images into immersive XR applications. The XR technologies provide a transformative approach to surgery, offering realistic and immersive experiences that improve communication, collaboration, and surgical outcomes. Surgeons benefit from enhanced spatial awareness and accurate visualization of patient-specific anatomy, leading to improved surgical accuracy and patient care. The integration of AI further enhances Holoeyes' capabilities and the XR technologies by enabling advanced image analysis, segmentation, and anomaly detection. This facilitates precise surgical planning and personalized treatment approaches.

The systematic review confirms the increasing evidence supporting the clinical benefits of VR, the metaverse, and AI in surgery. These technologies have demonstrated promising results across various surgical specialties.

In summary, Holoeyes holographic image-guided surgery, along with XR, has the potential to significantly improve surgical outcomes and transform surgical practice. The integration of XR, the metaverse, and AI enhances surgical visualization, planning, and education, leading to improved communication, collaboration, and patient care. Continued research, development, and collaboration are necessary to fully unlock the potential in these technologies in surgery.

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