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Extended reality platform for minimally invasive endoscopic evacuation of deep-seated intracerebral hemorrhage: illustrative case

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BACKGROUND Extended reality (XR) offers an interactive visualization platform that combines virtual reality (VR) for preoperative planning and augmented reality (AR) for intraoperative navigation overlay.

OBSERVATIONS XR was used for treating a case of spontaneous intracerebral hemorrhage (ICH) requiring neurosurgical intervention to decompress a hemorrhage in the subcortical area involving the thalamus that was starting to compress the midbrain. The selected surgical technique was an endoscopic aspiration combined with neurosurgical navigation. Because of the deep-seated location of this ICH, a patient-specific 360XR model rendered using Surgical Theater was used for preoperative planning and intraoperative navigation to allow for enhanced visualization and understanding of the pathology and surrounding anatomy.

LESSONS The XR platform enabled visualization of critical structures near the ICH by extracting and highlighting the white matter tracts from magnetic resonance imaging (MRI) with tractography, which improved preoperative planning beyond using state-of-the-art neuronavigation techniques alone. Once the trajectory was set, the model was integrated with the neuronavigation system, and the planned approach was referenced throughout the procedure to evacuate the clots without further injuring the brain. The patient tolerated the procedure well and was doing well 11 months after his spontaneous ICH.

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KEYWORDS intracerebral hemorrhage; minimally invasive surgery; virtual reality; augmented reality

Spontaneous intraparenchymal hemorrhage (IPH), a type of intracerebral hemorrhage (ICH) that occurs as a result of a small penetrating blood vessel rupture involving areas of the thalamus, pons, basal ganglia, or cerebellum,[1] is considered to be relatively common, accounting for 6.5% to 19.6% of stroke cases.[2] The most significant risk factor for this type of spontaneous ICH is hypertension, to such an extent that it is often termed "hypertensive hemorrhage." These types of IPHs are associated with a high mortality rate, more than 50%[3] in some studies, particularly in patients with large, deep-seated ICHs.[4] Furthermore, patients who survive often struggle with significant neurological deficits.

Medical treatment of these hemorrhages focuses on blood pressure control, glucose management, seizure control, and reversal of any coagulopathies. However, medical treatment can be frustrating and dissatisfying given that maximal optimization only mitigates the primary and secondary injury caused by a large compressive lesion.[5,6] To that end, in the 1990s, Batjer et al. showed that surgical decompression for deep-seated hemorrhages led to further injury and worse outcomes.[7] This became a widely held belief for many years; it was not until the routine use of minimally invasive surgical (MIS) techniques that surgical treatment of hypertensive hemorrhages began to be reconsidered.[8,9] When surgical treatment is recommended for a spontaneous ICH, the goal is to remove as much blood clot as possible with the least amount of brain injury from the surgery itself.[5] From the literature and our own experience, midbrain injury and dysfunction portend a poor outcome.[3]

ABBREVIATIONS 3D = three-dimensional; AR = augmented reality; CST = corticospinal tracts; CT = computed tomography; CTA = CT angiography; DTI = diffusion tensor imaging; ICH = intracerebral hemorrhage; IPH = intraparenchymal hemorrhage; MIS = minimally invasive surgical; MRI = magnetic resonance imaging; VR = virtual reality; XR = extended reality.

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Interestingly, we have seen a number of cases in which these symptoms and associated injury evolve from an ICH yet were not necessarily correlated with an obvious increase in hemorrhage size. Because MIS technique can reduce mass effect hemorrhages while minimizing brain tissue damage, would this subset of patients, who do not present with midbrain dysfunction or injury but begin to develop these symptoms, benefit from MIS decompression and reduction of the mass effect from the hemorrhage?

Recently, MIS approaches using either a tube-like disposable device such as Vycor or NICO device or endoscopic techniques have been explored for treating ICHs.[8] While MIS techniques can reduce brain tissue damage, infection rates, and length of recovery, the surgical procedure can be technically challenging with limiting factors.[10] During these cases, the surgeon is required to use techniques other than standard tactile feedback and visual cues, depending on neuronavigation for orientation and location within the brain. Therefore, surgery on these hemorrhages is only safe with thorough surgical planning and continuous reference to the neuronavigation screens intraoperatively because of lack of standard visual cues. Because neuronavigation mainly displays the standard imaging in the three separate planes, the surgeon has to constantly reconstruct the three-dimensional (3D) lesion in his or her mind. Because visualization during these surgeries is limited, even using state-of-the-art neuronavigation techniques, the use of virtual reality (VR) and augmented reality (AR) allows overlay of the 3D pathology and its relationship to critical structures that would otherwise not be seen and appreciated, making it critical to the safety and efficacy of these procedures.

In this report, we present an endoscopic MIS evacuation case to treat a patient with spontaneous IPH using an extended reality (XR) platform. Preoperatively, the system was used for surgical planning in VR analyzing various trajectories into the hemorrhage. Intraoperatively, neuronavigation guidance was integrated with the 360° XR (360XR) model and the endoscopic images to create an AR environment that enhanced visualization throughout the case. For neurovascular surgery, the XR platform described here has been successfully used for patient engagement, preoperative planning, intraoperative visualization, and evaluation of postaneurysm clipping or endovascular intervention.[11–13] Diagnostic imaging studies such as computed tomography (CT), CT angiography (CTA), or digital subtraction angiography can be fused to build a comprehensive and interactive 360XR model.[12] In this case, the 360XR model assisted the surgeon in planning in VR and provided a direct trajectory to the deep-seated IPH that avoided critical structures, enhanced by magnetic resonance imaging (MRI) with diffusion tensor imaging (DTI). In the operating room, the XR platform's AR solution for endoscopic surgeries was used to provide intraoperative guidance via AR overlay of the 360XR model. Use of Endoscopic Surgical Navigation Advanced Platform (EndoSNAP) for preoperative planning in VR followed by intraoperative AR guidance has been demonstrated for skull base tumor resection.[14–18] To our knowledge, this is the first report involving VR and AR solutions for treating a deep-seated hemorrhage.

Illustrative Case

A 59-year-old man with a history of hypertension presented with sudden onset of aphasia, right hemiparesis, and lethargy. Head CT demonstrated a $3.0 \times 2.1 \times 2.9$-cm IPH involving the thalamus and compressing the midbrain (Fig. 1). Overnight, the patient became progressively lethargic and developed dysconjugate gaze and anisocoria, with the left pupil becoming smaller and variably reactive to light. The patient improved with standard medical management; however, it was believed to be a temporizing measure and believed that he was early in the disease process and that his condition would likely deteriorate given the proximity of the hemorrhage to the midbrain and his evolving symptomatology. Therefore, the patient was taken for an MIS evacuation of the hemorrhage.

A 360VR model was created by merging the patient's preoperative CTA, head CT, and MRI with DTI scans on the Surgical Planner (Surgical Theater, Inc.) for presurgical planning in VR. The model displayed the skull, arteries, lateral ventricles, corticospinal tracts (CSTs), and hemorrhage in detail (Fig. 2). Using nordicBrainEx software (NordicNeuroLab), the MRI and DTI scans were merged and processed to create the fiber tracts that were incorporated into the model using the scans' x, y, and z coordinates. The rendering of the VR model took approximately 25 minutes. For preoperative planning, the surgeon used the VR headset (Oculus Rift) and controllers to navigate through the patient's model to place a surgical trajectory that would ensure protection of the internal capsule and the CST running through the brainstem and basal ganglia (Fig. 3).

In the operating room, the patient's 360XR model was imported to the EndoSNAP (Surgical Theater, Inc.), which was connected to the endoscope (Karl Storz) and navigation. General endotracheal tube anesthesia was performed, and the patient was secured in a supine position. In the standard fashion, the StealthStation S8 navigation system's AxiEM electromagnetic intraoperative guidance system (Medtronic) was registered to the patient with an excellent degree of accuracy. An initial plan for the trajectory of the approach was created with the StealthStation using imaging in all three planes to create the least damaging approach possible yet lining up the long access of the hemorrhage to maximize clot evacuation. We then turned our attention to integrating Surgical Theater with the Stealth Navigation. The plan created in the StealthStation was then projected into the VR environment, and we noted that the approach that followed the long axis of the clot was too lateral and broached the internal capsule. We then revised the approach using the 360VR model, allowing us to fly through the plan and ensure that no vital structures were compromised (Video 1).

VIDEO 1. Clip showing the two main aspects of the left thalamic ICH discussed in this report. First, the preoperative CT scan, 360VR reconstruction, and VR trajectory planning are presented. Then, the clip displays the intraoperative endoscopic live feed with the matching view of the 360VR model side by side as well as the postoperative 360VR model of the residual hematoma. Click here to view.

The EndoSNAP was set in dual mode to display the VR model alongside a matching view of the endoscopic video feed throughout the procedure (Fig. 4). The 360XR model was also manually overlaid onto the endoscope feed to verify proximity of the Stylet tip to the CST bundle during the procedure.

Using the neuronavigation and the preplanned trajectory, the opening for the left frontal burr hole was marked. A burr hole was created in the usual standard fashion down to the dura, which was opened with a cruciate incision. The pia was coagulated with bipolar cautery and opened sharply. The 19-Fr peel-away catheter (Cook Medical) was registered to the S8 navigation system as well as the endoscope. The flexible stylet allowed us to track the catheter to provide a matching view of the 360XR model from the tip of

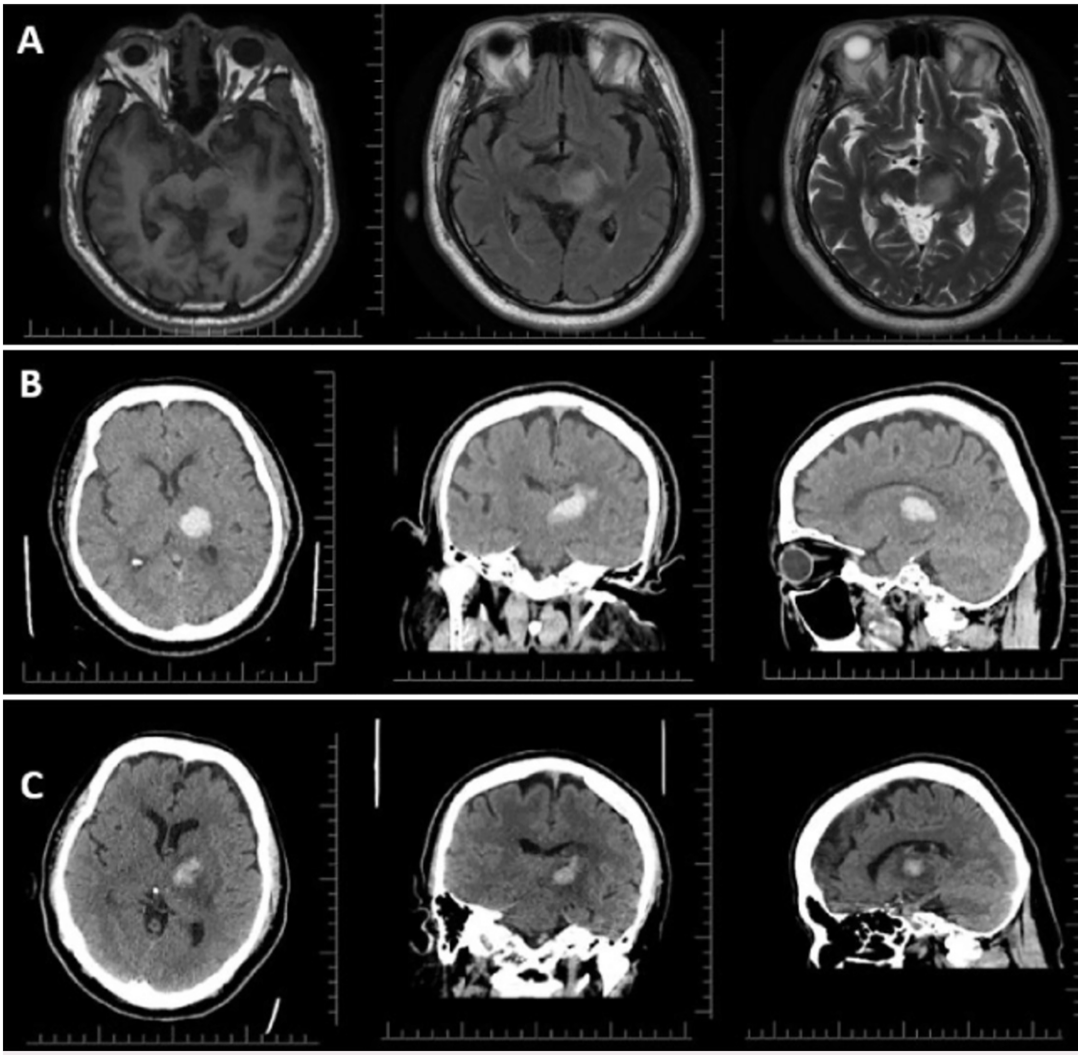

FIG. 1. A: Preoperative axial T1-weighted precontrast (*left*), T2 FLAIR (*center*), and T2 periodically rotated overlapping parallel lines with enhanced reconstruction (PROPELLER; *right*) images of the left thalamic ICH demonstrating pressure and edema on the midbrain. **B:** Preoperative axial (*left*), coronal (*center*), and sagittal (*right*) head CT images displaying a hyperintense hematoma with a total volume of 4.97 cm^3. **C:** Postoperative axial (*left*), coronal (*center*), and sagittal (*right*) head CT scans showing the residual hematoma with a total volume of 1.71 cm^3. The Surgical Planner calculates total volumes from the CT scans using the hyperintensity of the hematoma.

the tracked tool. For instance, the catheter was tracked so the surgeon was able to interact with the model, which displayed a virtual endoscope-like view from the perspective of the tip of the catheter (Fig. 5). The catheter was then advanced approximately halfway into the hemorrhage. The S8 stylet was removed, and the endoscope was then placed down into the catheter, immediately providing visualization of the hemorrhage. The Artemis system (Penumbra) running through the endoscope was used for gentle suction as well as active aspiration of more fibrinous clots. Copious amounts of saline were used to irrigate the area, and the hemorrhage was evacuated using gentle suction and active aspiration. Not all the clots were removed in the area along the midbrain and the internal capsule to minimize further brain injury. Throughout the entire procedure, the 360XR model was referenced in a side-by-side view to the endoscope, providing real-time visualization of the midline as well as the internal capsule, which was lateral to the hemorrhage (Video 1). This was especially critical when visualization with the endoscope was obscured by the hemorrhage. Next, using the 360XR model in combination with the neuronavigation as guidance, a left frontal external ventricular drain was placed with good flow. The patient was extubated and brought to the neurointensive care unit in stable condition, namely lethargic and right hemiparetic. After 48 hours, the patient's examination was notable for weakness that was unchanged from preoperative state and aphasia; however, the aphasia was improved compared to previous examinations. The patient was discharged from the intensive care unit after 6 days into rehabilitation, where he slowly improved and eventually was discharged home after 27 days of inpatient rehabilitation.

Four months after his spontaneous IPH, the patient was advised to continue with physical therapy and cognitive therapy as prescribed. At 11 months, the patient's speech was fluent, naming was mostly intact, and his comprehension was intact. The patient's motor examination only showed a mild weakness in the right shoulder

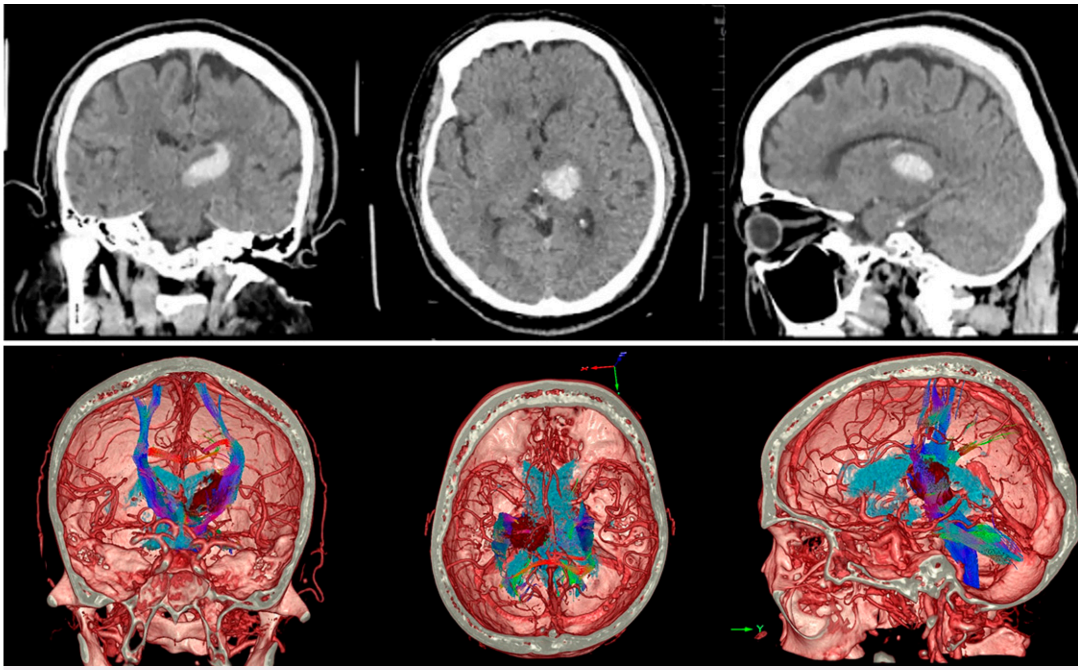

FIG. 2. Upper: DICOM images in the coronal, axial, and sagittal planes, respectively. **Lower:** The 360XR model was positioned to match the three planes of the DICOM images, and the model includes the extracted ventricles, IPH, and DTI white matter tracts of the corona radiata.

abduction 4+/5. Overall, the patient was assessed as doing very well.

Discussion

Observations

IPHs are associated with a high mortality rate,[2] with a mortality rate at 1 month of 40%[19] and a 10-year survival of 32% on deep hemorrhages involving subcortical structures.[20] Due to the prevalence of ICHs, the efficacy of MIS techniques has been evaluated and compared to other ICH management plans.[5,9,21,22] A comparative study between the endoscopic surgical technique and medical management showed that the 6-month mortality was 42% in the surgical treatment group, which was significantly lower than that of the medical management group (70%; $p < 0.01$).[5] Another association was that minimal to no deficits were more frequent in the

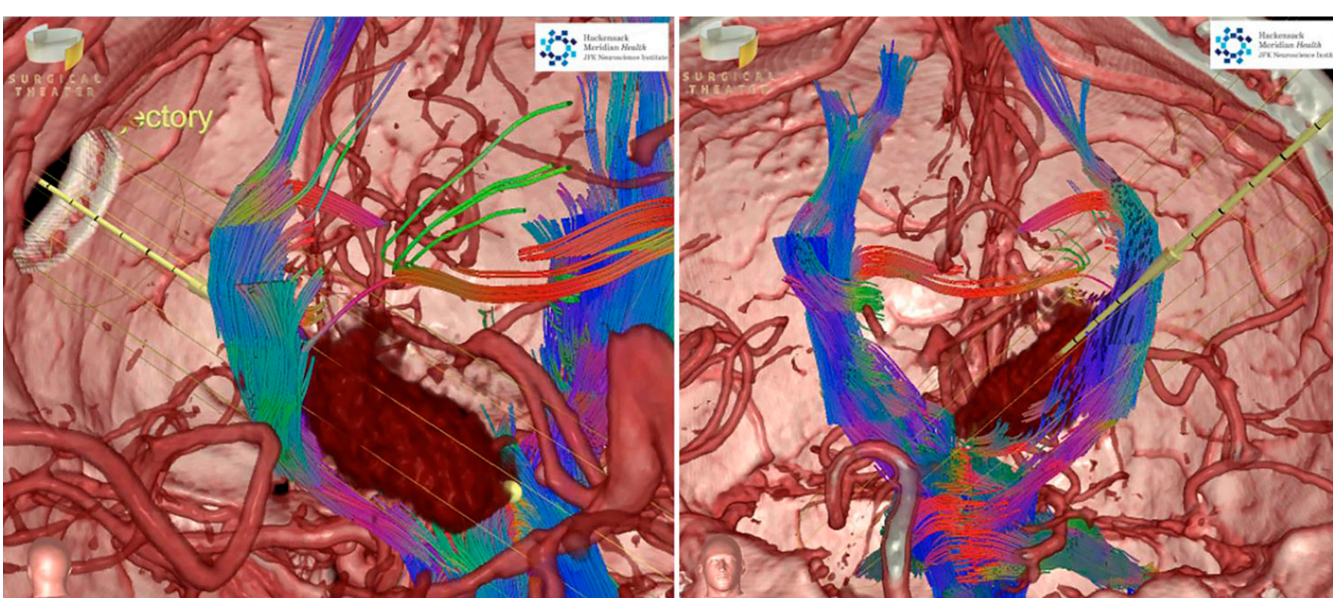

FIG. 3. 360VR model of the CTA scan fused with the extracted DTI fiber tracts in the directional colors and the extracted hyperintense hemorrhage (*red*) from the CT scan.

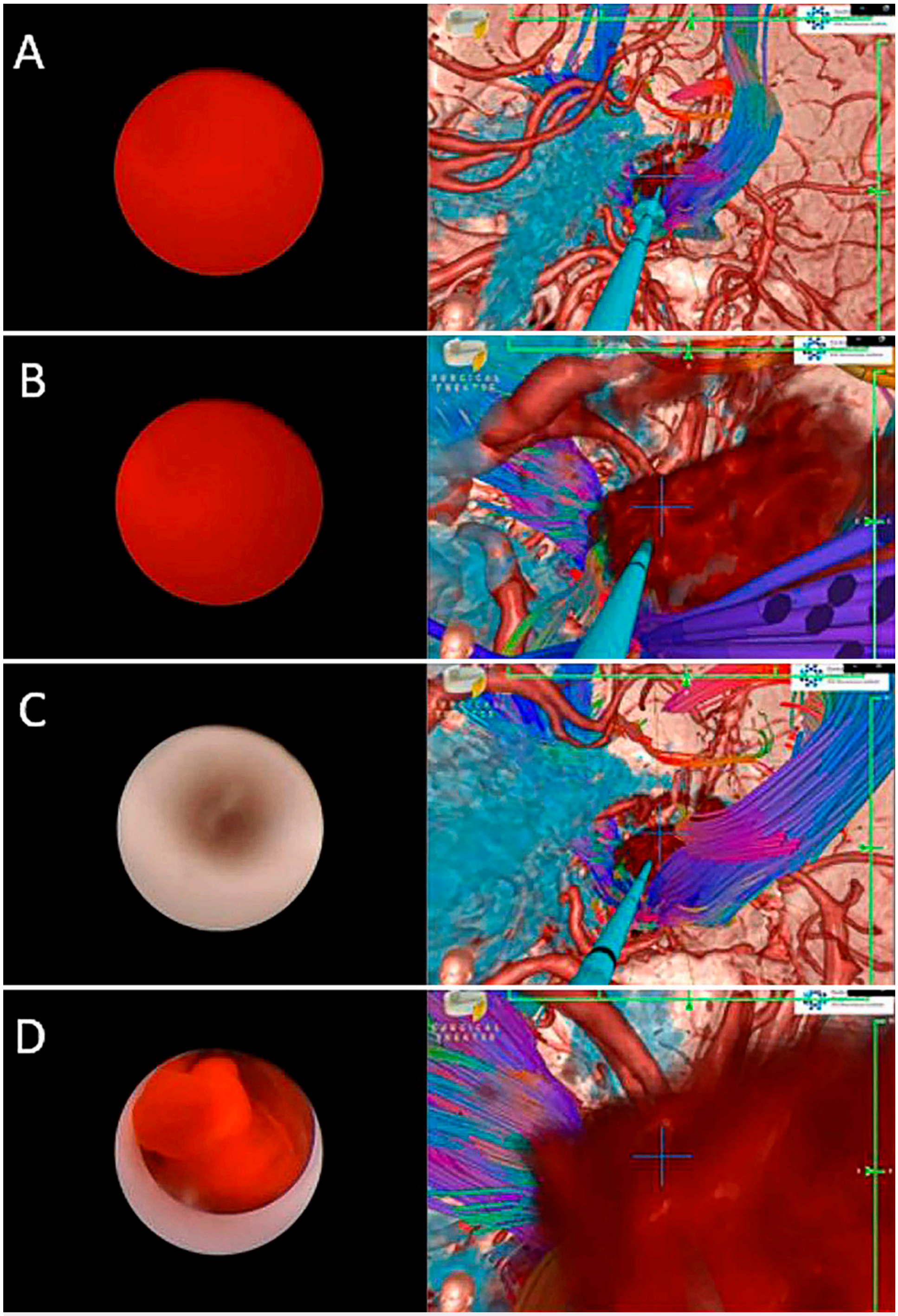

FIG. 4. A side-by-side view showing evacuation of the hemorrhage via the endoscope in the peel-away catheter (*left*) and the VR model integrated with the navigation system (*right*) to show real-time location and relationship to the internal capsule and other critical structures.

surgically treated group, mainly on smaller hematomas.[5,21] The endoscopic aspiration technique has also been linked to a decrease in the 6-month mortality rate compared to other surgical approaches, such as stereotactic aspiration and craniotomy for the treatment of spontaneous basal ganglia hemorrhages.[22] Currently, no particular MIS approach has proven to be superior in improving clinical outcomes for ICH management when comparing all MIS techniques. Nonetheless, data indicate that MIS may reduce secondary injury such as local mass effect, hemotoxicity associated with blood breakdown products, and hydrocephalus.[8] However, current trials are underway to further improve MIS

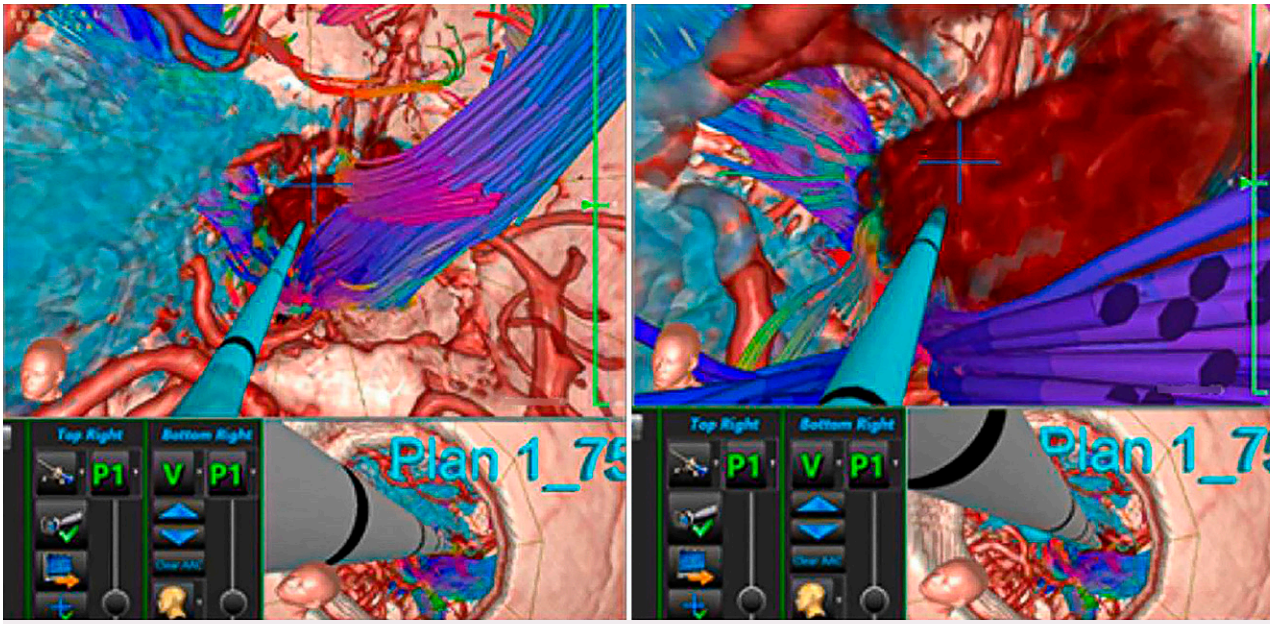

FIG. 5. The light blue tool is the planned trajectory to the IPH, the gray tool represents the tool being tracked intraoperatively, and the top view with the blue cross is the perspective of the tip of the stylet.

techniques for ICH evacuation, and XR may provide further enhancement by providing enhanced visualization to better prepare surgeons before and during the procedure. Additionally, the limited visual and haptic feedback of MIS techniques in general may make them more difficult to learn and perfect, and VR and AR may help lessen the learning curve.

This case illustrates the power of using 360VR for preoperative planning and integrating the system into navigation and visualizations systems to create an extended reality platform used during surgery. The operative plan, namely the location of the opening and trajectory into the hemorrhage, was originally created using the StealthStation and standard navigation techniques and imaging. The patient-specific 360XR model enabled visualization of all the scans simultaneously in a single 3D interactive model that displayed in high resolution the relationship between the hemorrhage and the CST that ran through the brainstem. The original plan was loaded into the 360XR model, and it was obvious that it needed to be revised to effectively avoid vital structures and make the plan safer and cause less injury due to the approach (Video 1). Once that trajectory was revised and finalized, the EndoSNAP was integrated into both the neuronavigation system and endoscope's DVI video outfeed. This integration allowed for the model to be reflected with an overlay on the endoscopic live video feed (Fig. 5). The endoscope and catheter were easily tracked by the neurosurgical navigation system using a trackable stylet to stay in the planned path to the hematoma. Use of the XR platform aided in the successful evacuation of the deep-seated IPH using the MIS endoscopic technique without creating worsening or new deficits, facilitated the patient's recovery, and shortened his hospital stay.

Several studies have used 3D modeling and/or AR for the surgical treatment of ICHs. In one study, AR technology facilitated accuracy and precision on hematoma positioning and puncture trajectory in 25 patients.[23] Using a smartphone, a 3D model of the patient's CT scan was overlaid on the patient's head to preoperatively plan trajectories to ICHs. During this application, no other imaging was incorporated in the 3D model, and navigation was not used in combination with the AR model. Another 3D modeling platform has been used for preoperative planning for a deep-seated hematoma evacuation and found to be extremely useful as a reference for orientation for craniotomy positioning.[24] The use of AR and 3D modeling during the operative process helps to plan a minimally invasive approach, resulting in good outcomes and relatively short procedure time.[24] Furthermore, it is important to note that these previous studies did not use true virtual reality for preoperative planning or augmented reality in combination with intraoperative neuronavigation for ICH surgical intervention. In our case, the VR-planned trajectory was continuously referenced throughout the procedure by checking side-by-side displays of the 360XR model and endoscopic video feed. Additionally, during the evacuation, the 360XR model was overlaid onto the live endoscopic image to visualize the fiber tracts over the endoscopic view. The surgeon felt that the enhanced visualization aided in avoiding those areas and only aspirated clots outside the CST bundle.

Lessons

This case underscores three important principles. First, it suggests that early and aggressive treatment of ICH of any size that is near to and pressing on the midbrain and brainstem before permanent injury occurs may be a critical step in maximizing recovery. Second, the use of VR appears to simplify surgical planning and make it more efficient, thereby improving the surgeon's confidence in the planned approach. Lastly, integrating the 360XR model into the navigation system and using it in real time as an overlay onto the operative field to supplement the direct visualization through the endoscope provides more intuitive and natural visualization of the hemorrhage and location of the procedure. Furthermore, it highlights vital structures that would otherwise not be seen, likely increasing the safety and efficiency of the procedure.

Several limitations were experienced during the case. Because there were not enough stable structures, it was difficult to refer to and confirm the rotational accuracy of the overlay. Thus, only the distance between the tracked tool or device and the fiber tracts was taken into consideration when using the AR overlay. However, the distance displayed had the accuracy error calculated from the patient registration on the navigation system. Another potential limitation is that the tracts were rendered by combining the DTI scan with statistical models rather than solely with the patient's imaging. Although these limitations were encountered, preoperative DTI studies have been found to minimize morbidity in other complex neurosurgical procedures.[25] The use of XR technology should be further studied for smaller hematomas in ICH cases because functional imaging is rarely performed due to the urgency of ICH intervention and potential distortion of the DTI because of clot.[26]

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Disclosure

D. Barbery is employed by Surgical Theater and is a full-time field specialized technician at the Neuroscience Institute at JFK Medical Center that provides technical support for all clinical cases. This study did not receive any funding or financial support. No other disclosures were reported.

Author Contributions

Conception and design: Steineke. Acquisition of data: both authors. Analysis and interpretation of data: both authors. Drafting the article: Barbery. Critically revising the article: both authors. Reviewed submitted version of manuscript: both authors. Approved the final version of the manuscript on behalf of both authors: Steineke. Administrative/technical/material support: Barbery. Study supervision: Steineke.

Supplemental Information

Video

Video 1. https://vimeo.com/728850526.

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