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Mixed Reality Assisted Navigation Guided Microsurgical Removal of Cranial Lesions

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ABSTRACT

AIM: To demonstrate the possible use of mixed reality (MR) technology in neurosurgery for multiple purposes, including preoperative planning, training, and three-dimensional (3D) navigation.

MATERIAL and METHODS: Using magnetic resonance imaging (MRI) and computed tomography (CT), 3D holographic images of three patients were created and inspected using a remote control. Preoperative planning was performed in a conference room using holographic images. Intraoperatively, the 3D images were matched and the adjacent structures were examined.

RESULTS: The MR System (MRS) was a useful tool for preoperative planning and intraoperative navigation during the cranial intervention. It reduces operative time, decreases complication rates, increases surgical success, and enhances surgical outcomes. Eventually, MRS may be more economical.

CONCLUSION: The MRS can be used for intraoperative navigation by displaying a 3D hologram at the surgeon's fingertips and for preoperative 3D examination of the lesions and its surrounding structures. The MRS enhances surgical efficacy, reduces healthcare costs, and has a shorter learning curve than the conventional methods. It also enables customized patient-specific surgery.

KEYWORDS: Mixed reality, Augmented reality, Neuronavigation, Neurosurgery

ABBREVIATIONS: MxR: Mixed reality, **AR:** Augmented reality, **ER:** Extended reality, **VR:** Virtual reality, **MRI:** Magnetic resonance images, **iMRI:** Intraoperative magnetic resonance imaging, **AVM:** Arteriovenous malformation, **MxRG:** Mixed reality glasses, **iCT:** Intraoperative computed tomography

INTRODUCTION

In modern neurosurgery, intraoperative magnetic resonance imaging (iMRI), neuronavigation, ultrasound, and fluorescein-guided surgery are frequently employed (6). With the advancement of technology, it is now feasible to use sophisticated imaging techniques and surgical navigation systems to determine tumor borders more precisely and perform broader excisions while ensuring patient safety and minimizing the risk of postoperative complications (52). Virtual reality (VR), augmented reality (AR), and mixed reality (MxR) are increasingly being used in medical education to enhance students' comprehension of anatomical structures and relationships. These technologies enable the creation and display

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of three-dimensional (3D) images that can be viewed and interacted with from various angles, resulting in a more immersive and interactive learning environment. Particularly with MxR, virtual images can be projected onto actual objects and environments, allowing for a more realistic representation of medical concepts (31,33,35,38). There have also been studies on the application of MxR glasses (MxRGs) in neurosurgical education (3,7).

The Role of Mixed Reality Applications in Neurosurgery

Neuronavigation and contemporary imaging methods, such as MRI and CT, have significantly impacted the practice of modern neurosurgery. It is particularly crucial to precisely determine the vascular and cortical regions of the lesions. To plan and navigate neuronavigation-based operations, it is crucial to accurately visualize the 3D structure of lesions, particularly those that are with vascular adjacency or are located at the cranial base. Thin-section imaging techniques can provide detailed 3D images of the lesions and their adjacent structures, which can guide the surgical approach and enhance the precision and safety of the procedure (34, 60). Multiple studies have demonstrated the importance of VR and AR technology in surgical training and planning. They decrease the operative time and complication rates, enable extensive resection of glial tumors located in eloquent regions, and boost patient satisfaction (15,48,58).

AR allows the projection of virtual objects onto physical environments, enabling visualization of both the real and virtual elements without interaction or manipulation. Conversely, VR produces a fully immersive virtual environment in which the user can only see and interact with virtual objects. Recent studies on AR systems have been extensive. Despite limited data, both systems are considered promising and can outperform the current navigation technologies (42).

MxR is a more advanced version of AR and VR systems that enables users to view the real world through virtual reality eyewear and interact with holographically created and positioned virtual images. By integrating both virtual and actual elements, this technology allows a more immersive and interactive experience (38,43). Although the use of MxR in neurosurgery is still being explored, and studies on this topic are limited, preliminary studies suggest that MxR may be comparable to neuronavigation in determining the neighborhood and localizing lesions in patients with cancer (30). In this study, we examined the potential benefits of utilizing MxR for preoperative planning and intraoperative navigation in three patients, aiming to determine its feasibility and relevance in neurosurgical procedures due to a lack of comprehensive neurosurgical usage analysis of this technology.

MATERIAL and METHODS

Study Participants

Three patients aged 24, 25, and 65 years were chosen based on their lesion's location and its proximity to vascular structures. The study participants, which included a patient with an arteriovenous malformation (AVM), a patient with a cerebellar glial tumor, and a patient with a sphenoid wing meningioma, were selected from a cohort of patients who presented to the clinic in April 2022. Before being enrolled in the study, the patients and their first-degree relatives were provided with comprehensive information regarding a mixed reality system (MxRS), and informed consent was obtained.

This study was approved by the Ankara University Ethics Committee convened under the chairmanship of Prof. Dr. Hakan ERGÜN on 24.10.2022 (Approval number:I09-592-22).

Mixed Reality System

We used the BrainLab System (Munich, Germany) for cranial navigation at our clinic. We briefly used the BrainLab Navigation System, Magic Leap eyewear, and MxR technology for preoperative and intraoperative planning and navigation.

MxRG use a computer to project virtual 3D images onto the physical environment in real-time, enabling the user to remotely interact with these images from various angles. Virtual 3D images were generated by importing the patient's radiological images into the glasses coupled with a computer. Consequently, the reflection of the same 3D holograms onto the physical environment using multiple glasses made it possible to observe and interact with it from various angles. It was possible to examine the location and vascular structures in close proximity of the lesion in the 3D environment, perform a virtual craniotomy by interacting with the images in real-time using a preoperative control, and examine the important neighborhoods in 3D by separating them.

Preoperative Planning

By uploading thin-section contrast-enhanced T1-sequence MRI and MRI angiography images to a computer system, 3D holographic images were created for this study. The day before the surgery, these images were uploaded to the MxRG and examined by the surgical team in the conference room. This allowed the team to plan for the craniotomy, better understand the relationship between the pathological and normal anatomy, and identify the optimal margins for the bone flap. During the preoperative planning, the 3D holographic images were examined repeatedly.

Intraoperative Planning and Navigation

Intraoperatively, the preoperative plan was implemented using MxRGs. The patients' preoperative images were loaded onto the MxRG, and 3D holograms were manually positioned on the patient. The procedure commenced with the use of a microscope and a MxRG. Owing to the lack of a compatible software, the microscope–glasses-linked navigation system could not be installed when the glasses and microscopes were being used. Instead, 3D holographic images, which were in our immediate vicinity and were manually projected onto the patient intraoperatively when deemed necessary, were examined using a MxRG without moving the microscope at all. Only the head was moved. Consequently, the lesion and the essential structures surrounding it were examined immediately, and macroscopic navigation was provided without the use of any additional software.

The patient's virtual 3D radiologic images could be positioned anywhere in the actual environment. During surgery, we could readily examine the radiologic images. In addition, the 3D holograms were assisted by navigation in the actual world. Using the patient's MRI to generate 3D holograms resulted in an almost identical representation of the surgical field.

RESULTS

Case-1

A 25-year-old female presented with migraines, vertigo, and a history of two surgeries for her left cerebellar lesion. She exhibited normal motor muscle strength, a quiescent tremor on the left side, and a positive Romberg's test. Examination of the cranial nerves yielded normal results. On the MRI, two cerebellar lesions and edema were detected. The first lesion, which was 1.5 cm in diameter, was located at the previous surgical site. The second lesion, which was 1 cm in diameter, was located 1 cm above and in front of the previous surgical site and was associated with first lesion (Figure 1). The preoperative images were uploaded to the MxRG, which were worn in conference room for preoperative planning. The lesion and its surrounding vascular structures were anatomically observed (Figure 2). The lesion was located 1 cm below the transverse sinus and 3 cm medial to the sigmoid sinus. Utilizing the pre-existing craniotomy defect from two prior procedures, the current craniotomy was planned using MxRG in the presence of holographic images. The patient's vascular anatomy was examined in three dimensions and the sinus region was confirmed. The lesion was supplied by the distal branches of the posterior inferior cerebellar artery and drained by the sigmoid sinus. The compaction of the pontine structures was mapped and confirmed using preoperative 3D holograms (Figure 3). In the operating room, the preoperative plan was uploaded to the MxRG. Following neuronavigation, the holographic images were matched to the patient and

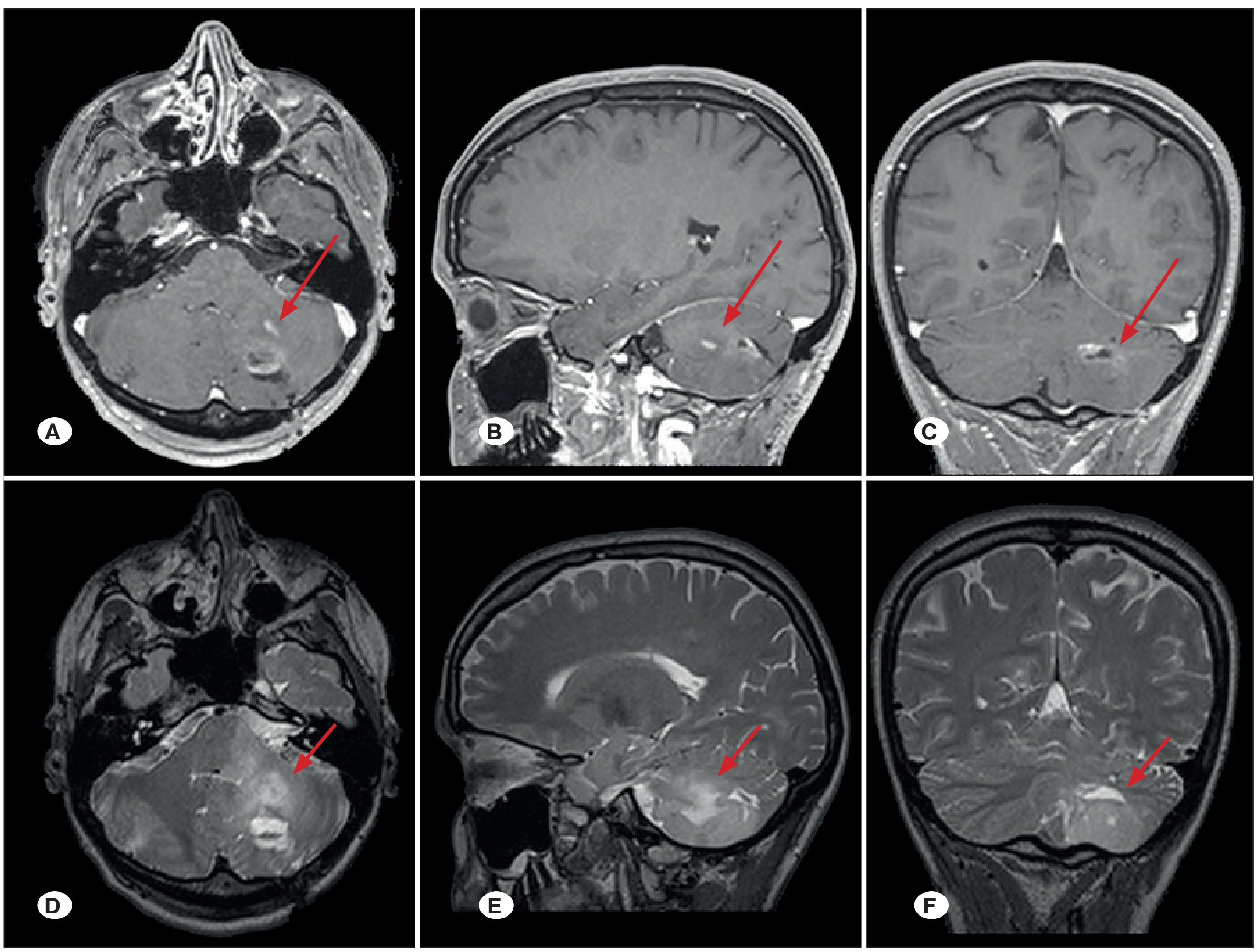

Figure 1: Preoperative gadolinium-enhanced MRI scans showing two lesions in the left cerebellar hemisphere that are approximately 1–1.5 cm in diameter. T2-weighted MRI sequences reveal concomitant edema. **A)** Contrast-enhanced axial section. **B)** Contrast-enhanced sagittal section. **C)** Contrast-enhanced coronal section. **D)** T2-weighted axial segment. **E)** T2-weighted sagittal section. **F)** T2-weighted coronal section. **MRI:** Magnetic resonance imaging.

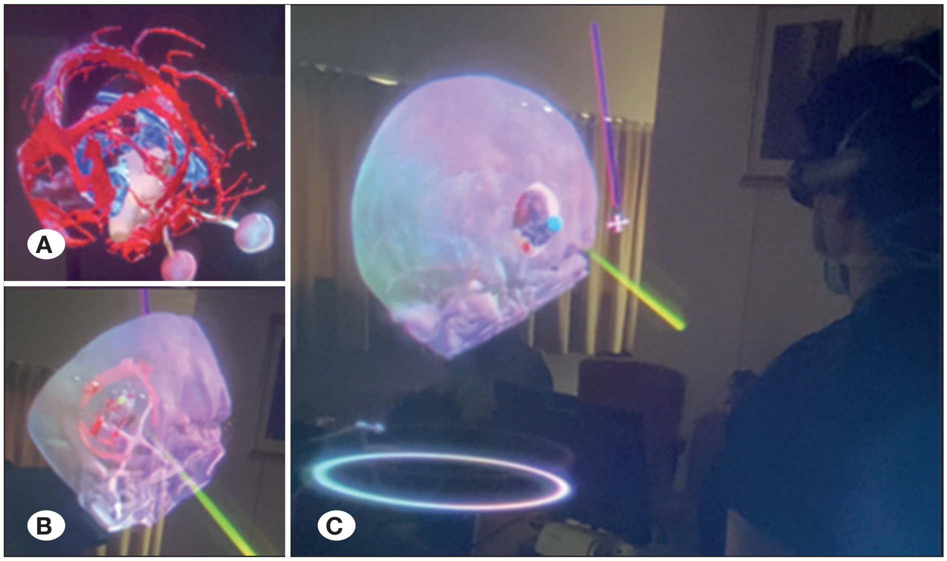

Figure 2: Preoperative planning was performed in a conference room. Using the 3D scans, the position and dimensions of the craniotomy flap and the connection between the tumor and vascular systems were investigated. **A)** vascular neighborhoods and feeders of the lesion. **B)** interaction of the lesion with the sinuses. **C)** Preoperative VR planning for craniotomy and surgical approach. **3D:** three dimensional.

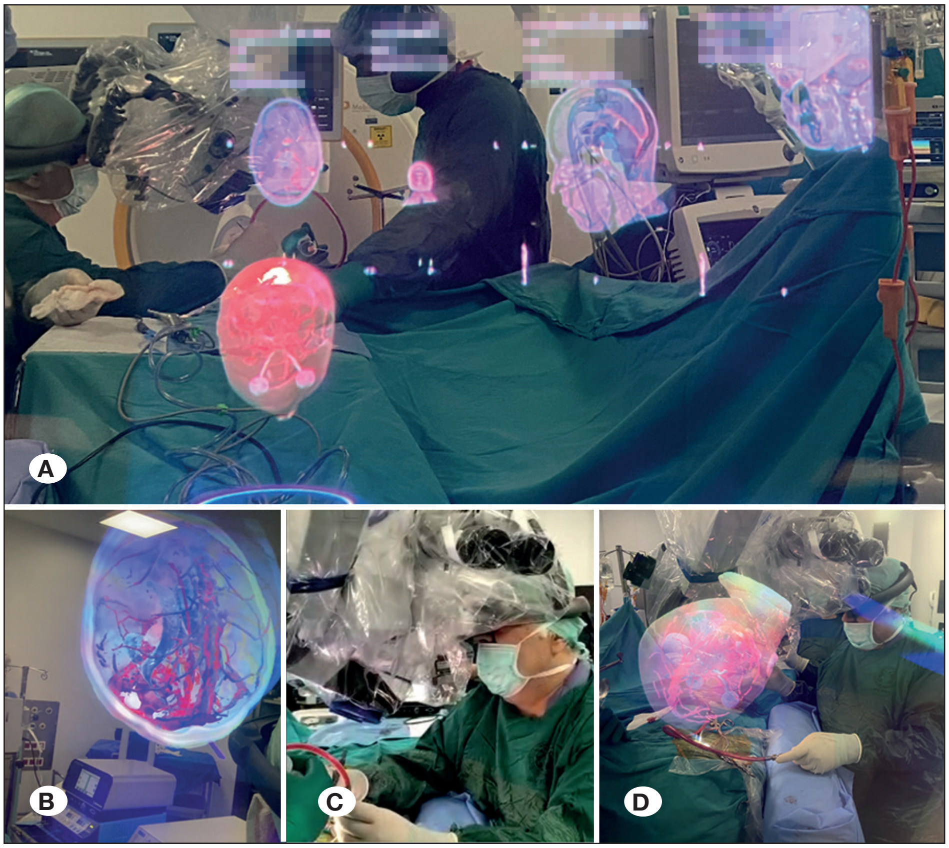

Figure 3: Intraoperative use of the mixed reality system. The figure shows the 3D hologram of a skull and the patient's cranial MRI sections in close proximity to the operating surgeon. With the mixed reality system, the surgeon can continue performing the operation without leaving the surgical field. **A)** The same images can be seen on the screen of the assistant accompanying the case from the outside **B)** Intraoperative examination of the mass and its vascular neighborhood. **C)** Simultaneous use of glasses and microscope **D)** the vascular architecture is controlled with the assistance of a three-dimensional hologram. **3D:** three dimensional; **MRI:** magnetic resonance imaging.

projected in the operating room. The images were altered by the residents using a control device according to the surgeon's instructions. While investigating the surgical field with a microscope, the lesion's adjacent structures were examined with holograms and a microscope, and successful completion of surgery was confirmed (Figure 3). No additional neurological deficits developed after the surgery. The operative time was approximately 3 hours. The total volume of blood lost during the surgery was 250 ml. It took 5 minutes to prepare the MRI navigation during the operation. The duration of hospital stay was 8 days.

Case-2

A 65-year-old female presented with migraines to our clinic. She had normal motor function, no visual impairment, and no history of epilepsy or syncope. A right sphenoid ridge meningioma was identified on the MRI (Figure 4). Preoperatively, the patient's MRI scans were transferred to the system and 3D holograms were created and uploaded to the glasses by the surgical team in the conference room. The vascular regions of the meningioma were observed preoperatively, and the lesion was found to be adjacent to the M2 branch of the middle cerebral artery. The craniotomy was planned preoperatively (Figure 5). Intraoperatively, the images were uploaded to the glasses, and the lesion was completely excised using neuronavigation and Mixed Reality 3D Anatomy. The middle cerebral artery neighborhood detected during the preoperative and intraoperative planning using MxRG was confirmed via the microscope intraoperatively. The vascular structures were preserved (Figure 6). No additional neurological deficits developed postoperatively. The operative time was approximately 2.5 hour. The total volume of blood lost during the surgery was 300 ml. It took 5 minutes to prepare the MRI navigation during the operation. The duration of hospital stay was 6 days.

Case-3

A 24-year-old male, who was intubated in the emergency department due to status epilepticus, was admitted to our clinic after a parenchymal hematoma was detected radiologically. On arrival, he was lethargic, cooperated minimally, and could not be evaluated for orientation. The global muscle strength was approximately 3–4/5. Due to the development of hydrocephalus during the follow-up, external ventricular drainage was performed. Diagnostic selective angiography revealed that the AVM was nourished by the M1 branch of the middle cerebral artery and P1 branch of the posterior cerebral artery and drained by the transverse sinus. On admission to our clinic, CT angiography, MRI, and MR angiography were performed. Preoperatively, the patient's radiological images were transferred to the system and 3D holograms were created and uploaded to the glasses by the surgical team in the conference room. On the 3D holograms, the lesion's feeding artery, it's draining vein/sinus structure,

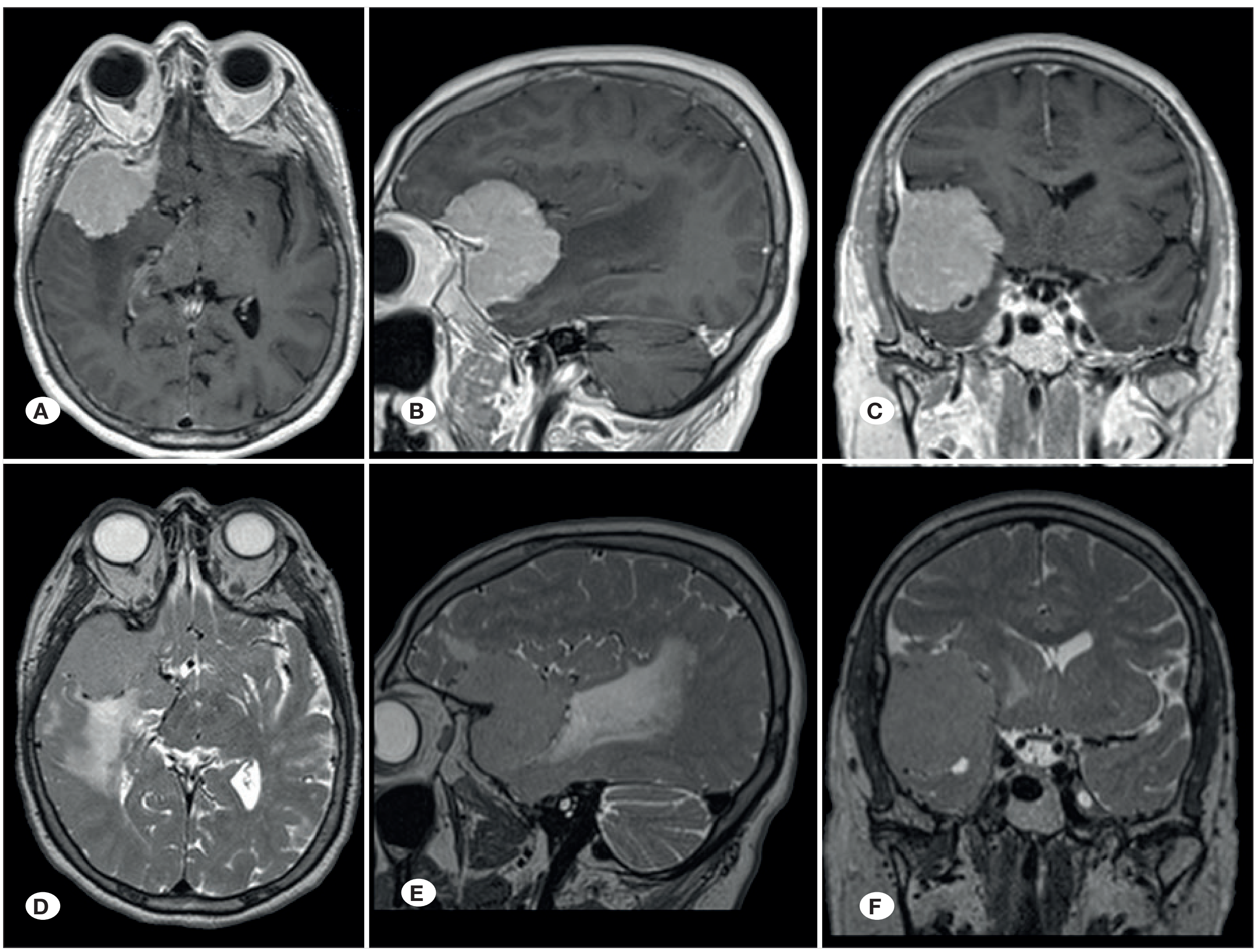

Figure 4: Preoperative MRI showing the presence of a meningioma in the sphenoid wing. **A)** Contrast-enhanced axial section. **B)** Contrast-enhanced sagittal section. **C)** Contrast-enhanced coronal section. **D)** T2-weighted axial segment. **E)** T2-weighted sagittal section. **F)** T2-weighted coronal section. **MRI:** Magnetic resonance imaging.

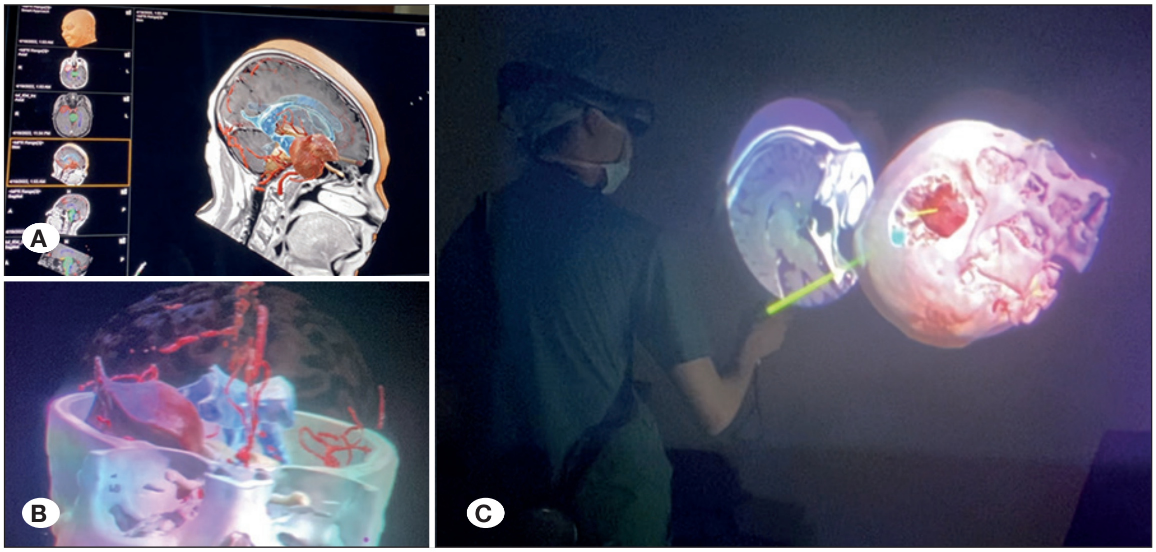

Figure 5: A) creation of the 3D holograms using thin-section cranial MRI scans. **B)** Determination of the lesion's location. **C)** Preoperative craniotomy plan. **3D:** three dimensional; **MRI:** Magnetic resonance.

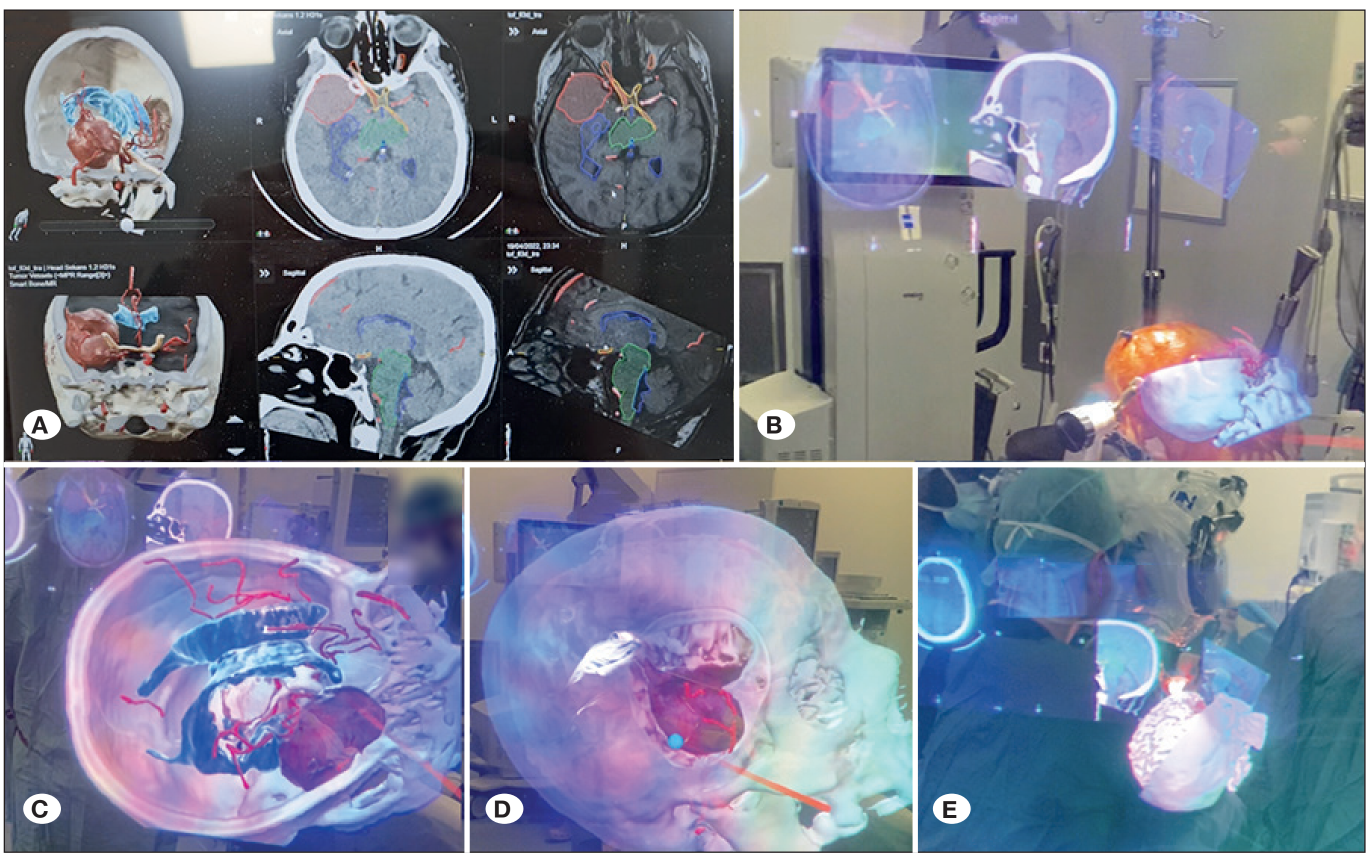

Figure 6: A) Preoperative plans were uploaded to the system. **B)** MxRS assisting with the navigation to facilitate alignment of the holographic images with the patient. **C-E)** The vicinity of the lesion, reexamination of the intraoperative craniotomy plan, and provisional anatomical orientation with MR intraoperatively. **MxR:** mixed reality; **MxRS:** mixed reality system.

and its surroundings were examined. A two cm AVM lesion was confirmed in the inferior temporal lobe, which was fed by the MCA-M1 and PCA-P1 and drained to the transverse sinus (Figure 7). The preoperative plan could not be utilized intraoperatively because the demo period for the MxRS had expired on the day of the procedure. Using neuronavigation and 3D anatomy, the lesion was completely and extensively excised. No additional neurological deficits developed postoperatively. The operative time was approximately 3 hours. The total volume of blood lost during the surgery was 50 ml. It took 5 min to prepare for the MR navigation. The duration of hospital stay was 8 days.

DISCUSSION

Neurosurgery is a challenging medical specialty that requires extensive surgical experience and education. Surgical experience is gained by observing numerous surgical procedures and conducting them repeatedly (4). According to a 2011 article published by the American College of Surgeons the cost of general surgery training is approximately $4 million, the annual cost of surgical training for each general surgery resident is approximately $12,516, and $30,000 is the annual teaching fee allotted to each faculty member instructing residents (17). In 2021, the estimated cost of a neurosurgery residency in the United States was $172,563

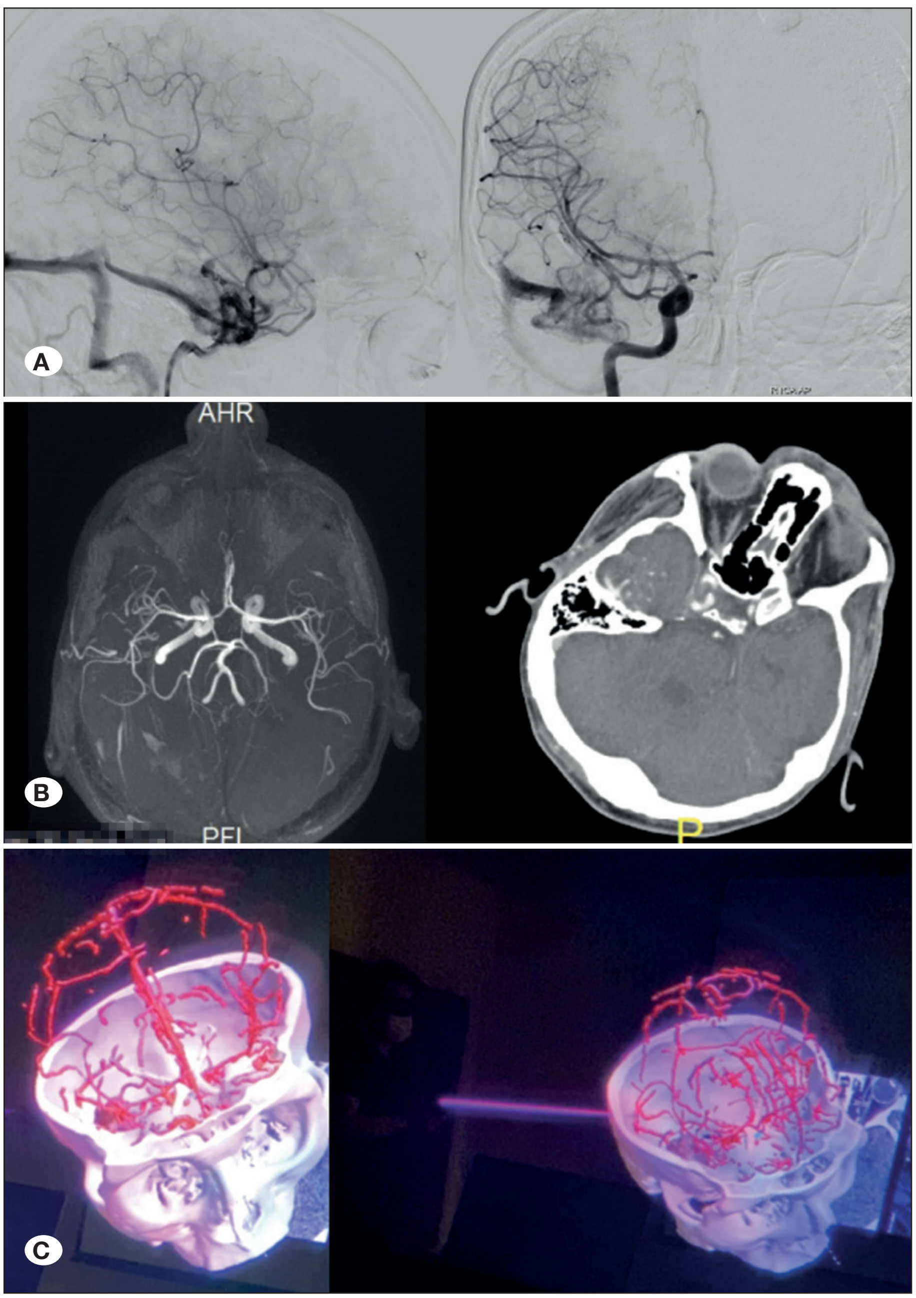

Figure 7: Preoperative imaging of the arteries. **A)** Digital subtraction angiohraphy. **B)** ***Left:*** magnetic resonance angiography and **right:** CT angiography. **C)** Mixed reality images. Several techniques are using to evaluate the structure of a preoperative lesion, including its feeder and drainage veins. **DSA:** digital subtraction angiography; **CT:** computed tomography.

per year or $1,207,941 for a seven-year neurosurgery practice (25). The significance of simulation systems in training was emphasized at the 2007 American Association of Neurological Surgeons meeting with the following statement: “Simulators provide harmless and repeatable practice, multiple and varied scenarios, immediate feedback, uniform standards, objective measures, and trend analysis. For neurosurgery, sophisticated simulators are a great advance in residency training. Although they are costly, they can be provided in specially designed training centers. Simulators would be highly useful in the certification and maintenance of certification processes as well as in continuing medical education, refreshment of skills, and even surgical rehearsal.” (50). Currently, AR systems are an inexpensive solution to providing simulations. In one study, the minimum cost of simulation systems in a neurosurgery practice was estimated to be $341,978, and simulation systems in neurosurgery training were shown to provide learning curves without compromising patient safety (22). Multiple studies have demonstrated that VR and AR applications can enhance learning motivation, experiential and contextual learning, and technical skills (16,27). Using AR applications in surgical education enhance depth perception, accelerate learning, reduce surgical complications, and improve surgical outcomes (23,47,65). Furthermore, neurosurgery assistants can use simulations to learn about uncommon cases and complex procedures which may not be encountered frequently in regular practice (12,59).

In neurosurgery, it is convenient to analyze 2D images in 3D. In conventional surgical practice, the adjacent pathology of a lesion is evaluated based on surgical experience and using 2D image. In intricate procedures, it is crucial to evaluate the lesion’s surroundings in three dimensions to better understand the pathology and determine the surgical approach (12). Preoperative examination of the patient’s 3D radiological images in a VR environment can reduce surgical time, cerebrovascular injuries, and complications, improve prognosis, and permit the development of case-specific treatment plans (19,56,57).

During surgical procedures, every minute adds to the financial burden on the healthcare system (14). Intraoperative imaging-guided surgeries reduce hospital stays, complications, and morbidity, thereby reducing the financial burden on the healthcare system (37,46). In neurosurgery, AR systems reduce the operative time and the incidence of complications (64). Current evidence suggests that a MxRS may be a cost-effective option for healthcare systems because of their relatively low cost and reusability. The MxRS enables the visualization of 3D images and virtual models in real-time, allowing for more precise surgical planning and execution. This can reduce the operative time and the likelihood of complications, resulting in reduced healthcare costs.

The MxRS not only has a use in training and preoperative planning, but also in the operating rooms of today. MxR applications can be used intraoperatively for the treatment of numerous diseases, including neurovascular, neurooncological, spinal, stereotactic functional procedures. Intraoperatively, MxR applications can prevent complications by superimposing images of tumors, vascular structures, and even a

Table I: A Comparison of MxR, iMRI/iCT, and Conventional Surgery According to the Literature

	Mixed Reality	iMRI/iCT Navigation	Simple Navigation	Conventional Surgery
Preoperative Plan	Preoperative 3D Images, Hologram	-	Preoperative 2D Images	Preoperative 2D Images
Surgical Training / Education	+ (3D with Hologram Reproducible)	-	-	-
Blood Lost (ml)	200 (50-350) ml	793 ± 1083 ml (5)	331 (238-970) ml (2,9,13)	570 (344-1810) ml (2,9,13)
Operation Time (min)	170 (150-180) min	255 ± 10.6 min (1) (iMRI)	207 (206-210) min (2,9,13)	279 (166-460) min (2,9,13)
Mean Target Registration Error (mm)	Not calculated in our cases, 2.5 (0.7-4.4) mm (20) in literature	0.87 ± 0.36 mm on iCT (11)	2.6 (2.1-3.1) mm (20)	No navigation
Time for Planning and Registration (min)	5-10 min	60 min (1)	68.2 ± 21.7 min (63)	37.8 ± 10.8 min (63)
Stay in Hospital (days)	7.33 (6-8) days	5.2 days (21)	5.93 days (9)	7.69 days (9)
Radiation Rate in During Surgery	None	2.73mSv on iCT (11)	None	None
Cost	Low cost hardware like Hololens and Google Glass (51) $3000 (49)	iMRI- $3–8 million (55) iCT- $800,000–2 million (29)	$300,000 (49)	No additional cost for intraoperative use

patient's tractography on real-time images. In addition, the surgeon can view the patient's radiological images intraoperatively without having to turn away from the surgical field to access them (8,32,61,62). The use of intraoperative MxR applications to treat high-grade gliomas improves surgical treatment outcomes. However shifting in cerebral tissues during surgery may reduce the efficacy of the navigation (40,58). In the current neurosurgical practice, intraoperative MRIs and CTs are effective methods for assessing intraoperative brain displacement. However, both these procedures are expensive and require a protracted preparation process. iMRI and intraoperative CT (iCT) are valuable instruments in neurosurgery; however, their ubiquitous use is hampered by the excessive cost of procuring a system, which ranges from $3 to $7 million for MRI and from $1.5 to $3 million for CT. Furthermore, there may be additional costs associated with renovating the operative suite to accommodate the system. It is difficult for many hospitals and clinics to adopt an iMRI because of these financial obstacles (53). In contrast, iCT can be beneficial in neurosurgery; however, it exposes the patient to additional radiation (45). Similar to iMRI, intraoperative ultrasound is an effective instrument for intraoperative navigation; however, there is no need for additional expenditures and devices (36, 44). A 2018 study demonstrated that using intraoperative ultrasonography to assist navigation can increase the accuracy of MRI navigation by making corrections during the procedure (24). For neurosurgical navigation, head-mounted displays are significantly less expensive than intraoperative imaging modalities such as iMRI and iCT. Although iMRI and iCT systems can cost millions of dollars, head-mounted displays are typically much more affordable, making them accessible to a wider spectrum of hospitals and clinics (10). A study examining the use of AR applications in stereotactic surgery determined that these applications could improve the safety of the surgery (54). Another study on ventricular drainage placement in patients with hydrocephalus determined that MxRGs were more effective than conventional methods (39).

Table II: Potential Benefits and Shortcomings of MxR, iMRI/iCT, Simple Navigation and Conventional Surgery

Mixed Reality Systems	Pros	• Can be use for neurosurgical training • Allows the surgeon to see and interact with virtual and real elements simultaneously in 3D • Enhances accuracy and precision of surgery by providing additional information and guidance in real-time • May reduce the need for multiple incisions and reduce surgical time • Has a positive effect on the amount of bleeding • Has the potential to improve patient outcomes and complications • Cheaper than intraoperative MRI/CT and can be as precise as intraoperative MRI/CT • Has a short learning curve • Friendly using
	Cons	• Requires specialized equipment • The technology is still in the early stages of development
Intraoperative MRI/CT	Pros	• Provides real-time information about the surgical field • Improves accuracy and safety of surgery by providing up-to-date information as the procedure is being performed • May reduce the need for multiple incisions and reduce surgical time • Has the potential to improve patient outcomes
	Cons	• Expensive to implement and maintain • Need specified surgical tools to work • Requires specialized equipment, training and trained staff
Simple Navigation	Pros	• Provides the surgeon with a map of the brain and allows them to track their position within it • Improves accuracy and efficiency of surgery by providing a clear understanding of the surgical field • May reduce the need for multiple incisions and reduce surgical time • Better patient outcomes than conventional neurosurgery
	Cons	• May be expensive to implement and maintain • Requires specialized equipment and training • May not be suitable for all types of neurosurgery
Conventional Neurosurgery	Pros	• Widely available and well-established technique • Can be effective for many types of neurosurgery
	Cons	• May be less precise and less efficient than more modern techniques • May require larger craniotomies, multiple incisions and longer surgical times

AR applications can be used for preoperative planning and intraoperative navigation in spinal surgery. They reportedly shorten the operative time and reduce intraoperative hemorrhage. However, studies regarding this effect on operative time and intraoperative hemorrhage are limited (18,26,28,41,64).

Literature regarding the three surgical assistive techniques (iMRI/iCT-guided, simple, and conventional navigation) were reviewed in terms of the preoperative plan, surgical practice, amount of intraoperative bleeding, operative time, margin of error when matching during navigation and the time spent on it, amount of radiation exposure to the patient, and length of hospital stay. Table I shows the comparison of navigation systems based on these terms with the data obtained from our clinic's MxRS and the data obtained from literature.

In terms of preoperative planning and surgical practice, MxRS is superior to other methods because of its ability to display 3D anatomy which can be manipulated and its reproducibility. When MxRS is compared with other techniques used in comparable cranial cases, the operative time (average, 170 min) and the amount of hemorrhage (average 200 ml) is lesser (1,2,5,9). This is because of the preoperative planning, standard operating procedures, and surgeon's sense of safety. Thus, a shorter hospital stay (average, 7.33 days) is anticipated compared with other studies. Furthermore, conventional surgical techniques have a shorter operative time (7.69 days) (9,21). This may be attributable to the lengthy preoperative examinations of patients scheduled to undergo surgery. Compared to the time allocated for the intraoperative preparation phase of navigation in other systems, MxRS requires lesser time (5–10 min) (1,63). We didn't measure the target margin of error. However, the margins of error reported in literature were comparable to those of other systems (20).

In cranial procedures using iCT navigation, the patient's average radiation exposure is 2.73mSv (11). The lack of radiation exposure is an additional benefit of the MxRS. The cost of the MxRS is reportedly approximately $3000 (49,51). However, the costs of iMRI, iCT, and simple neuronavigation system are are $3,000,000–$8,000,000, $800,000–$2,000,000, and $300,000, respectively (29,49,55). Considering the features of iMRI and iCT, costs can increase even further when preparations, such as the arrangement of the operating room to accommodate these technologies and requirement of a private isolation chamber for the personnel in the operating room, are factored in. The MxRS is more cost-effective than other systems because they do not have such requirements, are less expensive, and are as effective during and before surgery. Table II summarizes the advantages and disadvantages of MxR and other methods.

Limitations

Our study had some limitations. The MxR system in this srudy was used (Magic Leap glasses) was used for only a limited duration and patient population. A larger sample size is necessary to obtain more accurate results. Questions and ideas that emerged during the study could potentially offer hypotheses for future researches.

CONCLUSION

The use of MxRS for preoperative planning and navigation requires further in-depth research. These technologies have only recently been used in surgical procedures. It has a short learning curve for examining and comprehending 3D surgical anatomy, enabling reproducible 3D examinations in medical practice, and enabling determination of anatomical variations in peripheral structures. The MxRS used during neurosurgery is cost-effective and has the potential to reduce complications and shorten the operative time. However, additional research is required to understand the potential benefits and limitations of MxR in neurosurgery. It is important to bear in mind this technology is not a magical instrument; however, its user-friendliness greatly benefit surgeons. Additional research is required to determine the optimal use of MxR in various neurosurgical procedures and patients.

Declarations

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Availability of data and materials: The datasets generated and/or analyzed during the current study are available from the corresponding author by reasonable request.

AUTHORSHIP CONTRIBUTION

Study conception and design: YSC, MZ, ID, OO
Data collection: EE, BCA, EBM
Analysis and interpretation of results: BCA, EBM
Draft manuscript preparation: MZ, EE, BCA, EBM
Critical revision of the article: MZ, EBM
Other (study supervision, fundings, materials, etc...): YSC, ID, OO
All authors (YSC,MZ,OO,EE,BCA,EBM,ID) reviewed the results and approved the final version of the manuscript.

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