32 Microscope Integration and Heads-Up Display in Brain Surgery

Margaret Pain, Holly Oemke Madarash, Leslie Schlachter, Anthony B. Costa, and Joshua B. Bederson

Recent advances in frameless stereotaxis, microscope integration, image segmentation, three-dimensional reconstruction, heads-up display (HUD), and intraoperative surgical navigation systems such as *Navigation Update* show promise in improving the quality of neurosurgical interventions, particularly microscope-based brain surgery. Surgeons now have the ability to apply detailed patient-specific information about critical normal and pathologic structure and their anatomic relationships directly into the operative field. These technologies can link the visual focal point of the operating microscope to an overlaid three-dimensional reconstruction of the most relevant structures. The information that is projected into the eyepieces and overlaid on the optical display is updated in real time as a surgeon moves the microscope or adjusts the focal point depth, without the need to divert attention from the operative field to a computer screen or to introduce navigated instruments. Furthermore, the very recent introduction of the intraoperative *Navigation Update* system allows the operator to reregister the stereotaxic field to match intraoperative anatomic landmarks in less than 2 minutes, without the need for intraoperative CT, MRI or ultrasonography. This advance has the potential to significantly increase the utility of surgical navigation and addresses one of the most persistent and difficult challenges in this field, that of intraoperative brain shift. Together these evolving technologies have the potential to transform the operative experience for brain surgeons. This chapter describes how current integrated augmented reality platforms work and includes a proposed workflow for augmented reality implementation, case-based examples of successful implementation, and areas where further development is needed. Readers will be able to apply the ideas presented to their practice in surgical planning and intraoperative applications and to understand the limitations of the technology.

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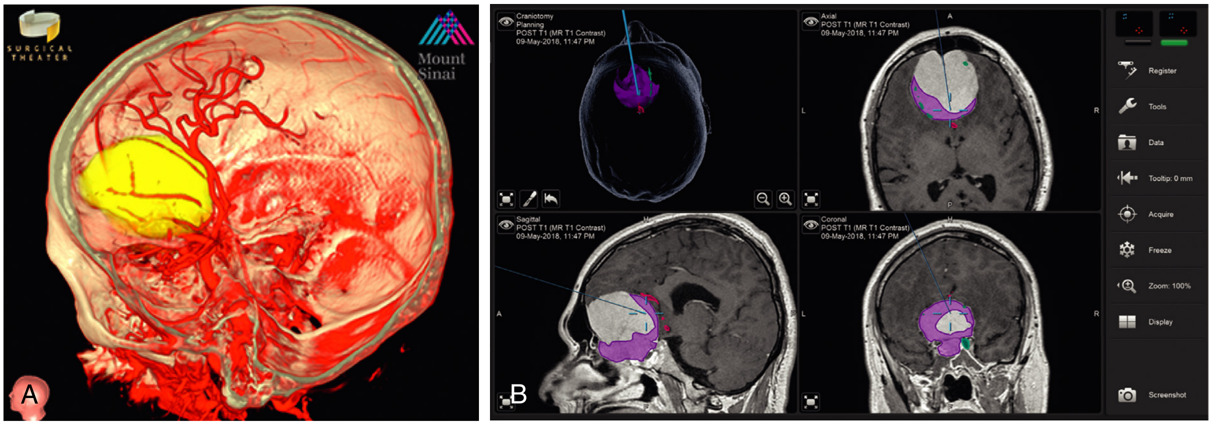

This case shows a 40-year-old male patient with no significant past medical history presented to his internist for profound vision loss and anosmia. His neurological examination was significant for superior hemianopsia with visual acuity in the inferior fields of 20/400 on the right and finger counting on the left, as well as anosmia. (A) Preoperative planning three-dimensional representation of patient's anatomy using *Surgical Theater*. (B) Intraoperative structure update demonstrating areas of the tumor remaining. See Video 32.1 for a discussion of the case.

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KEY CONCEPTS

- Heads-up display is a type of augmented reality in which digital representations of patient anatomy are cast over real anatomy. It is currently available for neurosurgeons through microscope integration.
- Segmentation software allows the clinician to create a three-dimensional representation of patient-specific anatomy for use in augmented and virtual reality environments.
- Both heads-up display and three-dimensional models help neurosurgeons translate two-dimensional preoperative imaging into a working understanding of the anatomic relationships relevant for surgical interventions.
- Registration errors create inaccuracies in image-guided surgery through scalar and translational shifts in the patient's anatomy relative to the locations registered at the beginning of the procedure.
- Segmentation errors create inaccuracies in image-guided surgery by depicting anatomic relationships that do not correctly describe reality.

Augmented reality (AR) platforms are a promising technique for translating the voluminous and complex information from preoperative imaging into digital representations that can be used to guide neurosurgical intervention. AR can enhance the user experience by applying known information to a real-world situation so that both real and digital information are immediately available for interpretation. Most current applications involve displaying digital information alongside or within the video screen, headset, or eyepieces of an operating microscope or endoscope. Benefits of this process are that it expedites the process of discovery or can influence decision making, but does not force particular actions. This is different from virtual reality (VR), in which real-world elements are present, and while the real world may be simulated, the user has no direct influence over events that occur within it. This chapter describes how current integrated AR platforms work and includes a proposed workflow for AR implementation, case-based examples of successful implementation, and areas where further development is needed.

WHAT DOES AUGMENTED REALITY ADD TO NEUROSURGERY?

Well-done surgery has a logical progression. It begins with an appreciation of normal anatomy and physiology. Surgery progresses as we use the framework of normal anatomy and physiology to elucidate exactly how pathology has occurred, and we use this framework again to correct it. Sometimes, these relationships are simple or obvious: an epidural hematoma causes neurological dysfunction through mass effect on the brain that increases as the hematoma grows. Other times, these relationships are cryptic: a glioblastoma causes dysfunction through mass effect and epileptogenesis but also through brain invasion and destruction. In either case, we anchor the surgical plan in what we understand about the pathologic relationships (e.g., that an epidural hematoma will exist between the dura and the skull) and use that to answer questions that may not be as obvious (e.g., the location of the blood vessel responsible for the hematoma development). Every time we bring a navigation probe into the surgical field, use a stimulation probe to find a facial nerve, or verify arterial blood flow with a Doppler probe, we are establishing the "ground truth" for a particular question.

Establishing the ground truth describes the intermediate step in the surgical decision-making process and when AR is most beneficial. The hypotheses that we generate about pathology must be verified by real-world observations to design a solution. We identify an epidural hematoma as such because of its appearance as a blood clot and its location between the dura and the skull. In the operating room, we must verify these two ground truths about the pathology to appropriately frame our search for the culprit blood vessel. For example, if we identify a blood clot but it is instead in the subdural space, the identification of the responsible vessel will proceed much differently.

To understand the potential power of AR for the neurosurgeon, it is important to reflect on how successful operations are executed but also on how avoidable errors occur. A seasoned neurosurgeon draws on clinical experience to estimate the likelihood of operative success and to anticipate steps that will be undertaken to achieve a desired outcome. Favorable outcomes occur when this estimation is based on greater experience.[1–3] Experience benefit happens primarily in two ways: refinement of motor skills for specific tasks and comprehension of the set of problems to be encountered during the case. We believe that problems can frequently be avoided with additional cognitive preparation. Surgery is most efficient when the surgeon can visualize the anatomy that is about to be encountered. Standard preoperative imaging may suggest lateral displacement of the optic nerves by midline suprasellar lesions, but the relationship of this displacement to the internal carotid arteries and chiasm may be less clear. AR allows the surgeon to understand these relationships in the plane of the surgical approach at the time when that knowledge is most critical. In our experience, most errors are related to inadequate preparation for the particular anatomic characteristics unique to the case. This is in contrast with VR, in which anatomic relationships can be viewed in any plane but not in the operative field.

In recognizing that intraoperative errors can also be systematic, we can also use AR to develop systems to prevent their occurrence. Even though the transverse sinus is not part of the critical anatomy of most posterior fossa cases, we include this structure in the AR for retrosigmoid approach cases to help improve our awareness of its position during drilling. Our AR workflow builds in detailed patient-specific anatomy, specific to the patient's intended operation and their neurological condition. When it works well, it can reduce cognitive load on the surgeon, permitting greater procedural efficiency and technical accuracy.

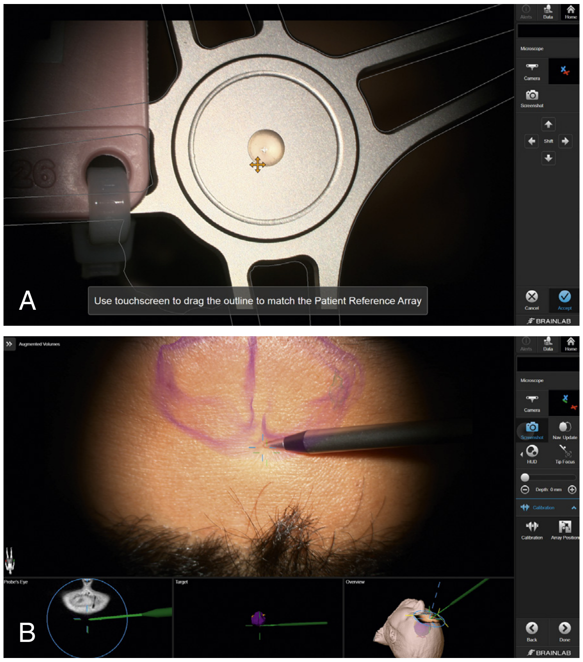


Figure 32.1. Microscope coregistration and registration array/camera. Panel (A) demonstrates calibration of the microscope to patient reference array. Panel (B) demonstrates this coregistration with accurate view of heads-up-display on skin.

WHAT IS AUGMENTED REALITY?

AR is an immersive environment that contains real and computer-generated elements. Digital information (e.g., visual, somatosensory, auditory) is used to enhance real-world experiences. HUD is a type of AR environment where visual information is overlaid on a real-world background. Coregistration of the microscope to produce HUD of preoperative imaging was identified early as a way to achieve AR in the operating room.[4,5] Other methods under development include head-mounted displays, half-silvered mirrors, projectors, and smart glasses.[6] Early use of smart glasses for navigation utilized motion capture cameras and three-dimensional (3D) models that were created preoperatively. Modeling techniques and holographic navigation are currently using open source software with somewhat manual segmentation.[7,8] Accuracy measurements at this time depend on the depth and complexity of the lesion as well as MRI and CT data used to build the AR model. Although it is unclear if these techniques are clinically acceptable, the developing technology offers many hands-free workflow advantages and addresses some of the visual distraction concerns as integration of patient-specific models and navigation evolves.

Microscope coregistration is available for Brainlab and Medtronic navigation systems. Both systems use a fixed optical registration star on the microscope registered to the optical star fixed to the patient (Fig. 32.1). The microscope is focused to a specific central point on the star so that the focal point in the eyepiece can be tracked in the same way as the stereotactic probes. A video display projection of the preoperative plan is injected into the eyepieces of the microscope. This digital overlay information is visualized on the normal confocal optical field. Because it is tracked with the navigation system, viewing perspective, focus depth, and zoom magnification are all depicted within the image and on the navigation screen (Fig. 32.2 and Video 32.1).

Currently, preoperative imaging can be displayed in two ways: direct display ("picture-in-picture") of preoperative imaging and heads-up display (HUD). Direct display brings digital two-dimensional (2D) radiology into the eyepiece of the operator (see Fig. 32.2H–I). The display changes with the focus of the microscope so that only the planes intersecting with the focal point are represented. The advantages of this representation scheme include the ability to constantly access certain preoperative imaging (currently not all scan parameters are compatible with this display) without information clouding the focal point. The disadvantages are that the surgeon must look away from the operative field to the picture-in-picture, the quality of the digital image is relatively poor, and only one imaging sequence can be viewed at a time.

HUD is possible through 3D processing and volume rendering of the preoperative imaging (see Fig. 32.2E–L). Segmentation is a technique of postprocessing radiologic data to recreate a 3D model of the anatomy to view specific structures rather than projection planes. Brainlab, Medtronic, Synaptive, and Surgical Theater have proprietary programs designed to automatically segment brain structures. Finally, all platforms also allow the user to manually paint as the simplest method of segmenting structures or areas of interest. Brainlab and Medtronic systems allow these segmented structures (manual or automatic) to be overlaid into the eyepieces of the microscope to create a HUD that is registered to the patient. The painted objects can be displayed in 2D with information about depth displayed in solid and dotted lines, where the solid line represents the plane of view of the microscope. More recent representations provide for a 3D holographic-like representation of the objects overlaid from video output into the eyepieces of the microscopic (see Fig. 32.2E–F). The advantage of HUD is that the structure-based segmentation can be gathered from a variety of preoperative scan sequences (e.g., arterial anatomy from an angiogram and cranial nerve anatomy from a FIESTA sequence), allowing the user to synthesize the preoperative radiology to build a 3D representation of the most important features of the pathologic anatomy. This segmented model, rather than one particular sequence, is then projected into the eyepiece so that it is constantly accessible and overlaps with the real structures. The disadvantages include a learning curve to make use of the data, the need to optimize the setup to facilitate ease of use, visualization limitations, and sources of errors outlined in the following sections.

Implementation

Many of the elements required for implementation of HUD and navigation tracking in the operative microscope are already part of the standard preoperative workflow. Acquiring the correct scans, performing effective structure segmentation, and setting up the operating room in a way that the information can be constantly accessible are the main areas in which HUD planning diverges from the standard workup (Fig. 32.3). Beyond this, the process of optimizing the HUD to enhance surgeon perception and understanding are user-dependent.

Preoperative Preparation

The first phase of our AR workflow involves gathering data to create a basic 3D VR rendering of the patient's pathology. The VR model is then brought into the patient consultation as the foundation for patient education and to help elucidate understanding of the pathology or surgical plan (Fig. 32.4). This step has helped us appreciate subtle (and sometimes not-so-subtle) neurological findings that were not the primary complaint but are important to the operative plan and patient's recovery. These models can also be utilized in clinical teaching conferences and resident education. 3D reconstruction has been shown to enhance anatomic understanding for learners as well as nonclinicians, and we use this as a basis to engage the patient and family in a discussion about the pathology.[9] Finally, the VR model is used to help guide the segmentation strategy for the AR model that will be used in HUD.

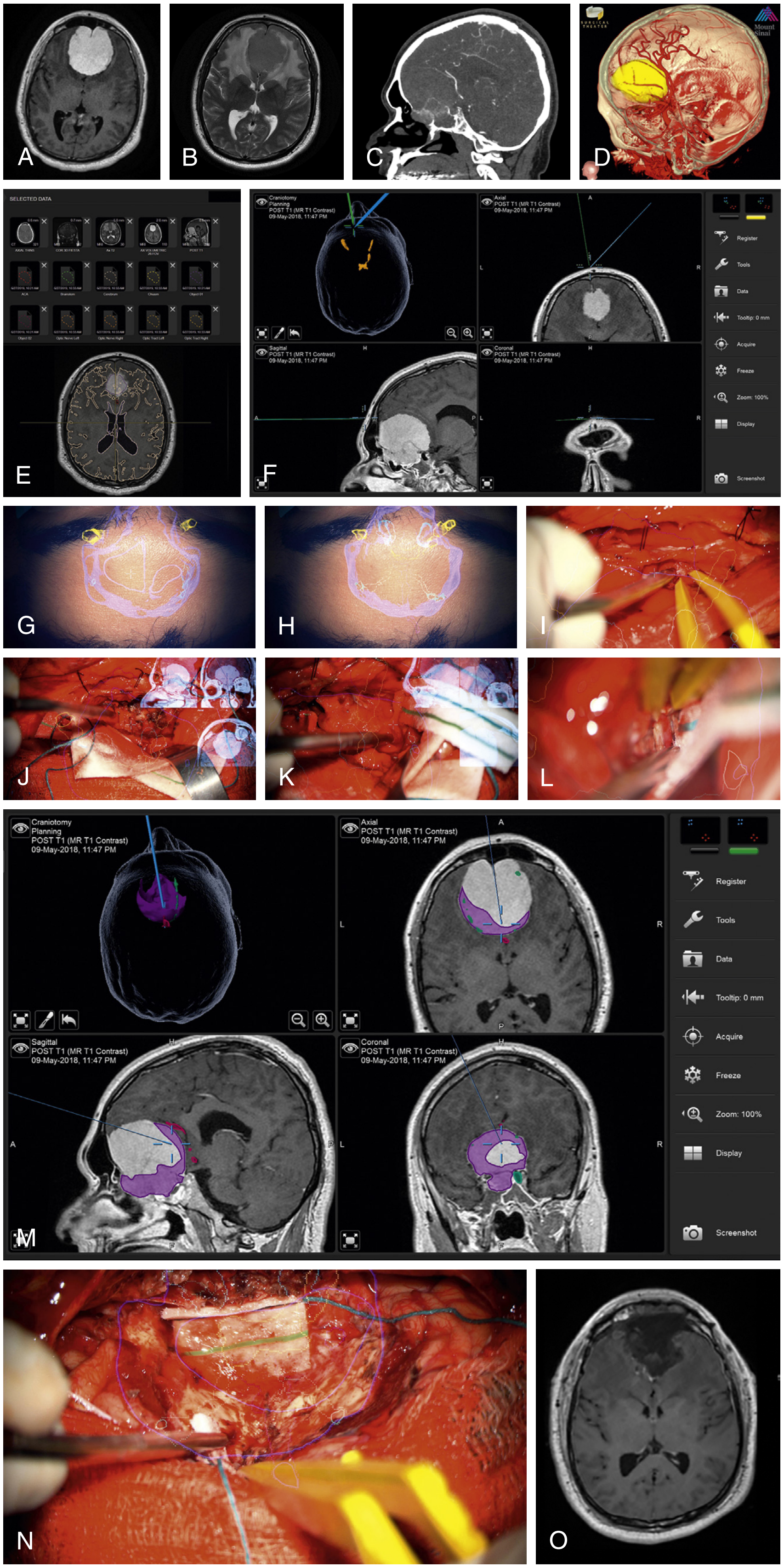


Figure 32.2. Case 1. A 40-year-old male patient with no significant past medical history presented to his internist with profound vision loss and anosmia. His neurological examination was significant for superior hemianopsia with visual acuity in the inferior fields of 20/400 on the right and finger counting on the left, as well as anosmia. (A) Preoperative axial postcontrast T1 MRI. (B) Preoperative axial T2 MRI. (C) Preoperative sagittal CT angiogram. (D) Preoperative planning three-dimensional representation of the patient's anatomy using *Surgical Theater.* (E) Scan selection and critical structure segmentation selection from a combination of atlas segmentation and manual segmentation using Brainlab *SmartBrush*. (F) Coregistration verified by focusing the microscope on the registration probe resting on the patient's skin. (G) Heads-up display view through the microscope eyepiece of the segmentation construct overlaid on the field. The focal depth of the eyepiece is deep to the skin surface, allowing display of segmented intracranial structures. (H) Heads-up display at a deeper focal depth, allowing for certain segmented structures to be carved away and revealing deeper portions of the segmentation model. (I), Heads-up display overlaid on the brain surface after opening the dura. Projections of the optic nerve *(yellow)* and tumor *(purple)* help quickly identify the plane of initial dissection around the capsule of the tumor. *Solid lines* indicate the boundaries of the structure at the current focal depth of the microscope. *Dotted lines* indicate the maximal boundaries of the structure in the plane of the microscope view. (J) Picture-in-picture and heads-up display of the operative field. Picture-in-picture shows hatch marks to indicate the focal point of the operative microscope. Heads-up display adjusts the display of the segmented model to outline the patient's anatomy according to the current microscope angle, focal depth, and zoom magnification. (K) Picture-in-picture and heads-up display indicating proximity of an undissected frontopolar artery *(green).* Anticipation of this structure allows resection to proceed efficiently until the surgeon nears the anticipated area of the artery. (L) Identification of the frontopolar artery *(green).* Estimated registration error/brain shift is approximately 3 mm. (M) Intraoperative structure update demonstrating areas of the tumor remaining. (N) Postresection cavity. Tumor border *(purple),* frontopolar arteries *(green),* anterior cerebral artery *(pink),* optic nerves *(yellow),* internal carotid artery *(blue).* (O) Postoperative postcontrast T1 MRI demonstrating complete tumor resection. The patient did well postoperatively and was discharged home on postoperative day 3. His vision improved significantly.

Scan Acquisition Parameters

Imaging studies play a crucial role in planning a surgical approach for resection of tumors and other space-occupying intracranial pathologies. High-resolution MR, small field of view (FoV) sequences provides a more detailed analysis of tumor location, including the presence of critical adjacent structures such as major vascular structures and eloquent brain parenchyma. These sequences can also be utilized directly by the interventionalist for in-procedure guidance.

Volumetric sequences are often T1 weighted and contrast enhanced, typically providing the best assessment of the margins of the lesion of interest, as well as any invasion of local structures. When evaluating vascular malformations, a volumetric axial T2-weighted sequence may be preferred because the major arterial and venous structures can be visualized as a result of flow voids that occur in both small and large vascular structures. Unlike some MR sequences, which may be acquired in a sagittal plane and then reformatted to create an axial view, a volumetric sequence is obtained as a true axial sequence of the full head and large FoV. Thus, all imaging data corresponds directly to the patient's anatomy and does not suffer from artifacts that may occur when reconstructing an axial sequence.

Simulation sequences are obtained using the highest possible resolution from the MR magnet. The sequences obtain thin slices, less than 1 mm, and are isotropic. Like volumetric sequences, they are obtained as a true axial. Certain software can take advantage of the data from simulation sequences to produce 3D models that demonstrate the tumor, normal brain parenchyma, the ventricles, and the calvarium including the skull base. These models can be enhanced with dedicated CT angiography (CTA) of the head for improved vascular resolution and volumetric CT imaging of the head for improved bony resolution. Diffusion-tensor imaging, which takes advantage of the diffusion of water along white matter tracts to reconstruct probabilistic tract locations, can also enhance the 3D model. All of the data from these simulation sequences can be uploaded to certain software that can project the resulting models directly onto the patient during the surgery, improving the accuracy and confidence of the surgeon's approach.

Choice of necessary sequences for segmentation depends on the patient's pathology and is slightly influenced by the intended approach. For example, when planning a frontal approach to an anterior skull base parasellar lesion, it is helpful to identify the anterior communicating artery encountered in the surgical corridor and carotids (from the CTA), optic nerves (T2 high-resolution) and tumor (volumetric T1). Table 32.1 describes the most commonly ordered preoperative imaging for standard locations and pathologies.

SURGICAL PLANNING

Determining which structures to include in the VR or AR model depends on the approach and requires the operator to have had enough experience with the approach to know what information is likely to be most helpful and what is likely to be less relevant. Table 32.2 displays the structures we commonly segment for the most commonly performed approaches and pathologies. In general, the pathology (e.g., tumor, aneurysm, arteriovenous malformation, fistulous point) is identified as a distinct structure. From there, critical adjacent structures are identified as necessary. Most final AR models contain between two and four separate structures (see Table 32.2). We have found that atlas-based segmentation (autosegmentation) is helpful and reliable for proximal arteries and intraorbital portions of the optic nerve. It is less reliable when these structures are significantly altered by pathology and not reliable for other cranial nerves or structures smaller than 2 mm. Semimanual segmentation is helpful in describing contrast-enhanced structures, bony anatomy, and tractography. These programs are useful in creating VR environments and in isolating specific functional tracts. Manual segmentation ("painting") can be used to distinguish structures that have anatomic boundaries but similar radiologic characteristics to adjacent tissues. It is also the only way that structures can currently be represented in HUD for Brainlab and Medtronic systems.

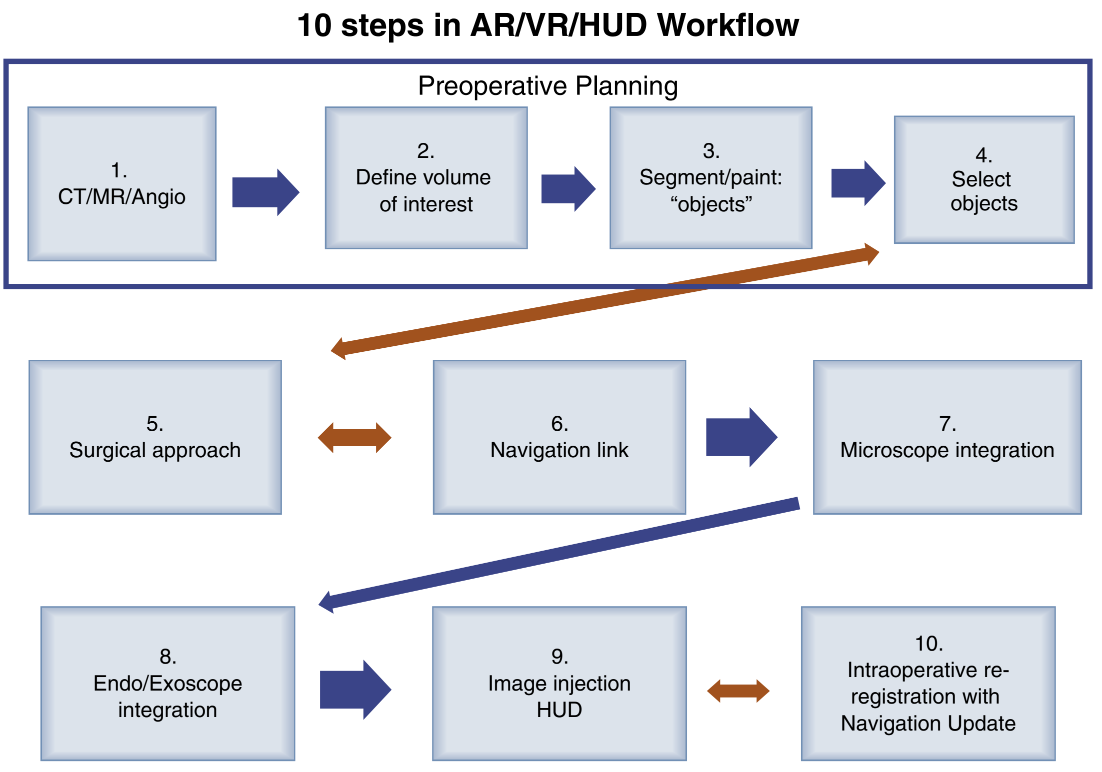
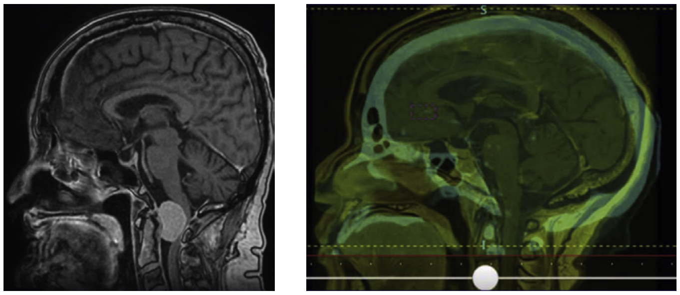


Figure 32.3. Workflow diagram of augmented reality implementation into clinical practice.

Preoperative Planning

1. Scan Acquisition

High-volumetric image sequences are acquired and fused —MRI, CT, CTA, Angio.

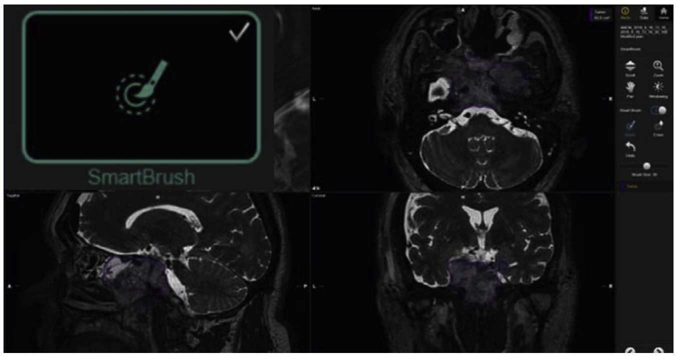


2. Define Volume of Interest

Patient-specific or pathology-specific consultation using 3D representations of the anatomy.

3. Segment/Paint Pathology

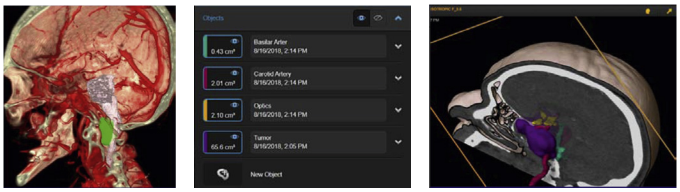
Patient-specific or pathology-specific consultation using 3D representations of the anatomy.



Surgical Planning

4. Select Objects

Patient-specific or pathology-specific consultation using 3D representations of the anatomy.



5. Surgical Approach

Patient-specific or pathology-specific consultation using 3D representations of the anatomy.

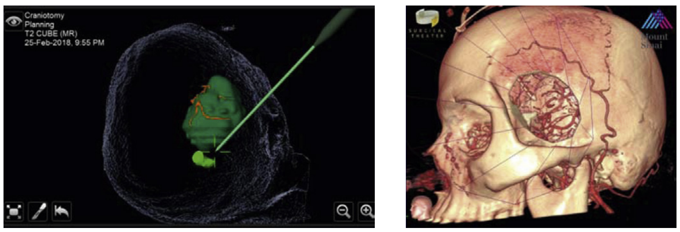


Figure 32.3, cont'd

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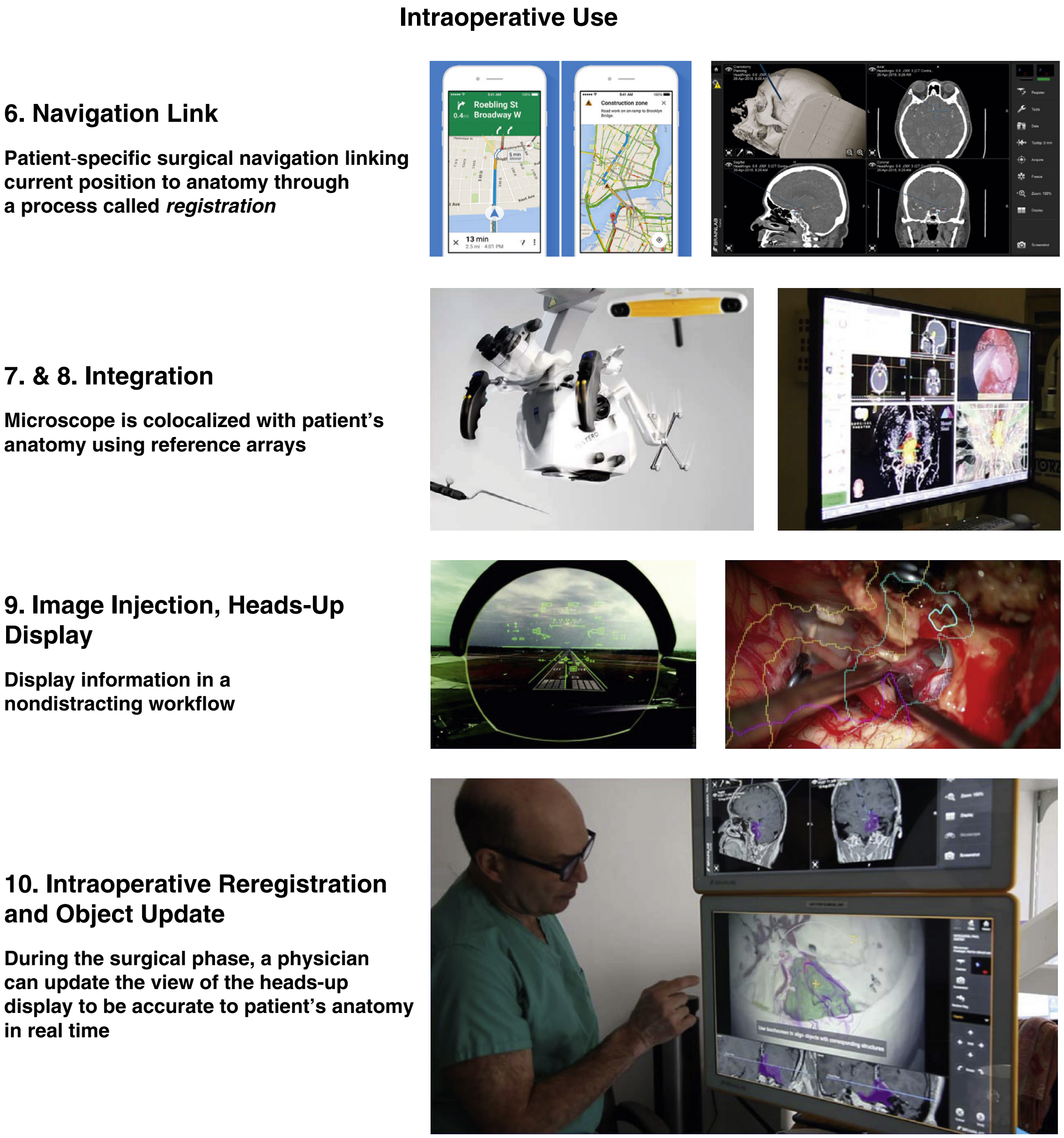

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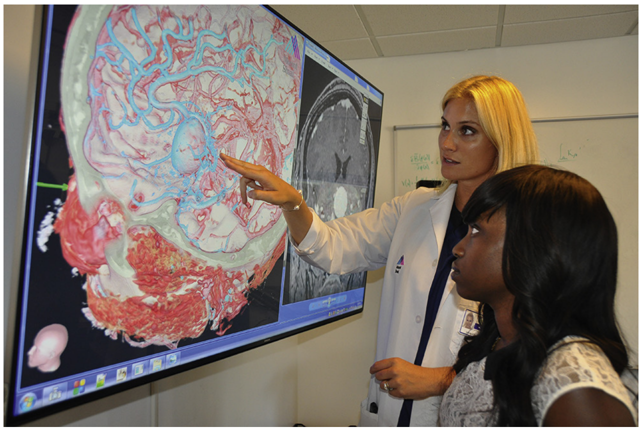

Figure 32.4. Three-dimensional simulation consultation performed by an advanced practice provider.

Before painting any particular structure, we review our preoperative data to find the sequences or series that are most sensitive and specific to that structure. Almost every simulation model involves one or more vascular structures. We prefer CTAs for most arterial segmentation, but it is frequently possible to segment venous anatomy based on this imaging as well. Very-high-quality vascular segmentation can be achieved if volumetric data from selective catheter angiograms are used. Brainlab and Stealth software allow the user to paint structures based on subjective assessment. We start by painting structures where the anatomic location is highly consistent among individuals (e.g., internal carotid artery) and use this to reason the location of the efferent branches.

Cranial nerve segmentation is best done with sequences that are sensitive for cerebrospinal fluid (e.g., T2, FIESTA, CISS). We begin painting in regions far enough away from the pathology that specific identification of the nerve is possible. Using this information as a framework, we then work toward the area of interest and identify the nerve at each step.

TABLE 32.1 Three-Dimensional Reconstruction Scanning Parameters by Pathology Location

Pathology Location	MRI	CT/CTA	Additional MRI Studies	Other Studies
Anterior skull base	Axial Volumetric	CT head CT sinus CTA for vascular involvement	Pituitary: Small FOV T1 and T2 high-resolution (CISS, FIESTA) Orbital: Small FOV T1 and T2 high-resolution (CISS, FIESTA) plus oblique T2 fat-saturation sequences	
Middle skull base	Axial Volumetric	CT head CTA for vascular involvement	IAC: Small FOV T1 and T2 high-resolution (CISS, FIESTA)	
Posterior fossa	Axial Volumetric	CTA for vascular involvement	Small FOV T1 and T2 high-resolution (CISS, FIESTA)	
Aneurysm	Axial Volumetric	Full-head CTA		3D spin angiogram
AVM/AVF	Axial Volumetric Sagittal T2 Cube MRV, MRA	Full-head CTA	If cortical: include simulation protocol with DTI	3D spin angiogram

3D, Three dimensional; *AVF,* arteriovenous fistula; *AVM,* arteriovenous malformation; *CT,* computed tomography; *CTA,* CT angiography; *DTI,* diffusion tensor imaging; *IAC,* internal auditory canal; *MRA,* magnetic resonance angiography; *MRV,* magnetic resonance venography.

TABLE 32.2 Critical Structures Outlined by Pathology Location

Location of Pathology	Painted Tumor	Painted Aneurysm	Painted AVM	Other Lesion	Vessel	Major Sinus	Painted Nerve	Total (179)
ACA		3	1		1		1	3
Anterior skull base	54	1			46		45	54
Cerebellar	3		2		1	1	2	5
Frontal	18		1		1	1	7	20
ICA		6			2		2	6
MCA		8			7			9
Middle skull base	32		2	1	1	28	19	34
Occipital	4		2			1	2	4
Parietal	3			1			2	4
PCA		1						1
PICA		3						3
Posterior skull base		5			4		4	5
SCA		1						1
Temporal	9		1	2			5	12
Other	14		3	1	7		9	18

ACA, Anterior cerebral artery; *ICA,* internal carotid artery; *MCA,* middle cerebral artery; *PCA,* posterior cerebral artery; *PICA,* posterior inferior cerebellar artery; *SCA,* superior cerebellar artery.

In many cases, we find that we eventually reach a limit in our ability to positively identify structures. At some point the vascular lumen becomes too narrow, the cranial nerve is no longer distinct from the surrounding anatomy, or the tracts cannot be further constrained. When significant uncertainty arises, we will not make predictions on the location of the structure. We feel that in these situations, the absence of information will help inform the surgeon of the degree of uncertainty, and we believe it helps mitigate the possibility that incorrect information will be used to establish ground truth decisions. This limit appears to be somewhat user-dependent, and team members who are less familiar with the anatomy or the interface tend to approach this limit sooner than more seasoned members.

ADJUDICATION AND MODEL MODIFICATION

Before use in the operating room, we review the case, the preoperative imaging, and the model itself in a multidisciplinary conference. This serves several purposes. We use the Surgical Theater simulation in a VR capacity to walk through the case. In comparison with AR, a VR platform allows for unconstrained discussion about the risks and benefits of different approaches, generation of hypotheses about the location and relationship of important anatomic structures, and the ability to anticipate the likeliest route for success. It serves as a sort of spatial priming for the order and configuration of the critical structures encountered during the case as well as a priming for abnormal but otherwise noncritical anatomic anomalies (e.g., the location of prior craniotomies). The walk through gives us the ability to identify the important questions we will need to solve to complete the operation (such as the location of the optic chiasm relative to the tumor), and if additional information would be helpful to build into the model, additional structures can be painted or other minor adjustments can be made before the patient enters the operating room.

PRACTICE

Microscope Integration

Apart from segmentation, microscope integration alone has two main advantages over traditional microscope utilization. The first is that it allows the surgeon easy access to the most relevant preoperative imaging at all points during the operation. When an anatomic question is encountered, the surgeon does not need to leave the field to look at images on the light box or navigation display.[8] Instead, the surgeon can reference the images within the screen of the microscope

TABLE 32.3 Heads-Up Display Usefulness

Pathology/Surgical Procedure	Measure of Utility
Intra-axial/superficial lesions	Skin incision Craniotomy Dural opening Cortical incision
Skull base lesions	Head/bed positioning Extradural and intradural drilling Arachnoid dissection
Vascular lesions	Skin incision Craniotomy Arachnoid dissection
Transsphenoidal approach	Head/bed positioning Extradural opening Intracranial drilling Dural opening

and continue to operate. As an example, while performing a potentially dangerous task like drilling the anterior clinoid process, it can be helpful to "see" the precise location and border of the internal carotid artery while the drill is spinning and doing active drilling, as opposed to having to stop drilling, look at the screen or picture-in-picture, and memorize the anatomy. The second advantage is that it allows the display field of the microscope coordinates to be precisely described by the preoperative imaging. Rather than using a stereotactic probe to select an unknown structure and potentially injure it, the microscope can be focused in the area of uncertainty, and the whole area can be studied in the preoperative imaging.

Once the microscope is coregistered to the navigation system, AR software can be applied through the eyepieces and used at multiple points in the operation. We have found it helpful in assessing the adequacy of the patient's positioning, determining the optimal skin incision and craniotomy, and throughout the arachnoid dissection (Table 32.3).[10,10a]

Registration

Medtronic and Synaptive use an optical registration system in which an infrared camera localizes with radiopaque spheres on a rigid head fixation to achieve passive tracking and precision. Brainlab uses reflective spheres on their reference frames for the patient, microscope, and tools. For optical registration, all three navigation platforms (Synaptive, Brainlab, and Medtronic) use spheres on various instruments and patient arrays in specific geometries that reflect light to communicate patient positioning, tool navigation, and other devices to be integrated. Patient registration creates a 3D map between the point on the patient and corresponding points on orthogonal images and allows the user to localize their location in all planes (axial, coronal, and sagittal). Each navigation system has unique standardized tools that are easily recognized by camera vision and software. When using this method, the positioning of the camera is important to consider as there must be a clear line of sight between the camera, patient reference array, and tools.

Verifying high-quality registration can be challenging. We have found the greatest success using primarily surface anatomy with complex topology (like the forehead and face), supporting the depth calculations with a limited number of points behind the hairline and down to the inion and asterion, and limiting the number of points taken from anatomic locations with large amounts of soft tissue (the neck below the inion and the face below the temporal fossa or the nasal bridge). After registration is complete, we authenticate this process by verifying that the probe tracks correctly in the axial, sagittal, and coronal planes. We look for tracking that corresponds exactly to the contours of the skin and make note when the probe appears to track above or below this surface. We verify the coregistration process by using the stereotactic probe and the microscope to focus on a common location. The software should represent the focal point of the microscope and the point of the stereotactic probe as the same location. (see Fig. 32.1B). We restart the registration process if there is a disparity of 3 mm or greater.

Intraoperative Adjustments

Distortions and changes in patient anatomy caused by operative interventions are a well-documented phenomenon.[11–13] Brain shift is an inevitable obstacle to maintaining registration of intracranial structures throughout surgical procedures. Without image-guided navigation, surgeons are forced to rely on alternative methods of establishing ground truths (such as intraoperative neuromonitoring, microvascular Doppler, and gross inspection). Intraoperative MRI (iMRI) was developed to address this problem as it can be used to describe both shift to relevant anatomic structures as well as distortions to the system.[14–16] However, iMRI is costly and time-consuming. This has generated interest in development of alternative reregistration strategies.

One possible avenue for reregistration involves exploiting the segmentation model. Most models contain pathologic and normal anatomic structures, and they are also inherently relevant to the critical portions of the case. *Navigation Update* is an application developed by Brainlab for intraoperative reregistration. It uses microscope coregistration and HUD to project the segmented model or in-plane radiologic study. This projection can then be adjusted through translation to fit the real anatomy visible through the eyepieces (Fig. 32.5). *Structure Update* is another application developed by Brainlab that allows the topology of a previously segmented structure to be redefined after surface registration (see Fig. 32.5K). This allows for the volume of partially-resected tumors to be calculated intraoperatively. Other software aimed at characterizing tissue deformation and extent of tumor resection is currently under development.[17–19] Together, these software developments lay the groundwork for software solutions to brain shift.

Errors

In our experience, there are two main categories of errors encountered in AR display and microscope integration: *errors of registration* and *errors of segmentation*. Registration errors lead to frameshift or scalar-type inaccuracies in the data displayed. It can mean that establishing the ground truth with a particular structure is either difficult or impossible to do, but it will not change the strategy of the operation. Segmentation errors lead to false representation of anatomic or pathologic relationships. Failure to recognize segmentation errors can lead to improper or inefficient establishment of the ground truth because the logical framework used to build successive ground truths is inaccurate. The strategies to avoid these two types of errors involve different support systems.

Registration Errors

Registration errors are best managed by creating maximal overlap between the patient's preoperative imaging and intraoperative positioning as well as optimizing the workflow of the operating room. Ultimately, registration is achieved by designing a mask of all possible surface locations and triangulating that mask to the intraoperative patient position using common known points (e.g., the nasion). A more comprehensive matrix will allow a greater diversity of known points to be used for triangulation. This underlies the reason for maximizing the number of radiographic slices in the registration scan. A deeper discussion for how to optimize the registration scan can be found in the "Scan Acquisition Parameters" section earlier in this chapter.

Precision in registration also depends on maintaining precision in the relationship between the patient reference array and the patient. As physical structures, both the patient and the array are vulnerable to movement during the operation that can lead to inaccuracies. To maintain precision, we prefer rigid head fixation, and we use

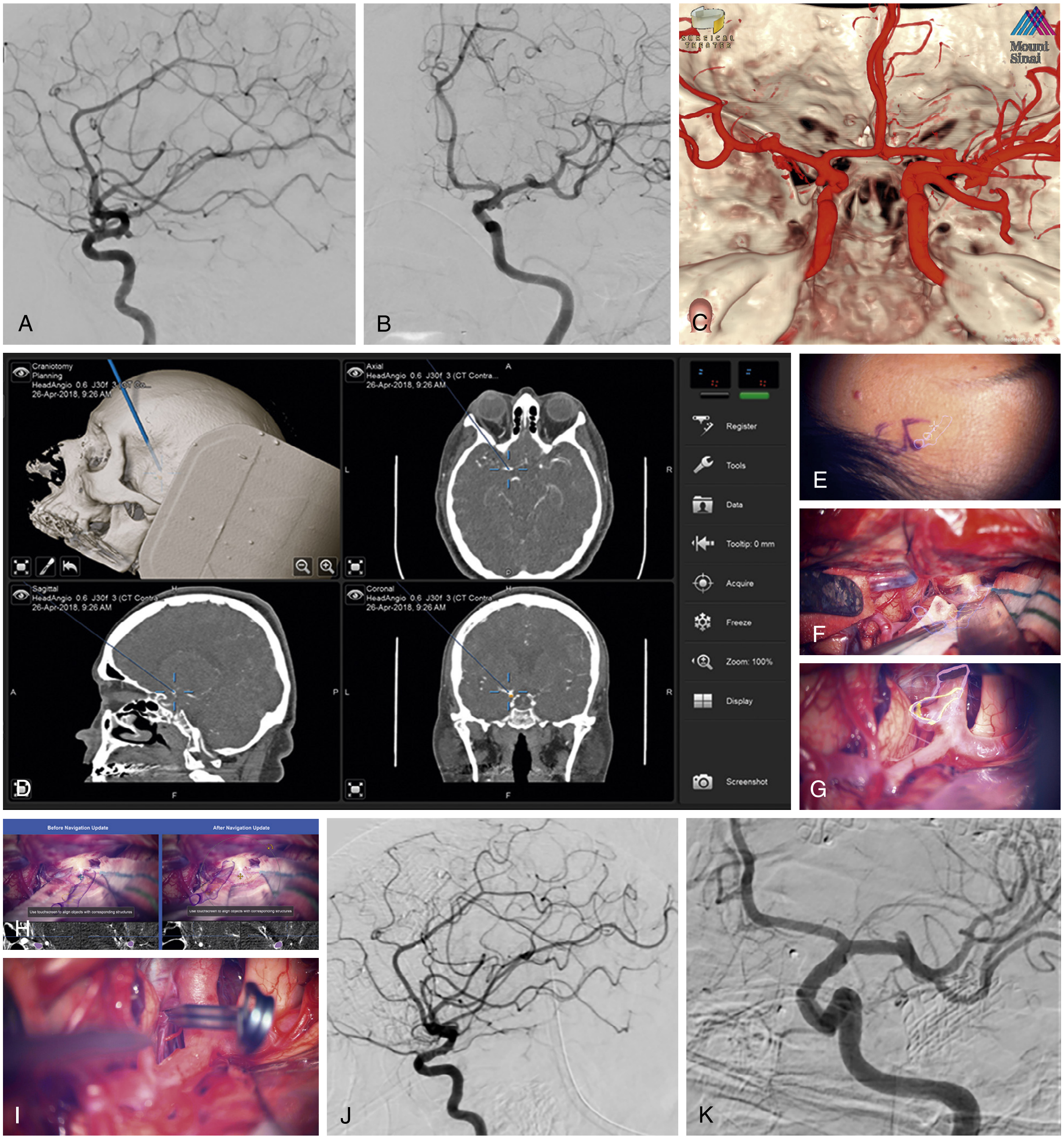

Figure 32.5. Case 2. A 55-year-old female patient with a family history of aneurysmal subarachnoid hemorrhage underwent evaluation for headaches. The workup revealed five aneurysms (left middle cerebral artery, left anterior choroidal artery, left posterior communicating artery, right anterior temporal artery, and right internal carotid artery bifurcation). (A) Preoperative digitally subtracted angiogram, lateral view. (B) Preoperative digitally subtracted angiogram, anterior-posterior view. (C) Three-dimensional reconstruction of bone and vasculature from CT angiography. (D) Navigation with preoperative critical structures outlined in *purple* and *gold*. (E) Heads-up display demonstrates location of efferent artery, afferent artery, and aneurysm domes and confirms that positioning of the head is adequate to achieve the goals of surgery. (F) Heads-up display demonstrates internal carotid artery and middle cerebral artery *(purple)* and anterior choroidal and posterior communicating artery aneurysms *(gold).* (G) Heads-up display demonstrates the dome of the anterior choroidal artery aneurysm with minimal shift (~3 mm). (H) *Navigation Update* was used to adjust. (I) Postclip ligation of the left anterior choroidal artery aneurysm. Microvascular Doppler demonstrates patency of the efferent vessel. (J) Postoperative digitally subtracted angiogram demonstrates occlusion of the left anterior choroidal, left posterior communicating, and left middle cerebral artery bifurcation aneurysms with patency of the efferent vessels. Lateral view. (K) Postoperative digitally subtracted angiogram demonstrating patency of the left anterior choroidal artery with occlusion of the aneurysm. The patient did well postoperatively and was discharged home.

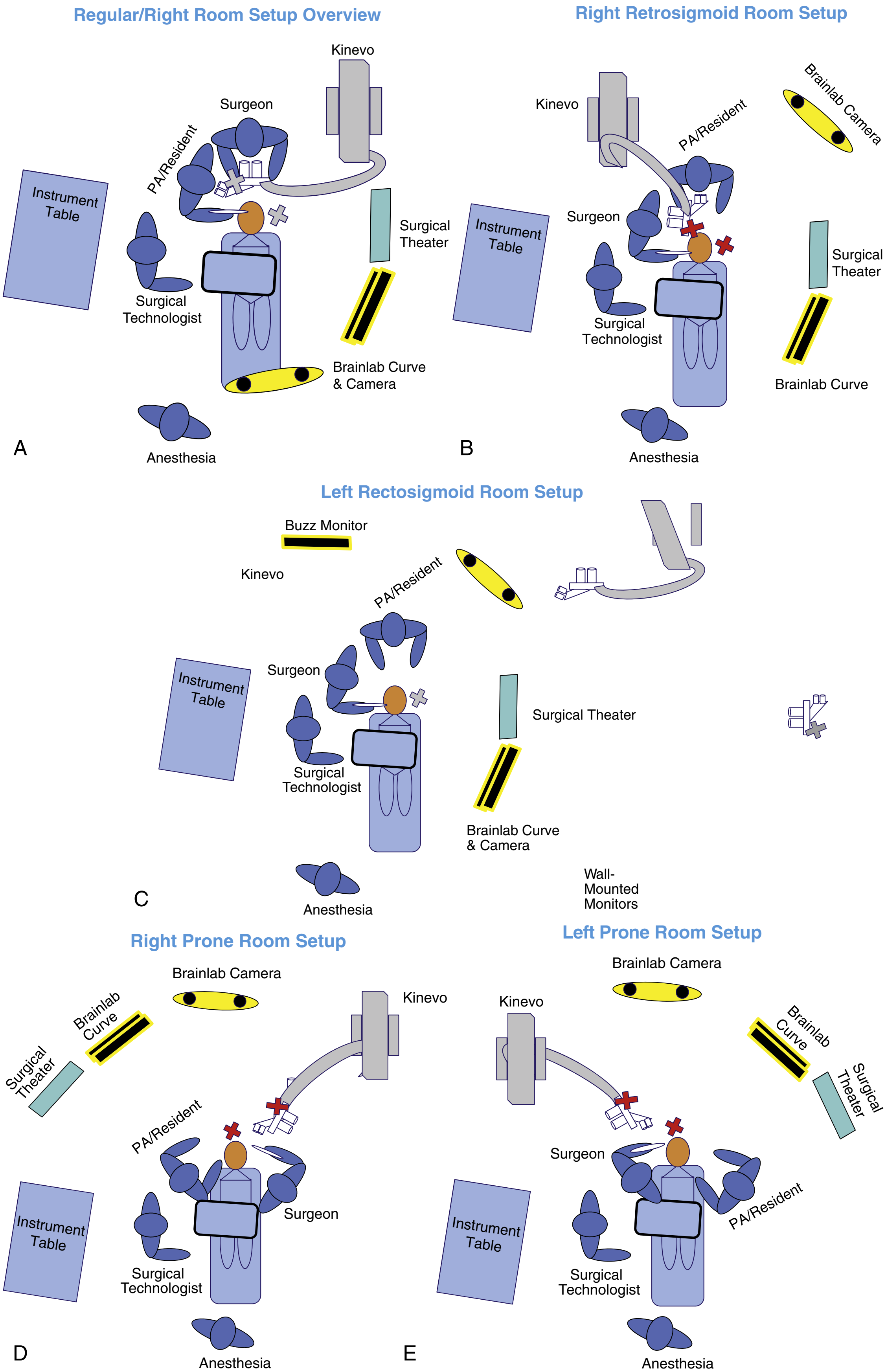

Figure 32.6. (A–E) Diagrams of standard operating room setups for standard skull base approaches.

an operating room setup that avoids movement or manipulation of the navigation array (Fig. 32.6). The physical constraints of every operating room are slightly variable, but the best working location of the navigation equipment meets the following needs: (1) maintains constant and direct contact of the whole navigation array/probe with the camera throughout the operation, (2) is subservient to the interests of the other working areas of the operating room (e.g., the working triangle of the anesthesiologist between the patient's airway, the anesthesia machine, and the anesthesia cart), and (3) enhances and does not hinder existing communication pathways in the operating room (e.g., the triangle between the microscope display, the surgeon, and the scrub technician).

Once registration errors are detected, three strategies can be used to overcome them. The first is to simply re-register the patient. Depending on the timing of the error during the course of the operation or the availability of surface landmarks, this may not always be possible. The second is to change the reference scan and windowing of the scan to form a better mask of the patient's surface anatomy. The third involves applying the segmented model as a registration mask so that only intraoperative anatomy is used to reregister the patient *(Navigation Update)*.

Segmentation Errors

Segmentation errors are best managed by obtaining imaging that can specifically identify structures of interest and utilizing that imaging only until reaching the limits of its specificity. Depending on the structure of interest, different scan acquisition parameters can be used to isolate it. For example, gadolinium contrast does a good job of specifically identifying the borders of a meningioma from other surrounding normal anatomy on a T1 MRI but does not perform well at this function on T2 sequences. For this reason, we use post-contrast T1 sequences to segment most neoplasms. Some structures cannot be distinguished based on contrast uptake however, and for these situations we tend to rely on studies in which the sensitivity for cerebrospinal fluid is very high (FIESTA, CISS), the specificity for bone is very high (CT), or the specificity for gradient changes in molecular tissue characteristics is high (FLAIR).

Creating an accurate and useful segmented model of the operative pathology depends on appropriate extrapolation from preoperative imaging and also benefits from prudence in structure choice. For example, it may be clinically important that a patient with a posterior communicating aneurysmal subarachnoid hemorrhage also has hydrocephalus, but this usually is not the direct focus of aneurysm clip ligation. A well-constructed segmentation model would contain information about the location of all structures relevant for the case and minimal additional information. In this case, an ideal model would contain the location of the ipsilateral optic nerve, ipsilateral internal carotid artery, anterior and middle cerebral arteries, posterior communicating artery, anterior choroidal artery (if possible), and the aneurysm. Additional information about the location other structures (e.g., the ventricle or the contralateral optic nerve) is not usually helpful and frequently somewhat distracting.

Segmentation errors can only be resolved if the source of the error is understood. An assumption about the boundaries or the location of a structure can produce errors. However, if the structure was segmented based on a scan with low structure specificity, this can also create errors. For example, a CTA is specific about the borders of a blood vessel but nonspecific about distinguishing an artery from a vein. Ultimately, if the source of the error cannot be sufficiently appreciated, we prefer to eliminate that structure from the segmented model. This helps maintain the integrity of the model for problem-solving purposes.

Role in Surgical Education

Rising costs of health care, medical education, and changes in societal expectations for the primacy of patient safety have encouraged the development of adjuncts in surgical education.[20] Trainees are forced to straddle limitations in their work-hour requirements with increasing expansion of medical knowledge and expectations that both general and subspecialty skill mastery is an achievable goal within the confines of their training programs.[21] Technologic development of learning tools and assistive devices is helping to bridge these gaps.[22,23] Current literature focuses on VR and simulators to teach skills in surgery and neurosurgery.[24–26] There may be a growing interest in the role that AR applications play.[9,27,28]

In our own practice, AR and particularly manual segmentation have an important role in skull base neurosurgical education. Residents demonstrate competence in anatomic and procedural understanding through their choice of segmentation structures and ability to use the best anatomic studies to create the models. The projection of painted structures through the microscope eyepiece gives students the ability to see the impact of positioning maneuvers, allowing them to refine this process in less time (Fig. 32.7). Finally, segmentation can be used to guide intermediate-level residents through portions of the procedure (e.g., sphenoid wing drilling in pterional craniotomies) with minimal attending supervision.

Areas for Further Improvement

AR is still in its infancy, not only in neurosurgery but in many other technologic applications. Because of this, there are likely to be many facets of application and optimization that we still do not fully understand. Some of the areas where research has been productive include understanding into how AR can worsen operator fatigue through increased eye strain and cognitive load. Eye strain is thought to be a combined outcome of disparities in accommodation and vergence between the native object and its augmented projection.[29] In most applications of AR, the digital information is displayed on a screen at a fixed point with a focal point at optical infinity. In contrast, real-world information is understood in three dimensions by synchronized adjustments in accommodation and vergence. To perceive both sets of information, the pupil must accommodate to the screen while the eyes focus at a point beyond it. This results in increased energy expenditure.[30] Although there are many simple things users can do to minimize eye strain, such as improve registration techniques and use painting techniques that optimize stereopsis, it is likely that technologic advancements will be helpful in this area.

Further advancements in neuroradiology and segmentation software are likely to yield stepwise advancement in AR. With improvement in tractography, MR spectroscopy, and advanced labeling technologies, we anticipate improvements in the specific labeling of important neurological structures. With advancements in field strength optimization, discrete identification of submillimetric structures may also be possible. As these two areas of neuroradiology develop, we anticipate improvements in our ability to develop computer programs that can automatically generate multidimensional patient-specific models. As texture analysis algorithms improve, they may also begin to give us meaningful data on texture that can be utilized by AR as well.

Inattention Blindness

Inattention blindness, or the user's ability to exclude significant events from conscious understanding while focusing on a specific task, has the potential to interfere with productivity in AR applications.[31] Classically, inattention blindness was described as a sports fan's inability to see a man dressed in a gorilla costume when asked to count the number of free-throw attempts in a basketball game. Although this sort of "tunnel vision" has the possibility of influencing perception and understanding of any type of operation, there is some data to suggest that AR more strongly influences its occurrence.[32,33] We see the issue of inattention blindness as dynamic and an important area for further research. With well-constructed segmentation

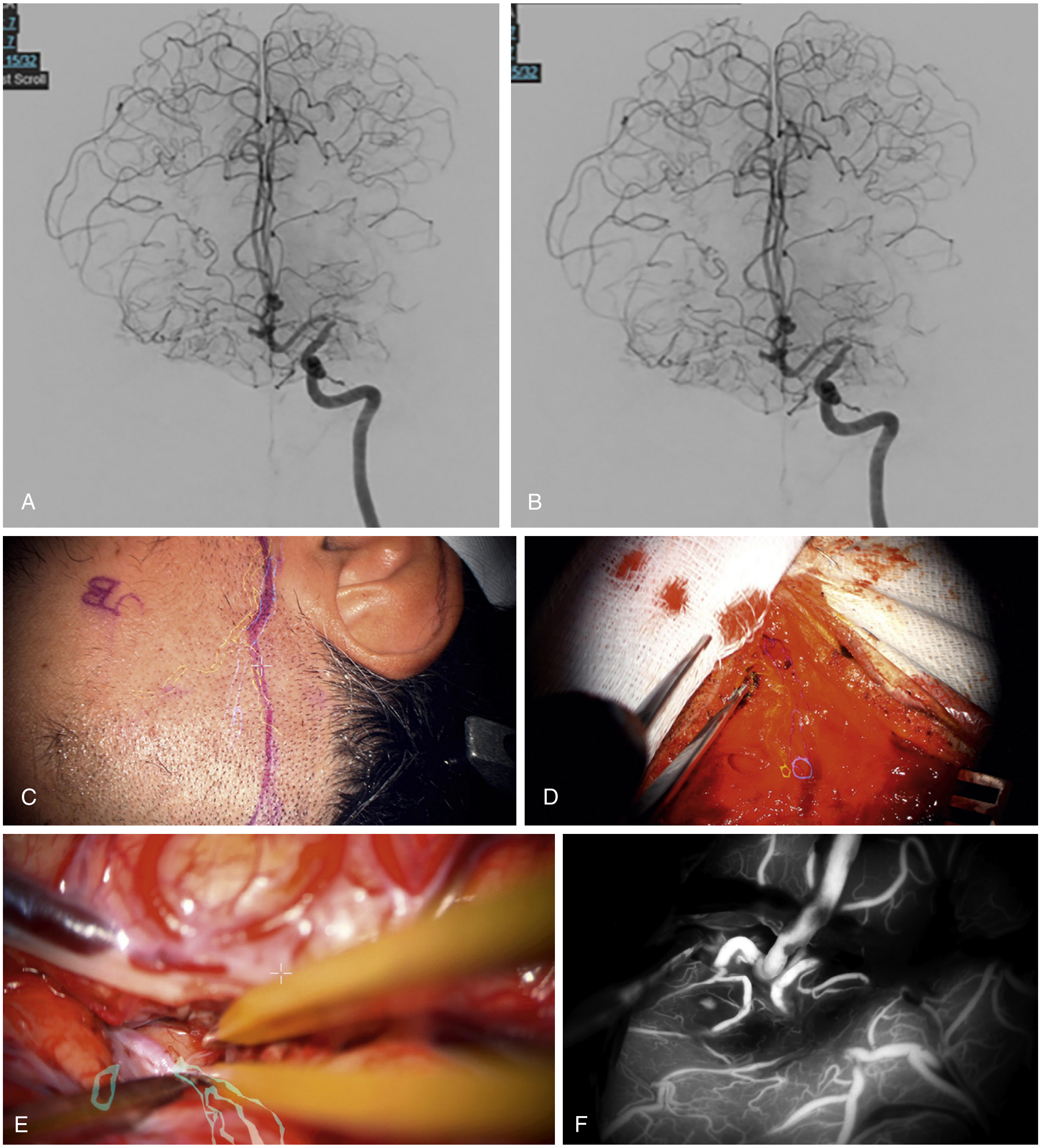

Figure 32.7. Case 3. A 47-year-old male patient with a past medical history significant for hypertension presented for a workup of increasingly frequent and severe episodes of expressive aphasia. The findings were suggestive of bilateral moyamoya disease. The patient underwent a left superficial temporal artery (STA) to middle cerebral artery (MCA) bypass and returned 6 months later for treatment of the right MCA stenosis. (A) Left internal carotid artery digitally subtracted angiogram demonstrating proximal MCA occlusion with collateralization through the anterior cerebral artery (ACA) and posterior cerebral artery (PCA). Delayed arterial filling of MCA territory. (B) Right common carotid artery digitally subtracted angiogram demonstrating proximal right MCA occlusion with collateralization through the ACA and PCA. Delayed arterial filling of MCA territory. (C) Heads-up display demonstrating superficial artery *(yellow)* and superficial temporal vein *(blue)* overlaid on the patient's scalp. (D) Heads-up display demonstrating paired artery and vein to guide efficient and safe proximal dissection of the artery. (E) Heads-up display demonstrating lateral Sylvian fissure dissection. Candidate recipient vessels were identified and painted *(green)* on the preoperative imaging based on their location and caliber. (F) Postanastomosis indocyanine green angiogram demonstrating patency of the bypass, retrograde filling of the proximal MCA, and orthograde flow of the distal MCA. The patient did well postoperatively and was discharged home.

models and adequate cognitive preparation, our AR workflow has helped streamline intraoperative decision making and highlight areas of uncertainty. Much of the existing work on inattention blindness in surgery has been dedicated to describing the frequency with which unexpected intraoperative findings go unnoticed.[32,33] Although this may be one metric of operative comprehension, other metrics (such as the surgeon's understanding of key anatomic relationships) may be more important and ultimately more influential to the success of an operation. There is also evidence that the degree to which inattention blindness influences comprehension can be influenced by the way a situation is displayed.[34–36] This suggests that further work in segmentation model and eye strain optimization is likely to reduce the impact of this phenomenon in AR development.

CONCLUSIONS

Microscope integration of neuronavigation and HUD represent the newest frontier in image-guided surgery and a practical application of AR in neurosurgery. These technologies have the potential to transform the operative experience so the surgeon can make full use of the preoperative workup. With successful implementation, AR has the capacity to improve operative efficiency, decrease the cognitive load of the surgeon, and therefore reduce surgeon fatigue.

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