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Future of Surgical Mixed Reality: Cutting-Edge or Cutting Too Deep?

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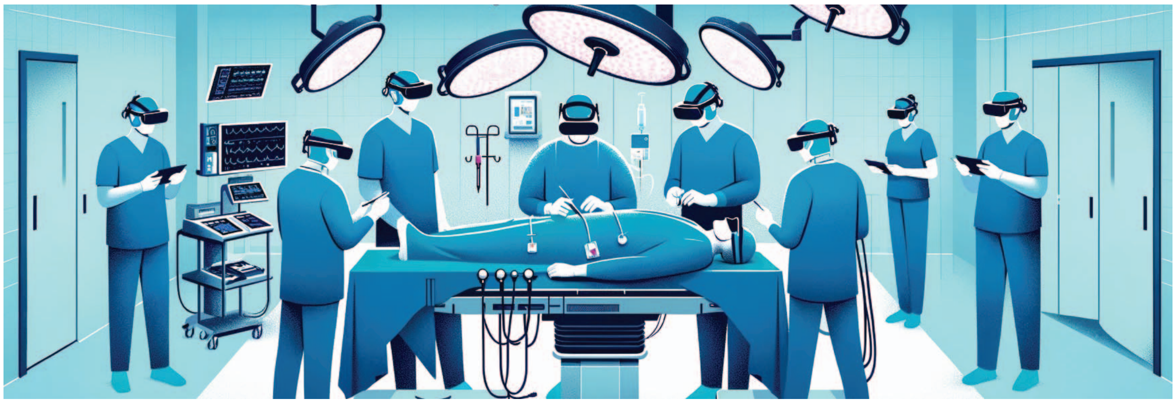

Figure 1: Illustration of an futuristic operating room in which surgeons and other stakeholders are using mixed reality while performing a surgery.

Abstract

Mixed reality technology has the potential to transform healthcare, notably through advanced intraoperative applications such as in-situ surgical guidance and virtual surgical displays. However, the adoption of MR in operating rooms faces several hurdles, including technical limitations, regulatory barriers, and challenges centered around user experiences. This paper examines these multifaceted issues, exploring the advantages and limitations of MR in surgery, the reasons for its slow adoption, and strategies to accelerate its integration. We pinpoint essential areas for future research, focusing on how MR influences the dynamics and workflows of surgical teams, and discuss both the potential solutions it offers and the new challenges it introduces. We conclude that MR can significantly enhance surgical practices but overcoming obstacles and altering workflows require gradual, evidence-based changes to ease adoption.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality; Applied computing—Life and medical sciences—Health care information systems

1 Introduction

Mixed reality (MR) allows users to overlay virtual content directly onto their visual field often without the limitations of placement or size [1]. This differs fundamentally from traditional interactive mediums like large displays or smartphones, where interaction is confined to the physical dimensions of the device [14]. The interactive flexibility offered by MR enhances the user experience, making it more natural and intuitive. In MR environments, users can interact with virtual objects similarly to physical objects; for instance, they can grab a virtual interface using their hands and freely move it in a three-dimensional (3D) space or pinch it to increase or decrease its size.

In recent years, success in MR technology has promoted its use in healthcare. Research in this domain has been pursued across both industrial [1] [2] [3] and academic settings [8]. The research applications of MR in healthcare can generally be divided into two categories: extra-operative and intraoperative. Extra-operative applications cover areas such as medical training and education [15], preoperative planning and visualization [12], and patient education and engagement [2]. On the other hand, prominent intraoperative applications of MR include surgical guidance and navigation [19], integration of virtual displays in place of traditional surgical feeds on monitors [11], and facilitating remote collaboration with off-site experts [4]. While extra-operative applications of MR are undoubtedly significant, this paper specifically concentrates on intraoperative applications of MR. Use of MR in intraoperative settings inherently requires a rigorous standard both in safety and performance, compared to extra-operative counterparts. This stems from the fact that stakes in the operating room (OR) are high, with patient safety and surgical outcomes directly hinging on the performance and integration of the MR technology.

Despite extensive research proving positive outcomes for use of MR in surgical tasks, its real-world adoption is limited. As with any emerging technology, integrating MR into surgical procedures comes with its own set of challenges and limitations. These challenges partly arise from the current technological state, including hardware limitations such as the restricted field-of-view in headsets or sensor accuracy issues, software dependability, and the absence of specialized hardware to integrate with existing medical systems. From a user-centered perspective, the challenges encompass the learning curve faced by surgeons and medical staff, potential distractions in a high-pressure environment (e.g., information overload or disruption of well-established routines), and concerns regarding patient privacy and data security. Moreover, there are hurdles related to regulatory approvals, which include meeting healthcare standards

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[1] https://www.medivis.com/
[2] https://sentiar.com/
[3] https://surgicaltheater.com/

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and acquiring the necessary certifications.

The title of this paper, “Future of Surgical Mixed Reality: Cutting-Edge or Cutting Too Deep?”, encapsulates the dual nature of this innovation. On one hand, it represents a cutting-edge advancement that could redefine surgical standards and patient care. On the other hand, it raises important considerations about the depth of its integration, the possibility of over-reliance, and the need to assess whether the advantages outweigh the extensive changes that would be required in operating rooms and medical training curricula.

In this paper, we delve into a range of multifaceted issues. Initially, we examine the current applications of MR in surgical contexts, highlighting both their advantages and limitations. We further explore the reasons behind the slow adoption of MR in surgical procedures and propose strategies to expedite this process. Subsequently, we shift our focus to future research areas, identifying problems that emerge due to the use of MR and others that MR could potentially resolve. Finally, we conclude by discussing whether the benefits of implementing MR in the operating room outweigh the significant alterations required in both the operating room workflow and the medical training curricula.

2 Intraoperative applications of mixed reality

Among the intraoperative applications, the most prominent ones include surgical guidance, MR surgical displays, and remote collaboration. We briefly explain the benefits of these applications, discuss the challenges associated with them, and catalog the current state cutting-edge technology.

Surgical guidance with MR allows surgeons to insert or navigate surgical tools to reach specific anatomical targets, as demonstrated in Fig. 2. The advantage of using MR in this context is its ability to superimpose guidance markers in 3D space on the patient itself as opposed to traditional methods where surgeons have to look at 2D displays disconnected from the patient. Mostly, surgical guidance with MR has been studied for ventriculostomy [3, 19] and pedicle screw placement [6, 16] procedures. However, a central challenge in this approach is the accuracy of the guidance system. In MR-based surgical guidance, there are several potential sources of error: the tracking error associated with tracking fiducial markers, the registration error associated with the hologram placement, and finally the human error, namely how good the user is at following guidance from the system or conversely how good the system is at guiding the user. All these sources of errors combined must be less than a few millimeters in order to ensure patient safety and positive outcomes as set by healthcare regulatory bodies. A few works in surgical guidance domain have demonstrated acceptable error rates near or below 1 millimeter, indicating promising developments in this technology. [10, 17].

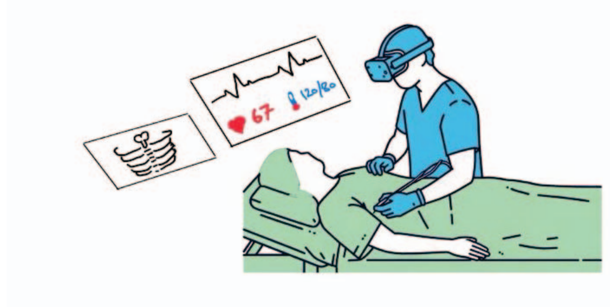

Figure 3: Illustration of a surgeon performing a surgery using mixed reality surgical feeds.

MR displays can be used to display surgical video feeds (e.g., footage from scoped instruments, patient vitals, and more) instead of conventional displays inside the OR [9], see Fig. 3. There are several benefits associated with this. Firstly, MR displays allow for hands-free interaction e.g., a surgeon can interact with an MR display using voice commands. Secondly, the use of MR displays maintains the integrity of the sterile field in the OR and provides unrestricted size and placement affordances. This enables surgeons to personalize their view of digital information in an ergonomic way. Additionally, substituting several conventional surgical displays with a single headset results in a reduced OR footprint. However, there are several challenges associated with MR displays. Surgical feeds require real-time updates e.g., endoscopic footage. In this case having a delay between the surgeon’s action and the surgical video feed can lead to an experience that does not align with the user’s expectation and thus can negatively impact surgeon’s performance and patient outcomes. A recent study published by Khan et al. [11] looked into the impact of visual delay on surgical MR displays. They found comparable performance between a conventional display and an MR display when the amount of visual delay is low.

MR can be used for collaboration during surgery, see Fig. 4. Most of the collaborative MR applications for surgery are related to remote assistance from experts. The surgical operating room can be captured using multiple cameras and then streamed to an

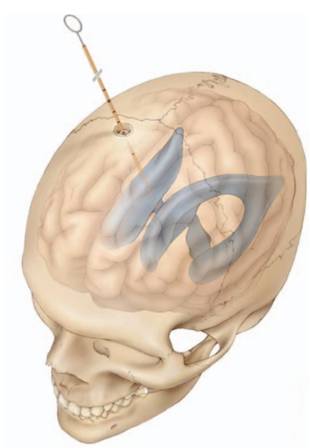

Figure 2: Illustration of a mixed reality based surgical guidance system displaying underlying anatomical structures for target acquisition.

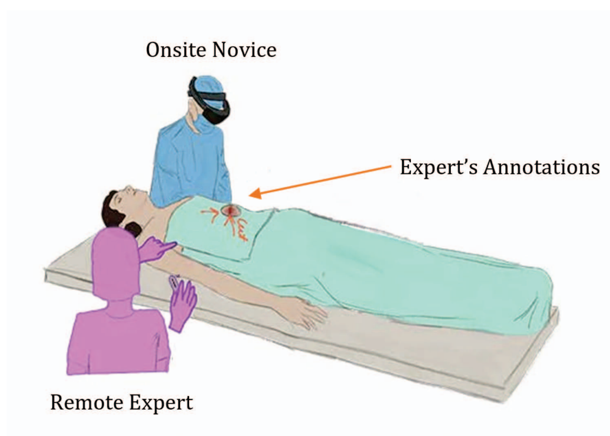

Figure 4: Illustration of a mixed reality remote collaboration scenario where a remote expert is guiding an onsite novice.

off-site expert. This setup enables the expert to virtually navigate the operating room as though they were physically present. On-site people also wearing MR headsets can see the remote expert's avatar. Such technology enables collaboration between surgeons located in different parts of the world, allowing experts to monitor and guide surgical procedures remotely. However, this application is not without certain challenges. Real-time remote collaboration is highly reliant on hardware to generate a high fidelity point cloud representation of the environment and then the network to stream that to the expert. High latency in data transmission can significantly impact the accuracy and timeliness of surgical guidance. Despite these limitations, a remote collaboration system proposed by [4] was still able to support successful remote mentoring of surgical procedures conducted by novices through features like 3D annotations, gesture communication, procedure video clips, and specialized MR interfaces. The verbal communication and visual context also helped overcome some visual alignment discrepancies. Thoughtful interface design and leveraging multiple communication channels, while not perfect, facilitates collaboration despite current hardware limitations.

3 Overcoming the obstacles

Although research in multiple medical domains has shown promising results for MR, its practical application in clinical or intraoperative settings remains largely unobserved. The transition of MR technology from promising research to widespread clinical use encounters several significant barriers, reflecting challenges at various levels. We have synthesized these barriers through an in-depth analysis of contemporary works in the field and extensive discussions with domain experts.

Limited real world evaluation. Much of the prior research on MR applications in surgery has been conducted in controlled and contrived settings (e.g., [3,19]). While these studies provide valuable insights into the potential benefits of MR, the lack of extensive real-world validation poses a challenge. The translation of findings from controlled environments to the dynamic and complex nature of actual surgical procedures requires careful consideration and validation. Conducting large-scale clinical trials and real-world studies is essential to validate the effectiveness of MR applications in diverse surgical scenarios. Collaborative efforts among researchers, technology developers, and healthcare institutions are crucial to ensure the applicability of findings in real-world surgical settings.

Regulatory approval challenges. The regulatory landscape in healthcare is stringent, and obtaining approvals for the clinical use of MR applications is a complex process. Navigating the regulatory framework involves demonstrating not only the efficacy and safety of the technology but also its compliance with existing healthcare standards. This intricate process contributes to delays in the adoption of MR technology in clinical settings. Establishing close collaboration between technology developers and regulatory bodies is crucial. Streamlining communication channels, providing clear documentation on safety and efficacy, and actively participating in regulatory discussions can expedite the approval process. Advocacy for more flexible regulatory pathways for innovative technologies is also essential.

Resistance from traditional mindsets. The medical field, particularly surgery, has a traditionally conservative mindset. Older surgeons, in particular, may be resistant to embracing new technologies such as MR. Overcoming this resistance requires targeted educational initiatives to inform and engage the medical community about the benefits and potential improvements that MR can bring to surgical procedures. Initiatives like workshops, seminars, and continuous medical education sessions can effectively demonstrate how MR technology can enhance surgical precision, improve patient outcomes, and contribute to the overall advancement of medical practice. Furthermore, the shift from a traditional OR to an MR-equipped OR should be a carefully measured incremental process. Starting with minor changes and gradually progressing to more substantial modifications over time is key. This strategy ensures a gentler learning curve, thus easing the integration of advanced technologies while potentially encountering less resistance.

Burden on healthcare systems. Currently, the surgical field is facing a decline in its workforce, with projections indicating that by 2030, many surgical specialties will experience a shortage of surgeons. It is estimated that clinical productivity needs to increase by 7-61% to mitigate this shortage [18]. The prevailing scarcity of surgeons significantly affects the time required to test new surgical technologies. Utilizing actual subject matter experts, such as experienced surgeons, for this testing is critical to ensure the technology's efficacy and safety. However, the demanding schedules of these professionals limit their availability, and the exhaustive, detailed nature of the testing process further extends the timeframe. Such delays in technology validation slow down the adoption of innovative surgical techniques, as exemplified in the slow integration of MR technology. As a result, healthcare systems must balance the critical need for technological progress in surgery with the practical challenges of engaging busy surgical experts in the testing and validation process.

Privacy Concerns. The integration of MR in the OR poses a unique challenge regarding patient privacy. MR headsets continuously map the environment, increasing the risk of exposing sensitive patient data and breaching confidentiality agreements and privacy laws such as the Health Insurance Portability and Accountability Act (HIPAA) [4] in the United States. To address these concerns it is essential to implement robust privacy safeguards tailored to the MR technology used in the operating room. MR systems must be designed according to privacy design principles [13], ensuring that patient data protection is a core feature of the technology. This approach could include disabling unnecessary camera functions or applying filters that automatically blur or omit sensitive information from the MR headset's field of view [20]. However, it is crucial that these operations are executed locally on the device to enhance security. Moreover, while developing MR, collaboration with legal and compliance teams is vital to ensure that the use of MR technology aligns with current privacy laws and regulations.

Hardware limitations. Surgical procedures, particularly in neurosurgery, can vary widely in duration, ranging from 1 to 14 hours or longer, depending on the severity of the case, with an average time of around 5 to 6 hours. This presents a challenge for current MR technology, as the existing hardware falls short in supporting such extended use. There is a gap of several order of magnitudes in terms of power, performance, and quality of experience between the technology that exists and what is ideal [7]. For MR glasses to be effective over long periods, they need to operate in the hundreds of milli Watts range, a marked reduction from the current 7 Watts state-of-the-art. Furthermore, the headsets must be lightweight, around 10 grams, in contrast to the current weight which is in the range of several hundred grams. For example, the Microsoft HoloLens 2 [5] weighs 566 grams. In terms of field-of-view (FOV), augmented reality (AR) headsets like the Magic Leap 2 [4], which represents the current state-of-the-art, provide a limited FOV of 43° vertically and 70° horizontally. This is considerably less than the ideal FOV, which is aimed to be around $165^\circ \times 175^\circ$. On the other hand, virtual reality (VR) headsets like the Varjo XR-4 [7], used in passthrough mode for AR-like experiences, offer a wider FOV of $120^\circ \times 105^\circ$. However, these headsets face challenges with distorted passthrough feeds and latency, significantly undermining their effectiveness.

[4] https://www.hhs.gov/hipaa/index.html
[5] https://www.microsoft.com/en-us/hololens/
[6] https://www.magicleap.com/magic-leap-2
[7] https://varjo.com/products/xr-4/

Therefore, to make MR headsets suitable for extended tasks like surgeries, substantial technological improvements are essential. Collaborative efforts between industrial hardware developers and academic researchers are key to achieving this. At present, developers creating MR solutions for surgical applications must rely on commercially available headsets, which lack of optimization for surgical contexts. For instance, surgeons, might prefer a lighter headset over one that offers perfect visual realism. This indicates a need for customizing headset development to align more closely with surgeons' specific needs, focusing on a balance between technical features and user comfort.

4 Research Horizons

Current MR applications designed for surgical use have a narrow focus. Typically, they are either designed for a single user, and in scenarios involving collaboration, at most, they focus on dyads. This approach overlooks the dynamic and complex environment of an actual OR where multiple users might simultaneously wear MR headsets, as envisioned in Fig. 1.

A critical aspect not yet fully explored is the potential impact of MR on surgical workflows as a whole. The integration of MR technology in surgery might necessitate a complete rethinking of traditional procedures and practices. This transformation could involve alterations in team dynamics, communication protocols, and decision-making processes. The potential for MR to revolutionize surgical workflows is substantial, yet the implications of such changes are not being sufficiently addressed in current discussions and developments.

MR presents a vastly different experience from physical reality, leading to both challenges and opportunities. In certain situations, the unique capabilities of MR can create complications that must be addressed, especially when multiple users in the same physical space interact with digital elements. Conversely, these same features of MR can also be harnessed to offer advantages.

Accommodating both personal and shared virtual objects. As discussed in Sect. 2 and illustrated in Fig. 3, MR allows stakeholders in the operating room to utilize virtual displays to view surgical video feeds, as opposed to traditional physical displays. In a multi-user MR environment within the operating room, stakeholders can create personalized viewing setups tailored to their specific roles and preferences. This level of personalization is not feasible without MR.

Moreover, MR allows users to generate both individual and shared virtual objects. For example, the lead surgeon might need exclusive access to the endoscopic surgical feed, whereas a virtual display showing patient vital signs could be a communal object, visible and interactive for everyone. A notable challenge in MR environments is the lack of awareness among users regarding others' personal virtual objects. This issue is distinct to MR, as in a physical setting, everyone is aware of the location of others' personal devices and shares a consistent perception of the surrounding space. Consequently, this can lead to conflicts where, for instance, a nurse might inadvertently place a shared virtual object in a way that obstructs the surgeon's view of the endoscopic feed, particularly during critical procedures, as illustrated in Fig. 5.

To address this, it's vital to develop ways to foster awareness of personal virtual objects to other users. Future research should explore methods to enhance this awareness to prevent such conflicts. Possible solutions could include representing personal objects with varying degrees of fidelity – for example, indicating just their position, or both position and size, in order to optimize visual clutter and minimize conflicts.

Establishing common grounding. A challenge in real-world scenarios is the lack of a shared viewing perspective among individuals. While a simple but crude solution might be to move and face the same direction, this is not always feasible due to task and physical constraints. For example, in an operating room, a conventional

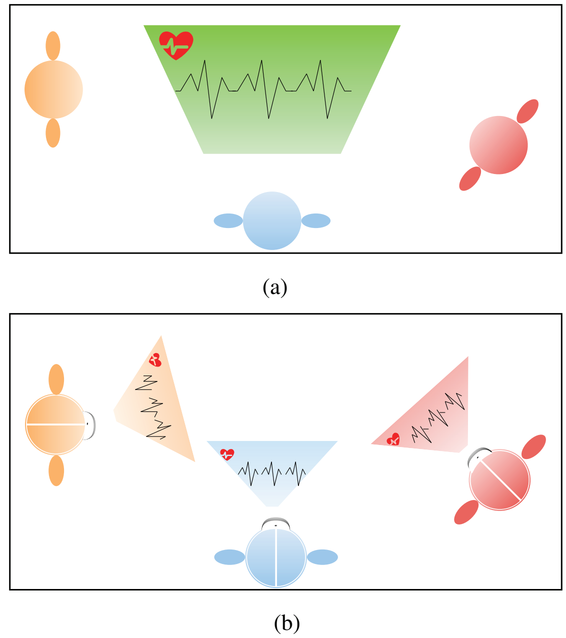

Figure 6: (a) Top-down view illustration of a scenario where users are gathered around a conventional surgical display, note that each user has a different viewing perspective of the surgical feed and some might not be able to see the feed contents. (b) Top-down view illustration of a scenario where each user has their own mixed reality surgical display placed in front of them, note that each user now has the same viewing perspective of the surgical feed regardless of their position in the real world.

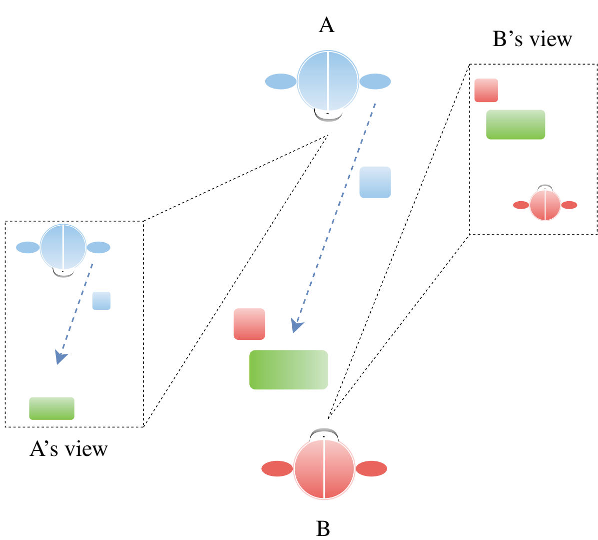

Figure 5: Top-down view illustration of a mixed reality scenario where a conflict occurs. User A places the shared object (in green) in front of user B's personal object (in red) which blocks user B's view. Note how user A is unaware of user B's personal object.

surgical feed display facing a surgeon might not be visible to other OR personnel from their respective positions, as depicted in Fig. 6a. These other stakeholders may be unable to leave their critical tasks to change their viewing angle.

MR technology offers a practical solution to this problem by enabling users to create individual replicas of the surgical feed, as shown in Fig. 6b. This capability facilitates common grounding and thereby enhances collaboration [5]. However, it also introduces a disconnect between physical and virtual realities. For instance, in a 3D space, a surgeon pointing at a specific area on their personal copy of the virtual surgical feed might be difficult for others to interpret.

Addressing this issue of shared attention might involve implementing additional awareness cues, such as gaze or finger pointers, or even simple highlights, that are synchronized across all copies of the surgical feed. Future research should explore how these cues can effectively be used for multiple people without causing excessive visual clutter from each person's awareness indicators.

5 Concluding Remarks

Mixed reality holds immense potential to revolutionize current surgical practice. However, its nascent state presents significant hurdles for successful OR integration. There is no doubt that a fluid MR-based surgical environment could significantly enhance a surgeon's performance. This enhancement comes from consolidating critical information within an easily accessible field-of-view, allowing for real-time access to crucial data for surgical decision-making. In current settings, this information is often scattered throughout the OR. To access this information, surgeons must divert their attention from the operative field, either through head movements or by physically stepping away from the patient, resulting in split attention. Alternatively, it also involves relying on others to relay information, which can lead to receiving second-hand interpretations rather than primary data (e.g., vital signs are 'good' instead of getting specific metrics like the heart rate is 85 beats-per-minute).

As one can see, however, incorporating MR requires a fundamental evolution of the physical architecture of an OR. The contemporary physical architecture becomes obsolete with the virtualization of many elements, such as monitored displays. In parallel, there is a need for a shift in the behavioral architecture. This includes changes in how a surgeon sets up the OR (e.g., equipment, patient, and surgeon positioning), interacts with ancillary staff (i.e., such as the circulating nurse, anesthesiologist and more), and the workflow of surgical procedures itself as access to new and more comprehensive information becomes a standard part of the process.

Surgeons tend to be resistant to change. Unfamiliar processes, unless they are simple to adopt, are often quickly abandoned in favor of the familiar. Therefore, change must be incremental. MR needs to demonstrate its value through small, distinct improvements. Over time, the accrued cumulative benefits will reshape surgical practices through the weight of evidence. Additionally, introducing MR early in medical training, coupled with the entry of a new, more technologically adept generation of surgeons, will likely ease the adoption of this technology. As MR technology improves and is used more in different clinical settings, the alterations it requires to me made to the OR workflow and medical training will become easier to manage. The effort needed to benefit from this advanced technology will lessen over time, making it more accessible and valuable in surgical practices.

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