30 Augmented Reality as an Aid in Neurosurgery

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This chapter includes an accompanying lecture presentation that has been prepared by the authors: Video 30.1.

KEY CONCEPTS

- Augmented reality enhances the neurosurgeon's perception of the surgical field with information of a virtual nature that is relevant to the procedure.
- It represents an advanced form of image guidance, integrated into the physical-world surgical scene and enabling the surgeon to visualize hidden anatomy.
- This technology aids in tailoring surgeries to individual patients' needs and anatomies, and can help to avoid complications.
- It also allows continuous monitoring of the system's accuracy and reliability.

INTRODUCTION

Augmented reality refers to a physical world environment, enhanced—or *augmented*—by information of a synthetic, computer-generated, and virtual nature. It is therefore distinct from virtual reality, where the environment is wholly artificial. By meaningfully enriching its user's perception of the world, this mode of visualization can help overcome limitations encountered while performing tasks.[1-3] The recognition of this potential has led to increased interest in the past years in investigating the application of augmented reality to neurosurgical procedures.[4] In neurosurgery, augmented reality has the possibility of providing a more intuitive surgical image guidance than traditional neuronavigation. The basic principle is to use the world as a reference map, and to associate and deliver information in order to improve perception and understanding.

Neuronavigation functions as a coordinate transformation coupling the three-dimensional (3D) virtual space of the preoperative imaging study and the physical space of the patient's anatomy, thereby greatly aiding in intraoperative orientation and identification of relevant anatomy. Although one of the most useful tools in the neurosurgical armamentarium, traditional neuronavigation has the significant setback of being point-based, relying on the use of a neuronavigation probe. The spatial information conveyed by this device is translated onto two-dimensional (2D) planes on the neuronavigation station's screen—classically, transverse, sagittal, and coronal planes, supplemented by "in-line" planes orthogonal to the axis of the navigation probe. The surgeon therefore needs to (1) divert attention away from the surgical field in order to (2) engage in the mental task of integrating the surgical view with the fragmented information on the neuronavigation screen. Augmented reality neuronavigation, on the other hand, obviates the need for the former and greatly helps in the latter, by spatially integrating select virtual information from the imaging study *directly into the surgical view* (see Fig. 30.1). Furthermore, this also allows assessing the accuracy of the virtual model and the registration with the physical world.

It is contemporary technological advances that allowed the advent of frameless stereotaxy (i.e., neuronavigation) in the mid-1980s and 1990s, providing not only a response to the limitations of frame-based stereotaxy but also wholly novel applications that have since become standard.[5] So, in the same way today, augmented reality not only addresses certain limitations specific to neuronavigation but also carries the potential for a paradigm shift in the way neurosurgical procedures will be carried out in the future.

PREREQUISITES

Three requirements are recognized for a system based on augmented reality: (1) as already mentioned, virtual models need to be generated and merged with a physical environment; (2) the virtual models need to be registered in 3D to the physical environment; and (3) projections of the virtual models, corresponding to the user's viewpoint, need to be calculated and displayed in real time.[2,3]

In neurosurgical terms, point 2 refers to the spatial registration of radiologic images to the patient's anatomy. This is customarily performed using a neuronavigation station. For this, a reference array attached to the patient is necessary to compute the spatial coordinates from the physical environment to the virtual space of the image data sets. Virtual models are obtained by segmenting structures of interest from these image data sets using dedicated software. Because they are created in the same virtual 3D space as the imaging study, the models are themselves also registered to the patient.

In order to augment the operation with these models, the actual means of viewing the surgical field also needs to be registered to the patient's 3D space. Of note, the process of displaying digital information on a screen on top of a real-time video stream of the surgical field is, in fact, image merging and not augmented reality. In an image-merging system, the surgeon is disconnected from the physical world by a digital device. It therefore exposes the surgeon to the risk of system delays or even to the risk of displaying digital content unrelated to the ongoing surgical action. For these reasons pertaining to safety, it is important that the surgeon always physically visualize the surgical field. As a consequence, optical devices used to display overlays require being registered and tracked. In Fig. 30.1, for example, the operating microscope is equipped with a reference star of its own, as well as a calibrated optical apparatus. The microscope can thereby be tracked in space. Because the microscope is connected to the neuronavigation station, the calculated projections of the virtual models, as seen from the surgeon's viewpoint, can be injected into the microscope's eyepiece. The shape and size of the vessel model in Fig. 30.1 are recalculated in real time in accordance with the microscope's trajectory of view, point of focus, and degree of zoom, fulfilling point 3.

OVERVIEW OF CURRENT SYSTEMS

There is significant variability in the modes of application of the augmented rendering. Nonetheless, all are attempts at simplifying the merging of imaging data to the surgical field, although not all setups adhere to the three defining points for augmented reality stated previously.

Figure 30.1. Augmented view through a navigated microscope of the left frontotemporal region, prior to surgical draping, in a patient positioned for clipping of a left middle cerebral artery (MCA) aneurysm. The superior tip of the left ear lobe is seen in the *upper left corner;* the patient's left eye is in the *upper right corner.* Augmented reality enables the surgeon to "see through" the patient, and to visualize in situ the patient's left internal carotid artery and its branches, including the MCA aneurysm. The aneurysm's neck is segmented in *green.*

In the absence of dedicated hardware, an augmented image can be obtained by using a personal computer and freely accessible software to overlay 3D magnetic resonance imaging (MRI) reconstructions on digital photographs of patients' heads and cortex.[6] Another report makes use of a projector during surgery[7] to cast an MRI slice onto the patient's head. However, this setup is confronted with the problem of image distortion inherent to the superimposition of a 2D image over the curved 3D surface of a head, in addition to parallax error.[8] Using a semitransparent mirror has also been described for superimposition of autostereoscopic 3D images during cranial procedures,[9] as well as of axial 2D computed tomography (CT)[10] and MRI slices to guide spinal percutaneous needle procedures.[11-17]

The setback of having to resort to additional material for the purpose of augmented reality navigation underlies the interest in integrating hardware that is already a part of a neurosurgical operating theatre; moreover, the precise calibration of the operating microscope's optical apparatus appears inherently suited for such a role. In 1982, pioneering work by Kelly and colleagues demonstrated the potential of computer linkage of imaging data with the operating microscope.[18,19] Four years later, Roberts and coworkers introduced the concept of frameless stereotaxy—or neuronavigation—with their development of a microscope coupled to CT image data through scalp fiducial registration, and whose spatial position and focal plane are tracked in real time, allowing for image injection into the microscope's eyepiece.[20] The injected models of the segmented structures, however, are limited to outlines or filled-in planes.

In an attempt to fully exploit the potential of 3D registration, Edwards, King, and associates developed a system dubbed MAGI (microscope-assisted guided interventions) that enhances the augmented visual experience with stereoscopic 3D-rendered model overlays.[21-24] They tackle the crucial problem of depth perception of the virtual models and of their fluid integration into the view of the surgical field. They appreciate that their system requires a high degree of reproducible accuracy for its advantages to supersede standard neuronavigation, and this is reached through automatized microscope calibration, but also at the price of implanting bone-anchored fiducial markers[25] for the purpose of registration.

Advances in imaging technique and registration algorithms have since allowed current commercially available neuronavigation systems to achieve a clinically acceptable accuracy not only with skin-fiducial paired-point registration, but also with the more recent and straightforward method of laser surface-based registration.[26-28] It is with similar microscope-based setups that our group[29-33] and others[34-38] have worked to investigate the usefulness of intraoperative augmented reality guidance during neurosurgical interventions. The advantage of these systems is that they augment not only the surgical field but, more importantly, the surgeons' view of the surgical field, obviating the need to look away toward a separate screen for this information and thereby optimizing the surgical workflow. Figs. 30.1, 30.2A, 30.4, 30.8A, 30.8C, 30.8E, 30.9, 30.10B, 30.11, 30.12A, 30.13–30.15, 30.16B, and 30.16C all show augmented surgical views through the operating microscope as seen by the surgeon.

Although our group uses the microscope augmented overlay prior to draping for preincisional orientation (see Figs. 30.1, 30.4A-B, 30.8A, and 30.13A), others have argued that the microscope is too bulky a tool for this purpose. Accordingly, systems providing a real-time augmented 3D rendering and relying on lighter hardware have been developed. Use was made of tracked handheld or head-strapped cameras, calibrated and registered to a neuronavigation station.[39-41] These devices, however, convey the augmented images onto a separate screen, requiring the surgeon to look away from the surgical field. The camera's direction of view is not necessarily that of the surgeon, requiring additional mental adjusting to these two scenes; furthermore, when the camera is not in line with the surgeon's trajectory of view, the surface projection of the augmented deep target model can be inferred to a point on the skin different from that in the surgeon's line of vision.[40]

Augmenting the video stream from the back-facing camera of a handheld portable tablet has also been reported,[42] and, like the microscope, presents the advantage of augmenting the surgical field in the user's line of view. Intuitively convenient for the predraping phase of a procedure, it loses its edge after draping. Indeed, although it is conceivable to drape a tablet in sterile fashion, having to hold one while operating, or having it held by an assistant, is less than ideal.

Similarly, head-mounted displays have also been explored as less cumbersome alternatives to the microscope,[43-48] in particular for surgeries in which the microscope is typically not used. These systems are still in developmental phase and have not reached true clinical application, primarily due to the inherent difficulty of calibrating such a device to the individual user's visual parameters. Uncertainty with regard to accuracy, especially for deep-seated pathology, is also a current limitation. The relative bulkiness of older generation headsets and the fact that the augmented view is not "shared" with the rest of the surgical team can be seen as additional deterrents to their practical implementation. Nonetheless, solutions to both these points are imaginable. Additional note can be made here of recent reports describing commercialized head-up displays that provide an inset, in a corner of the surgeon's visual field, of the neuronavigation or fluoroscopy screen, for catheter insertion during ventriculoperitoneal shunting[49] and for spine instrumentation.[50,51] Although these are not systems that truly augment the surgical field, they do provide information in the field of view that improves surgical understanding. Hand-eye coordination and surgical ergonomics are thereby enhanced, as the surgeon does not need to repetitively look away toward the neuronavigation screen.

The endoscope is a well-established channel of vision into deep-seated neurosurgical fields and, like the microscope, has a precisely tuned optical apparatus amenable to the integration of augmented reality technology. In contrast to the microscope, however, the endoscope has been the object of seemingly less interest in this regard so far. A system providing impressive 3D neuronavigation reconstructions on an autostereoscopic display has recently been reported for transsphenoidal approaches, but this information is nonetheless still visualized on a separate screen.[52] In 2002, Kawamata and colleagues published their clinical experience with an endoscopic augmented reality navigation system that provides real-time, patient-registered, 3D-rendered anatomic segmentations onto the endoscope's screen.[53] Moreover, the system corrects the virtual overlay to the lens distortion effect of endoscopic views. Although a pioneering setup, its augmented rendering does not truly integrate into the surgical field, and the 3D virtual models are visualized monoscopically on a 2D screen. The advent of 3D screens, combined with the application of appropriate visual cues to computer graphics, could significantly help in addressing this setback.

CURRENT APPLICATIONS

With the increase in the amount of pre- and perioperative information requiring consideration during a neurosurgical procedure, the neurosurgical paradigm is progressively shifting toward the customization of well-established, standardized approaches to the specific needs of the individual patient.[32] Achieving ways of translating these data to the surgical setting can help improve surgical ergonomics and increase the likelihood of achieving the operative goals set for a given case. Accordingly, augmented reality has the potential to meaningfully integrate into the surgical field those data that can be virtually modeled in the current state of technology. Nonetheless, significant forethought must be given to each individual case in order to anticipate (1) which information may prove useful during surgery and at what stage of surgery (so as not to overload the surgical view); and (2) in which form to augment this information for it to best serve its purpose.

Augmented Reality in Craniotomy Planning

Skin incision and the craniotomy (Fig. 30.2) can be customized to the individual patient's anatomy, through foresight of underlying key structures. The goal is to create a targeted surgical corridor tailored to the individual intraoperative needs, while avoiding unnecessary tissue exposure and disruption. This is illustrated by Cutolo and coworkers in their mannequin-based task of accessing an intra-axial lesion adjacent to an eloquent region with and without augmented reality,[46] and by our group's reported experience with progressively smaller craniotomies for aneurysm clipping (Fig. 30.3) and for extracranial-to-intracranial (EC-IC) bypass surgeries since the introduction of augmented reality into our workflow.[32,33] Furthermore, the possibility to visualize underlying anatomy beforehand can help avoid complications through foreknowledge, for example, of the position of venous sinuses (Fig. 30.4B and C), cortical draining veins, or of cranial sinuses and air cells.

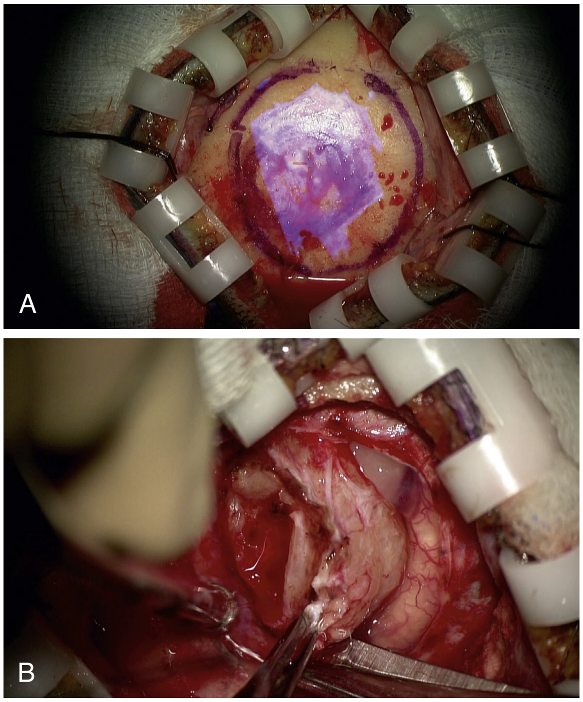

Figure 30.2. Use of augmented reality in skin incision and craniotomy planning. (A) Augmented microscope view indicating the location of a small convexity meningioma, modeled in purple. (B) This straightforward example demonstrates how the skin incision and the craniotomy can be perfectly tailored to be "no more and no less" than what is required for the purpose of surgery.

Augmented Reality in Neuro-oncologic Surgery

Intra-axial Lesions (Video 30.2)

The planning of the skin incision and craniotomy can be centered on the segmented tumor model (Fig. 30.5), and the location of critical—vascular or eloquent—anatomy can be visualized at an early stage of surgery. By being able to reliably anticipate these structures well before they are exposed, they can be meaningfully integrated into the surgical approach.

Models of white matter tracts can further augment the surgical field (Fig. 30.6). However, differences in algorithms for diffusion tensor imaging fiber tracking can lead to different reconstructions for the same fiber pathway.[54,55] Cortical mapping using navigated transcranial magnetic stimulation (nTMS) has shown a high degree of accuracy when compared with direct electrocortical stimulation, and nTMS-based fiber tracts are found to be more reliable than functional MRI in patients with brain tumor. As a consequence, the use of nTMS has translated into improved surgical and clinical outcomes.[56-59] Augmenting the surgical field with these data can help to understand their relation with the tumor in an ergonomic way. However, seeing that these data are based on preoperative scans, they are subject to brain shift. To address this well-known problem, we not only orient ourselves to the injected image of the tract (i.e., augmented reality image guidance), we operate along the injected image with the suction[60] or the resection tool,[61,62] each of which is used as a continuous subcortical mapping device (Fig. 30.7). In so doing, we intraoperatively combine both augmented anatomic and functional information, and use the latter to monitor and compensate for shift in the former. It is worth mentioning at this point that intraoperative MRI can compensate for brain shift by updating the neuronavigation system through automatic re-registration of the surgical field. User intervention can in turn incorporate these newly acquired data into augmented reality guidance.

Skull Base Surgery

Neuronavigation has been recognized as an invaluable tool during procedures involving the skull base.[63-68] 3D imaging data of

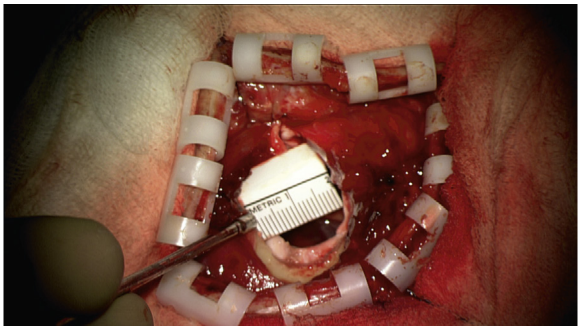

Figure 30.3. Mini–pterional craniotomy performed with augmented reality guidance for the clipping of an unruptured right middle cerebral artery bifurcation aneurysm.

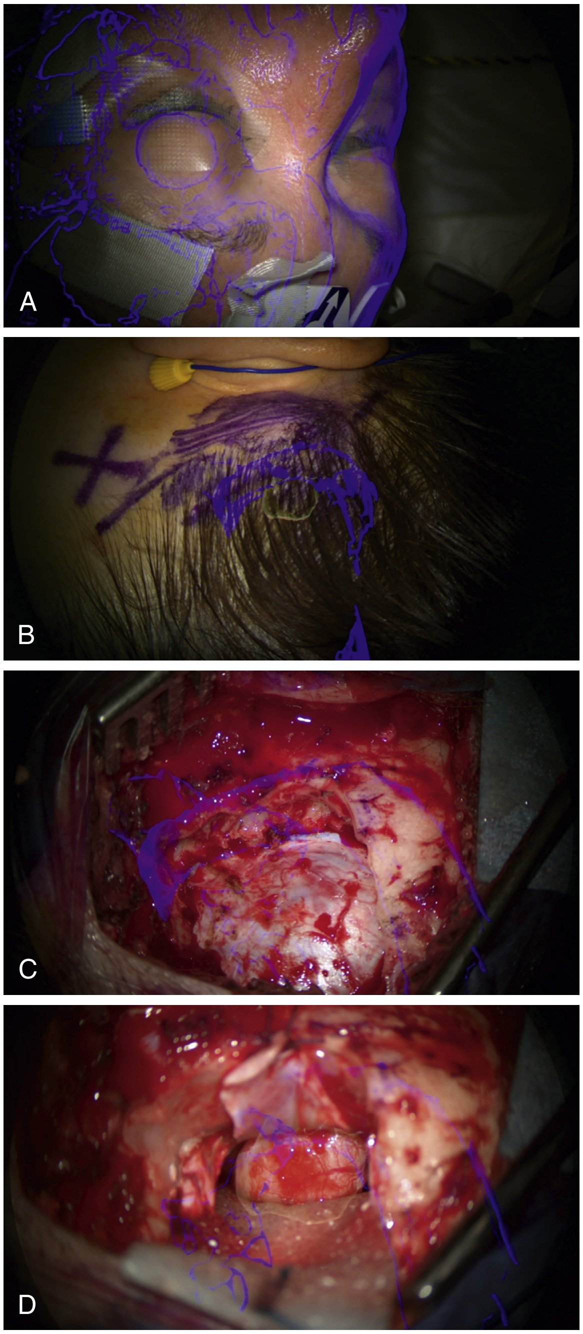

Figure 30.4. Augmented microscope views in a patient undergoing a left retrosigmoid approach for resection of a vestibular schwannoma. (A) First, the accuracy of neuronavigation is assessed through the overlap of the patient's virtual and real heads. Once the virtual data have been confirmed to be reliable, they can be used for surgical planning and navigation. (B) The virtual models of the left transverse and sigmoid sinuses (in *blue*) indicate their course below the skull. The tumor model is in *yellow.* (C) The retrosigmoid craniotomy is drilled flush with the contour of the virtual venous sinuses. (D) The tumor is uncovered after durotomy, and is in perfect alignment with its virtual counterpart. Note how the virtual model completes the still-hidden posterior portion of the schwannoma.

different modalities, such as MRI, CT, and angiography, can be fused to enhance the neurosurgeon's understanding of the relationship between the pathologic process and the complex bony, vascular, and neural anatomy of the cranial base. Moreover, neuronavigation during these procedures is less subject to brain shift.[69,70] However, regularly interrupting the surgical workflow to introduce a bayonet probe into a potentially deep-seated surgical field, while looking away toward a neuronavigation screen, can be not only cumbersome but also potentially hazardous. It is therefore not surprising that some of the first reported clinical applications of augmented reality involved the skull base.[23,24] The augmented "see-through" overlay provides an integral view of hidden critical structures, such as the labyrinth or the carotid canal (Fig. 30.8). Visual cues in the augmented rendering of current systems provide a sense of depth, particularly useful during the drilling of bone or for redo surgeries.[31] Also, it can help in choosing a surgical trajectory best suited to the patient's needs, as described by King, Edwards, and associates in a patient who underwent resection of a petrous apex cyst requiring an unusual approach to preserve hearing.[23,24]

The narrow surgical corridors of transsphenoidal approaches do not easily accommodate additional instruments such as neuronavigation probes. Here, the rationale of integrating neuronavigational information into the surgical view is stronger still. Both augmented reality–assisted microscopy[34,70-72] and endoscopy[53] have been reported in transsphenoidal surgery (Fig. 30.9), but reports have been less numerous than those involving transcranial surgery. This may be due to distrust in older neuronavigation systems' accuracy for transsphenoidal approaches, as well as to the overriding impression that neuronavigation might not be required in uncomplicated cases.[71-75] An unrefined augmented rendering[70] and bulkiness of hardware[72] potentially also curtailed further interest in this clinical application. Over the past decade progress in patient registration and neuronavigation accuracy and improvement of the augmented visual experience have addressed these concerns, which still remain the subject of ongoing research.[76,77] Emerging from the literature so far, augmented reality is believed to be useful in visually enhancing neighboring structures potentially at risk, such as the carotid arteries and optic nerves and chiasm, as well as outlining the tumor. It is reported as particularly relevant during redo procedures where midline structures may be absent, precluding anatomic orientation, as well as in cases of large

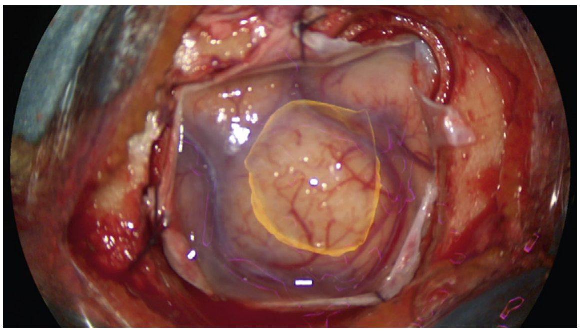

Figure 30.5. Augmented microscope view revealing the subcortical location of an intra-axial tumor. The skin incision and craniotomy are tailored to the injected image of the tumor in the microscope's eyepiece (seen in *orange*). Also illustrated here is how the augmented overlay can be used to monitor the system's accuracy: The unique course and shape of physical cortical vessels are seen to correspond with those of the virtual segmentations (in *light pink*). Seeing that there is concordance between the virtual and the physical vessels, the virtual segmentation of the tumor can be considered to reliably indicate the location of the physical tumor. This concept of virtual-to-physical vessel overlap is dubbed "signature vessel recognition."

invasive lesions.[34,53,71,72] Thomale and colleagues further pointed out its usefulness in operating on laterally situated pituitary microadenomas, in close proximity to the carotid artery.[71]

Other groups have favored an intraoperative side-by-side display of coregistered virtual and real neuronavigated endoscopic images.[78-80] Although such systems are not true applications of augmented reality, they may well achieve similar goals in conveying essential 3D information to the surgeon, without significantly impacting surgical ergonomics.

Augmented Reality in Cerebrovascular Surgery

The successful surgical treatment of an intracranial aneurysm is dependent on the surgeon's ability to compose a mental 3D representation of the target angioarchitecture and to transpose this to the surgical field.[81] Various publications have underlined the importance of this mental task and suggested ways of enhancing it. Patient-specific solid stereolithographic[82,83] and 3D printed deformable[84-87] aneurysm models have been used for presurgical planning and simulation. Virtual reality surgical platforms have also been described for this purpose.[88-94] Further, Rohde and coworkers hypothesized that intraoperatively displaying relevant 3D angiographic information to match the surgical view, along with the possibility for the surgeon to rotate this reconstruction during the procedure, could positively impact operative results.[95] These reports are all varying articulations of a common endeavor, where augmenting the surgical field can be seen as a next developmental step.

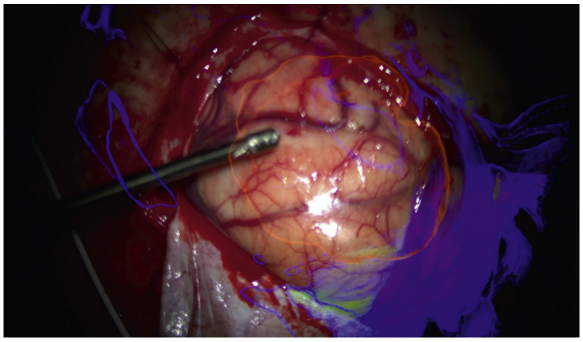

Figure 30.6. Augmented microscope view after craniotomy centered on the tumor segmentation (in *orange*). The lesion is located deep to the right prefrontal cortex, in close proximity to the corticospinal tract (in *blue* and *green*), which it is displacing slightly. Here, the microscope's focal plane is deep to the cortical surface, which is why the corticospinal tract can be seen looping around the tumor, and also why the brain surface is not sharp. This figure also illustrates the visual depth cue principle of occlusion: Note how a sense of depth is conveyed by the tumor overlapping the deeper portion of the corticospinal tract, which remains nonetheless visible through transparency modulation of the tumor. The tumor's enhanced boundaries, referred to as *edge depiction*, are helpful in perceiving this local occlusion.

In addition to its impact on craniotomies,[32] augmented reality is believed to minimize surgical trauma by targeting the subarachnoid dissection and by allowing an appreciation of the surrounding anatomy even before it is uncovered (Fig. 30.10). Once on the aneurysm, image injection aids in the choice of clip type and in clip placement by revealing the hidden portions of the aneurysm's neck (Fig. 30.11). Although all these points were judged helpful in our published experience with augmented aneurysm clipping, we considered that augmented reality significantly impacted one in six procedures on average, in that it was believed that surgery would have been unreasonably problematic had it been performed without augmented reality.[29] Indeed, augmented reality appears to be of particular added value in patients with complex anatomic configurations or surgeries with unusual, technically difficult approaches. We provided an illustrative example of this[29] in a patient with an aneurysm of both the middle cerebral artery bifurcation and the contralateral posterior communicating artery. The latter was clipped through an angle between the two optic nerves, guided by the virtual segmentation of the aneurysm's neck. There is increasing interest in the literature to maximally exploit unilateral approaches so as to spare the patient subsequent craniotomies,[94,96-104] and augmented reality appears to be a useful tool to this end.

The often complex and entangled angioarchitecture (Fig. 30.12C) of an arteriovenous malformation (AVM) can limit the utilization of augmented reality, due to the difficulty of actually segmenting useful anatomic structures for the purpose of intraoperative guidance.[30] This is particularly true of arterial feeder vessels (Fig. 30.12A and B), while draining veins tend to be easier to define. Kersten-Oertel and associates proposed a solution

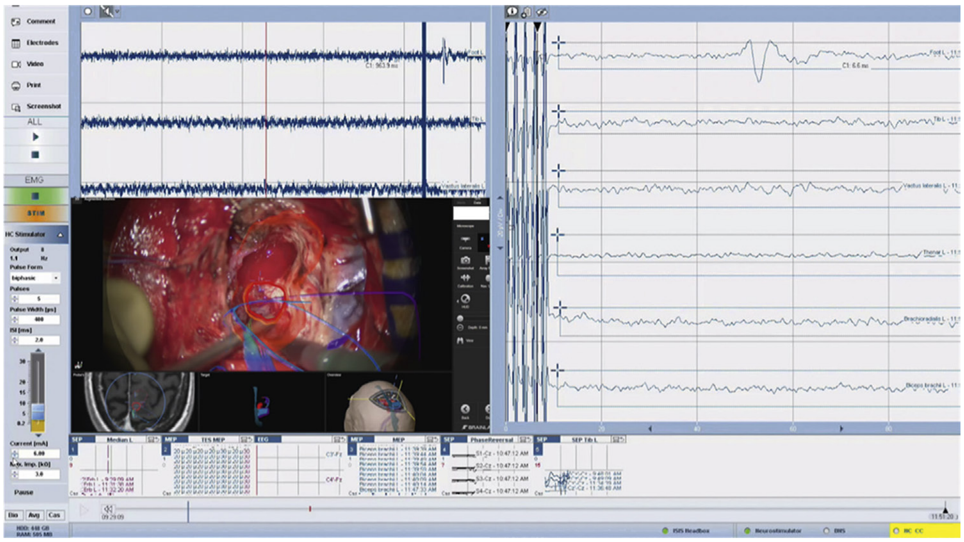

Figure 30.7. Intraoperative view of neurophysiology monitor, with the surgeon's augmented microscope view seen in the *bottom left*, during resection of a right frontal tumor. The tumor segmentation is in *orange*. The *red-orange* contour in the depth of the resection cavity represents the tumor outline in the microscope's focal plane. The *purple line* is the contour of the corticospinal tract, and the *blue line* is the contour of the tract in the microscope's focal plane. The rest of the screen represents neuromonitoring curves, in particular of motor evoked potentials.

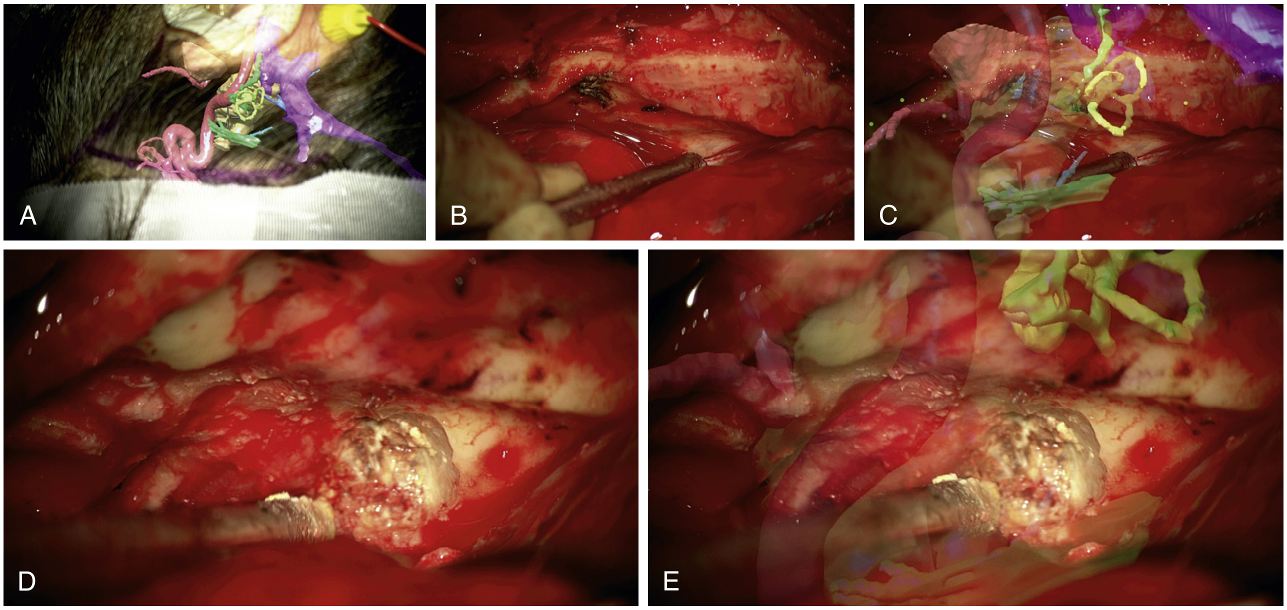

Figure 30.8. Augmented microscope views in a patient undergoing a middle fossa approach to a right petrous chondrosarcoma. (A) A postauricular corkscrew electrode is seen in the *upper right corner.* The right internal carotid and middle meningeal arteries are seen in *red;* the characteristic shapes of the vestibular semicircular canals are seen in *yellow;* the canal of the facial nerve is in *green,* in proximity to the vestibulum; cranial nerves VII and VIII are modeled in *light blue,* posterior to the vestibulum; the right transverse and sigmoid sinuses are in *purple;* the trigeminal nerve is also seen in *green;* the abducens nerve is modeled in *light blue,* seen in proximity to the trigeminal nerve; the tumor is the bulky mass colored in *yellow.* The angle of view in (A) is the same in (B) to (E). (B and C) Views of the skull base through a middle fossa approach, without (B) and with (C) image injection of the same structures detailed for (A). (D and E) Drilling through the petrous apex to the tumor (D), via a narrow angle between the internal carotid artery and the vestibulum, guided by augmented reality (E).

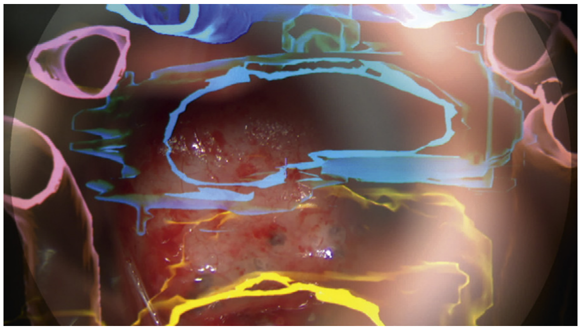

Figure 30.9. Augmented microscope view through a transsphenoidal approach, inside the sphenoid sinus, in a patient undergoing resection of a clival chordoma. The virtual models of the internal carotid arteries are seen bilaterally, in *red.* The optic nerves and chiasm are seen superiorly, in *blue.* The pituitary gland and stalk are seen in *light blue.* The chordoma of the clivus is segmented in *yellow.* Intraoperative orientation is enhanced by knowledge of the midline, as well as of the superior border of the clivus.

to this problem by applying simple pinpoint markings over feeder vessels to inform the surgeon of their location intraoperatively, rather than creating full anatomic—and often confusing—segmentations.[41] Integrating an AVM's hemodynamic information into the augmented overlay[30] can also be misleading for drainage vessel identification, as these structures fill early due to arteriovenous shunting.[41] Although these points can be seen as setbacks to the use of augmented reality in AVM surgery, they are in fact merely indicative of how each individual case requires thought as to which information to augment for the purpose of surgery (Video 30.3).

An illustrative example of this was recently reported by our group in a case of a ruptured basal ganglia AVM.[105] A lenticulostriate artery was found to be the sole feeder vessel, and a prenidal pseudoaneurysm of this artery was identified as the point of rupture. Two transarterial attempts at embolization were unsuccessful due to vessel tortuosity, and a transvenous route was therefore elected. This approach, however, requires intraprocedural arterial control due to the risk of rerupture in case the embolic agent fails to reach the pseudoaneurysm and only obliterates the nidus. As an endovascular transarterial approach had already proven itself unfeasible, this arterial control was achieved surgically, aided by augmented reality, which allowed unambiguous identification of the feeder vessel. The latter was temporarily clipped proximal to the pseudoaneurysm, and the clip was removed after successful embolization.

Surgical field augmentation with a pinpoint marking of the fistulous point on preoperative imaging studies[a] has similarly been described to guide dural arteriovenous fistula disconnections.[41] We have also shown how such markings (examples of which are seen in the preincisional augmented microscope view of Fig. 30.13A) allow targeted dissection and precise intraoperative identification of preoperatively selected vessel segments for EC-IC bypass procedures. This obviates the need for unnecessary dissection of cortical vessels that turn out to be unsuitable candidates for anastomosis. Moreover, craniotomy size is also minimized as a consequence, with diameters ranging from only 2.2 to 3.3 cm in our published series of superficial temporal artery–to–middle cerebral artery anastomoses.[33] Although the arguable role of indirect bypass in cerebral revascularization could be advanced in favor of large craniotomies,[106,107] it should be noted that craniotomies were customarily performed large so as to increase the likelihood of finding a suitable recipient vessel for direct bypass, and not as a means of targeting ischemic regions in particular.[108] This should further be weighed against the advantages of mini-craniotomies in this patient population.[33] Finally, we found augmented reality to be of significant help in

[a]A figure illustrating the same principle in a spinal dural arteriovenous fistula is shown in the following section on augmented spinal procedures.

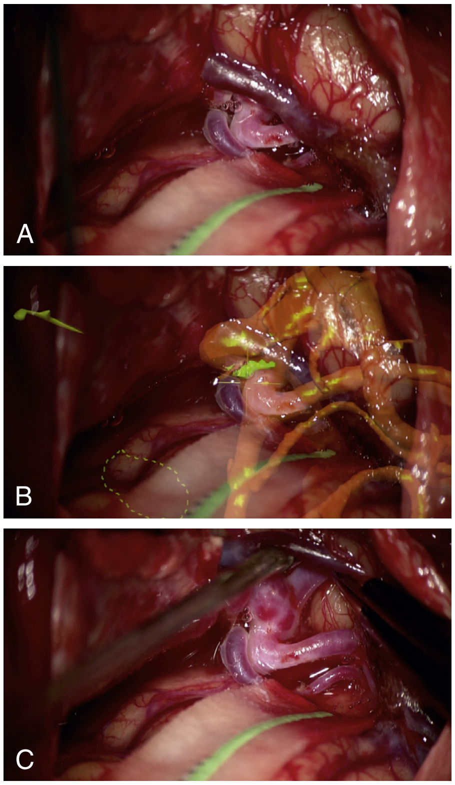

Figure 30.10. Use of augmented reality to target subarachnoid dissection during aneurysm clipping. (A) Right pterional approach viewed through the microscope in a patient with an unruptured middle cerebral artery (MCA) bifurcation aneurysm. (B) The same view, augmented with the virtual MCA, reveals the aneurysm's precise location, thereby guiding dissection (C). With augmented reality, the arterial loop visible in A can be unequivocally identified as the superior M2 branch, illustrating the concept of "signature vessel recognition" (see also Figs. 30.5 and 30.16).

expediting the safe dissection of extracranial donor vessels, which often adopt tortuous trajectories (Fig. 30.13).

Reports in the literature concerning augmented reality for cavernoma surgery resemble the paradigm already described for intra-axial tumor resection.[36,40]

Augmented Reality in Spinal Procedures

In contrast to augmented reality systems for cranial surgery, augmented reality applications in spine surgery are currently still mostly limited to feasibility reports at a wet lab phase. This is due, for the greater part, to the well-known difficulty in registering the mobile spine to a navigation device with sufficient surgical accuracy for clinical application. Moreover, determining the most meaningful medium of visualizing the augmented features is yet another obstacle. Indeed, spine surgery has come to represent such a broad spectrum of macro- and microsurgical procedures, techniques, and approaches that it is unlikely that a single augmented reality setup will fulfill expectations for all of these. It is even conceivable that multiple setups will be used for the different phases of a single surgery.

Some groups extended to spine surgery the use of augmented reality setups well established for cranial surgery (Fig. 30.14; Video 30.4). Using Brainlab Cranial Navigation, one technical report shows how microscope image injection of preoperatively drawn osteotomy planes guided a T12 pedicle subtraction osteotomy in a patient with a congenital wedge-shaped hemivertebra between T12 and L1. A reference array was clamped to the L1 spinous process; due to the presence of T11–L1 fusion, successful registration of the whole T11–L1 block

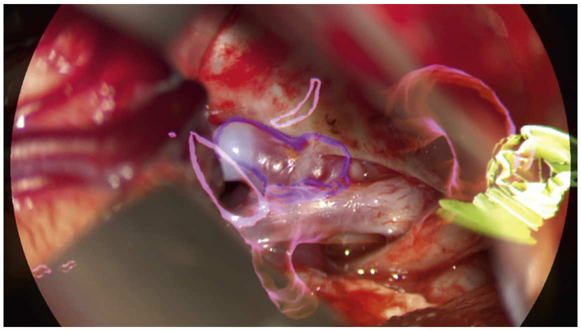

Figure 30.11. Augmented microscope view of a left pterional approach for clipping of a posterior communicating artery aneurysm. The segmentation of the internal carotid artery is seen in *red,* the aneurysm (body and neck) is in *purple,* and the left optic nerve is in *yellow.* The virtual aneurysm reveals the hidden portion of the aneurysmal neck, enhancing the intraoperative understanding of the neck's conformation and aiding in clip selection and positioning. Note how the virtual segmentation seamlessly completes the visible portion of the internal carotid artery, proximally (ophthalmic and cavernous segments) and distally (bifurcation into A1 and M1). Note also how the more superficially located virtual optic nerve partially occludes the virtual internal carotid artery, conveying a sense of depth.

to preoperative CT was achieved through anatomic landmark paired-point matching.[109]

Our group made similar use of Brainlab Cranial Navigation during the resection of a retro-odontoid neurenteric cyst through a right C1 laminectomy. Hypothesizing minimal movement at the C0–C1 level, microscope-based augmented reality guidance was used to define the precise position of the vertebral arteries, the tumor, and the medulla, but only after registration accuracy had been confirmed intraoperatively.[110]

In their recent reports of 10 patients undergoing augmented reality–assisted surgery for extra- or intradural spinal lesions and 10 other patients with intradural spinal tumors, Carl and colleagues also used microscope image injection of virtual models segmented with Brainlab software. Intraoperative low-dose CT of the prone patient was carried out for the purpose of registration, with the reference star either attached to a spinous process, taped to the skin, or—in cases involving the upper cervical spine—attached to the head holder as in our group's case described earlier. Virtual model segmentations, however, were performed on preoperative imaging studies, acquired in the supine position; these imaging data were fused to the intraoperative CT in a nonlinear mode using dedicated software, but nonetheless requiring user intervention to verify the results of fusion for each vertebra.[35,111]

While all these reports relate to spinal microsurgery, the microscope remains an impractical tool for spinal instrumentation, calling for alternative, better suited modes of implementing augmented reality during such procedures. Moreover, the possibility of reducing intraprocedural radiation is a further incentive for the use of this technology during instrumented spine surgeries.

Abe and coworkers used a commercial head-mounted display coupled with a tracking camera for augmented reality–guided percutaneous vertebroplasty in osteoporotic vertebral fractures. They pointed out that the development of a more robust registration method is required before being able to apply this system to percutaneous transpedicular screw insertion.[112] Similar caution is echoed by a recent cadaver lab case report testing a commercially available augmented head-mounted display system relying on manual registration, in which augmented reality guidance led to grave screw misplacement.[113]

Various augmented reality setups have been reported in recent years for the guidance of transpedicular instrumentation on spine models and cadavers.[114-116] Encouraging clinical results have

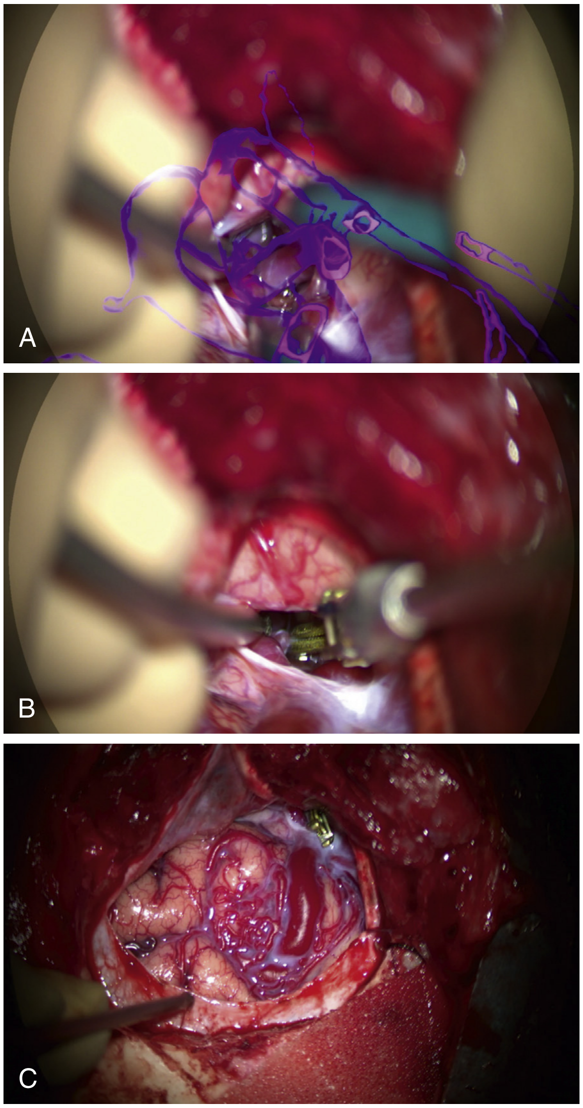

Figure 30.12. Microscope view of a right sylvian arteriovenous malformation (AVM), fed by a sole branch of the middle cerebral artery and draining into the transverse sinus. The virtual feeder vessel segmentation is facilitated here by the fact that this AVM is fed by a sole branch and not by several. (A) The virtual segmentation of the feeder vessel targets the dissection, keeping it to a minimum. The characteristic shape of the vessel confirms that the encountered artery is the feeder (signature vessel concept). (B) Clipping of the feeder vessel. (C) Reduced magnification showing the nidus and the prominent draining vein, prior to proceeding with resection of the nidus and sectioning of the draining vein (not shown). It becomes apparent in this unmagnified view that the entangled nature of an AVM can preclude its virtual segmentation. A more sober alternative to full anatomic vessel segmentations is to use virtual pinpoint markings over vessels of surgical importance (as illustrated by the two small *green circles* in Fig. 30.13A, and by the *light blue dot* in Fig. 30.14B), thereby indicating to the surgeon their location in the operating field and allowing the surgeon to home in on them during dissection. However, this technique prevents the surgeon from using the vessel's characteristic shape (signature vessel concept) for its unequivocal intraoperative identification.

come from reports by Elmi-Terander and associates regarding thoracolumbar screw placement using a ceiling-mounted, motorized C-arm with 2D and 3D capabilities, allowing for the display of augmented video of the surgical field through four cameras integrated into the C-arm's flat detector.[117-119] Interestingly, this system, developed by Philips Healthcare, uses dedicated skin markers for patient tracking and motion compensation by generating a mesh model that interconnects the relative positions of individual markers. The C-arm can generate images of multiple vertebrae in a single acquisition, and both bony segmentation and patient registration are automatized.

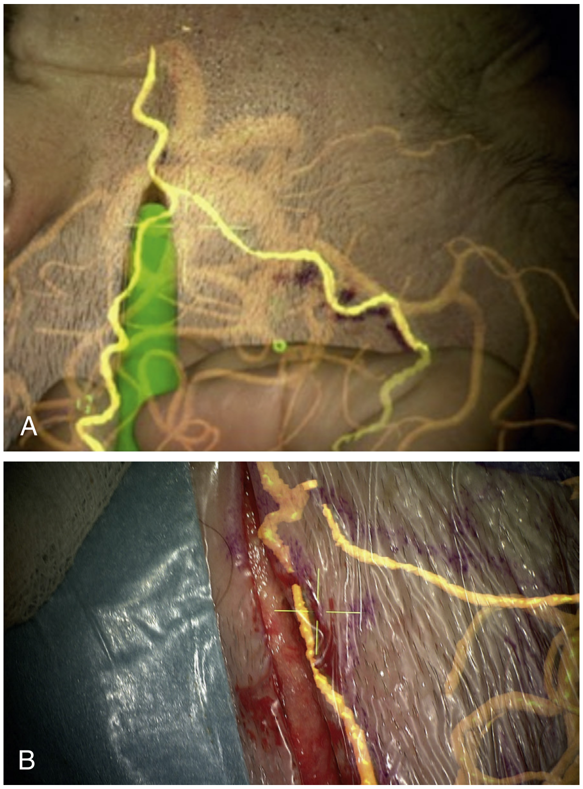

Figure 30.13. Use of augmented reality in extracranial-to-intracranial bypass surgery. (A) Augmented microscope view, prior to surgical draping, of the left frontotemporal region. The left eye is in the *upper right corner* of the image and the ear is in the *upper left corner.* The virtual internal carotid artery's branches are seen in *red,* and the models of the frontal and parietal branches of the superficial temporal artery (STA) are seen in *yellow.* The preoperatively selected intracranial recipient vessels are marked by two small *green circles* (pinpoint markings). Note how transparency modulation and the overlap of the virtual STA and middle cerebral artery convey a sense of depth. (B) Dissection of a branch of the STA in another patient, guided by augmented reality.

CURRENT LIMITATIONS AND FUTURE DEVELOPMENT

Registration and Tracking of the Surgical Field

An accurate registration of imaging data to the physical-world anatomy of the surgical field is a prerequisite, without which augmented reality becomes not only unworkable but also potentially dangerous. As neurosurgeons, we expect no less from these systems than the highest degree of reliability, while demonstrating little patience for pre- or intraoperative user interventions to achieve this. Although such expectations appear legitimate from our clinical viewpoint, they set a high bar for system developers. We know from traditional neuronavigation that registration accuracy is dependent on a large number of physical, technical, operational, and biologic factors.[28,55] Potential sources of error are greater still when the calibration error of the surgical viewing device—required for the generation of augmented reality—is further added to this chain.[120]

Gildenberg and Labuz commented on their observation of the widespread underuse of neuronavigation equipment,[121]

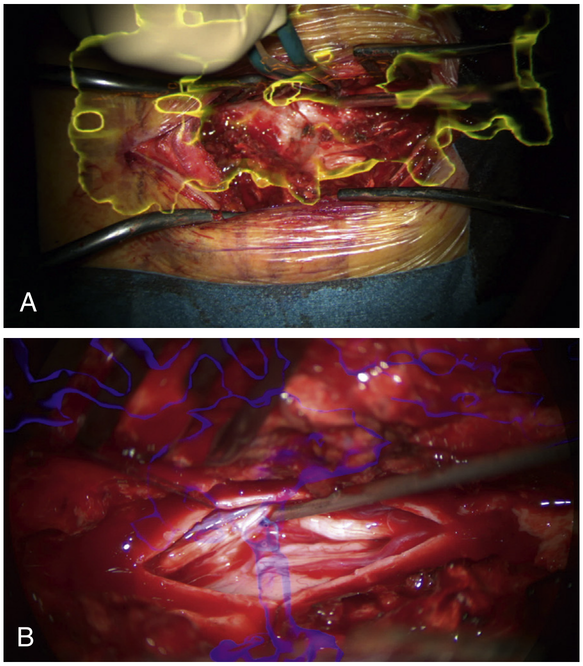

Figure 30.14. Use of augmented reality in spinal dural arteriovenous fistula surgery. (A) Augmented microscope view of a posterior midline thoracic approach exposing the right lamina of T9 in a patient undergoing disconnection of a T9 spinal dural arteriovenous fistula. The segmentation of the T9 vertebra and of adjacent vertebrae is seen in *yellow.* (B) Same view after right T9 laminectomy and durotomy. The segmentation of the spinal dural arteriovenous fistula (in *dark blue*) and of the fistulous point (*light blue dot*) aid in the intraoperative understanding of the pathology and in localizing it with precision. Dissection can thereby be targeted and unnecessary mobilization of neural structures avoided.

interpreting this as a consequence of the imaging data being presented in 2D, and of its lack of integration with the surgical field. They thereby underline the untapped potential of neuronavigation. However, we would also suggest adding a certain degree of distrust in the system as a further motive for its previous underuse. Currently, reported registration accuracy for the surface matching technique is 1.8 mm for frontally located lesions and 2.8 mm for nonfrontal lesions; it is 2 to 5 mm for skin fiducials; and is in the order of 1 mm for implanted bone-anchored fiducial markers, considered the "gold standard."[25,26,28,70] Although these estimations are excellent achievements, they are only mean values, with varying standard deviations (that are lowest for bone-anchored fiducials) representing variability in the results of individual registrations. It is this variability that requires future attention in order to increase the reliability of navigation systems, if we indeed intend to transition toward augmented intraoperative 3D navigation.

Awaiting these developments, automatic registration with intraoperative CT[35,122] and MRI[123,124] have been reported as ways of narrowing registration error, but with the disadvantage of lengthening procedural time. In addition, both modalities can be used during surgery to update neuronavigation through a renewed image acquisition. Of note, ultrasound is generating increasing interest as a less time-consuming means of patient registration and of updating navigation.[125-127] However, if the image datasets are by whatever means renewed intraoperatively, the virtual models used for augmentation also require re-segmenting—hardly a task in which to engage in the midst of surgery. In order to bypass the time-consuming step of complete image reacquisition, nondeformable and, more interestingly, deformable registration algorithms of preoperative MRI using intraoperative ultrasound are the subject of current research.[127-131]

A practical consequence of applying an augmented overlay onto the surgical field is that it allows the surgeon to readily assess the degree of neuronavigation accuracy from the very start of the procedure by comparing the overlap between the virtual and the real. This can be done prior to draping by overlaying a virtual segmentation of the patient's head, where facial and auricular features (concha and crus helix) are of particular interest (Fig. 30.15; see also Fig. 30.4A). After incision, identifiable bony anatomy (sutures or bony prominences) can be used as a second assessment, and finally, after dural opening, the unique, characteristic shape of exposed cortical structures can be used as a third phase of evaluation.[29-31,33] Difficulties related to the segmentation of sulci[132] have led us to favor the use of vessels for this purpose. Moreover, vessels are relatively easy to segment from imaging studies and their size is on a par with the usual microsurgical field of vision. Dubbing this concept "signature vessel recognition," we could assess the accuracy of neuronavigation to a submillimetric level (as can be appreciated in Figs. 30.5, 30.10, 30.11, and 30.12A), and more importantly use it for a rigid realignment of the virtual models (Fig. 30.16).

The use of cortical vessels for registration is not a novel concept.[133,134] It is conceivable that technological development integrated into the operating microscope allows it to identify a vessel through user intervention, and to automatically track it throughout the operation, serving as the basis for an algorithmic nonrigid deformation update of the preoperative imaging data.[132] Several publications with this aim have already reported encouraging results.[135-137] Furthermore, if proven reliable, such an intelligent navigation system would allow a near real-time update of the augmented rendering.

Applying these thoughts to spine surgery, it is similarly conceivable that a navigation system could also be developed to track the shape of the posterior bony aspects of respective vertebrae, without the need for multiple intraoperative re-registrations that are usually necessary as instrumentation is carried out from one vertebra to the next. However, whether these anatomic shapes are perceived with the naked eye (by directly assessing the mismatch between the augmented overlay and the physical world) or through an intelligent navigation system, they are notably lacking during percutaneous spinal instrumentation. A weak registration process and an unsatisfactory method of tracking the surgical field during such surgeries consequently come with a risk of screw misplacement.[112,113] Novel methods of registration and tracking will therefore need to evolve in accordance with the specificities of respective operative techniques. Skin fiducial tracking is one such development currently being explored for percutaneous instrumentation,[118] and the use of ultrasound for iterative intraoperative re-registrations may represent another.[138,139] Moreover, as mentioned in a previous section of this chapter, one of the incentives for the development of augmented reality technology in spinal procedures is its potential to reduce intraprocedural radiation. So, the goal for further innovation of augmented reality systems in spine surgery will have to follow up on this promise and will require exploring methods of re-registration that avoid radiation as much as possible.

Visualization of the Augmented Rendering

Future work will also need to focus on improving the augmented visual experience. One aspect of this will rely on user feedback to determine the most optimal setup for a given operation. The other aspect will require optimizing the augmented rendering to a given setup.

An additional limitation of augmented reality–assisted navigation—this time related to the user rather than directly to the system itself—is inattentional blindness, where attentional constraints impede the cognitive processing of the augmented scene, leading to the omission of unexpected findings despite these being in the user's full view.[140] Indeed, in an augmented environment the surgeon has to operate with visual cues of a virtual nature in addition to those cues that are real. Therefore the challenge for future development will be to ensure the seamless integration of the virtual data into the surgical field.[1]

For a comprehensive augmentation to result, virtual images have to be integrated to the real environment in abidance with visual and cognitive depth cues. Also, they must not override physical anatomy, and furthermore must take into account virtual-to-physical color and shade interactions.[2] Virtual imagery will fade out if the physical environment is too bright, and it will dominate the scene if the physical environment is too dark. Also, focus on virtual and physical objects needs to match for a clear simultaneous view of both, as is illustrated in Fig. 30.6.[3]

Depth perception is mediated by binocular and monocular depth cues. Monocular depth cues are multiple. Motion parallax—the seemingly slower speed of moving far-away objects—conveys an impression of distance (dynamic depth cues), as do ocular focus and eye convergence (oculomotor depth cues). The overlap of two objects, their relative size, the relative increment in detail and contrast of closer objects to those farther away, as well as linear perspective, and the interaction of shadows cast by objects, are all further ingredients (pictorial depth cues), which, when combined binocularly, convey an overall 3D visual experience through stereopsis.[2,141] Occlusion—or the overlap of two objects in a different depth position—is a strong medium of depth perception without which the virtual object simply appears as floating in front of the field of view. Taking this factor into account for the purpose of augmenting a surgical field may seem contradictory, as the unique advantage of augmented reality is precisely to break free of the constraints of anatomic occlusion and to provide the surgeon with see-through

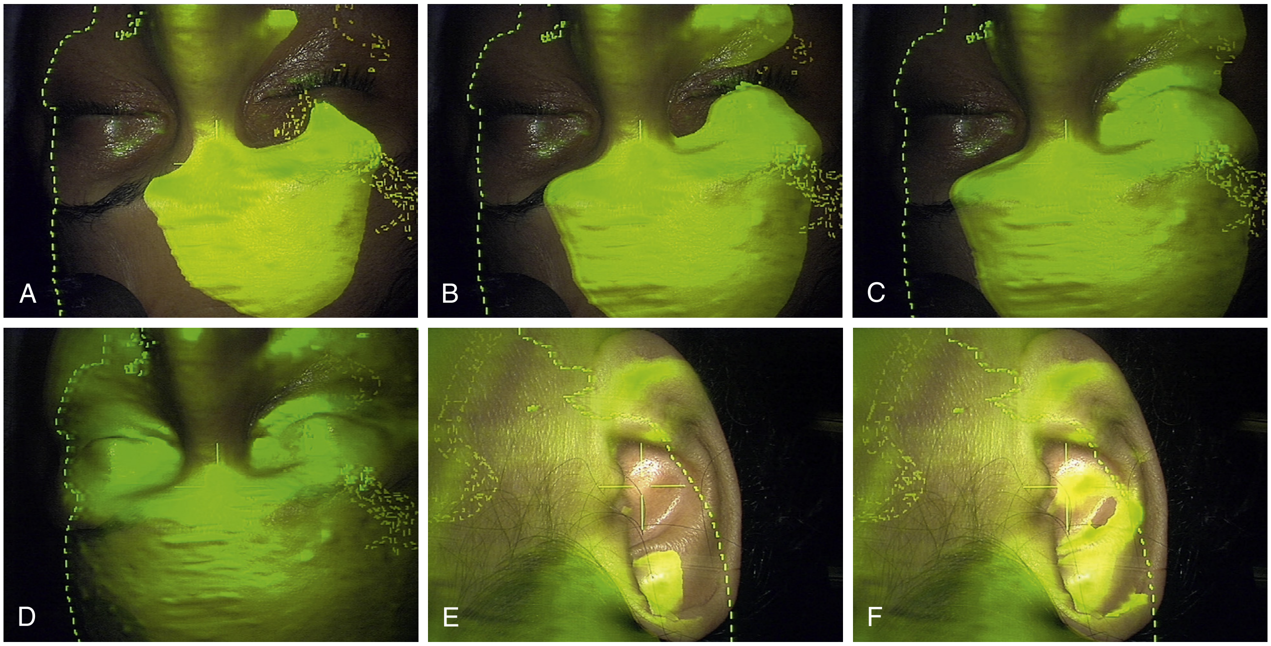

Figure 30.15. Augmentation of the surgical field for assessment of neuronavigation accuracy. The overlap of virtual and real head (A–D) and ear (E and F) features, seen through the microscope, allows evaluating the accuracy of neuronavigation from the very start of surgery.

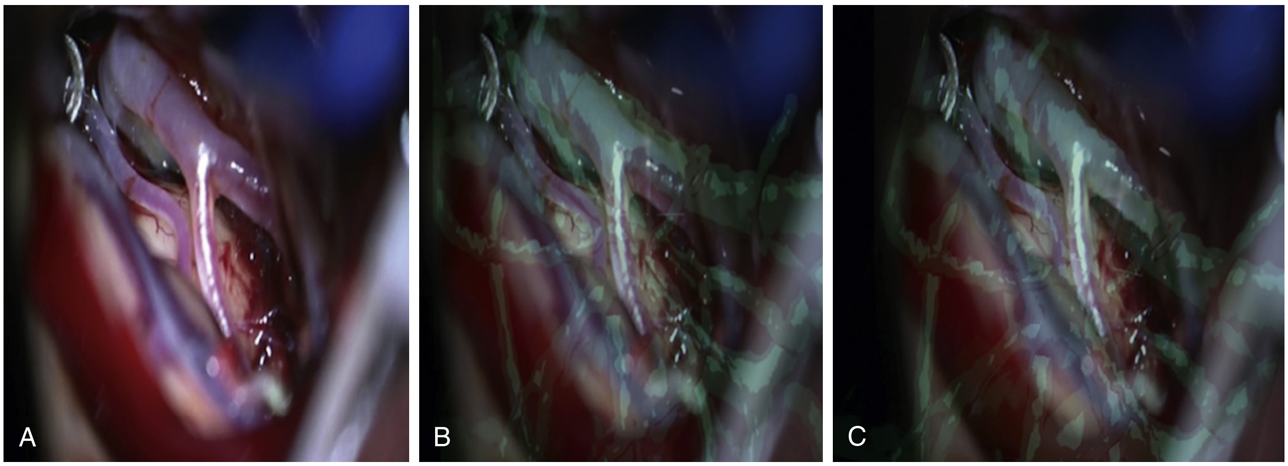

Figure 30.16. Use of signature vessel recognition to screen for and correct neuronavigation system inaccuracy. (A) Microscope view of vessel with bifurcation. (B) Same view with image injection of the virtual vessel, where mismatch can be appreciated. (C) Same view after re-registration and correction of mismatch.

capabilities. Complex transparency renderings of the virtual segmentations can be used to overcome this. Figs. 30.6, 30.11, and 30.13 are illustrative examples of this. However, inadequate transparency modulation can also lead to an overload of visual information, as seen in Fig. 30.8.[2,142]

Seeing the multitude of ways to modulate the depth perception of augmented renderings,[2] it is essential in the future to determine which combination of these is truly relevant for the completion of a given neurosurgical task. With a view to improve augmented reality visualization in cerebrovascular surgery specifically,[41] Kersten-Oertel and colleagues' research indicates that the strongest visual cues for this purpose are chromadepth (where a color is assigned to a level of depth), fog (the relative decrease in contrast perceived with objects farther away), and edge depiction (the enhancement of the boundaries of objects, helpful in perceiving local occlusions; illustrated in Fig. 30.6). Interestingly, adding stereopsis to these cues did not improve relative depth perception.[141] It has been suggested that interactive dynamic depth cues can further enhance these static ones.[143]

The means of tackling visual cue–related problems will also depend on the display of the augmented rendering, various examples of which we have previously discussed. 3D autostereoscopic screens appear as promising devices. They do not require dedicated viewing glasses; the resulting 3D images can be viewed from a wide angle, and moreover, simultaneously by multiple viewers.[142,144] It is conceivable that such a screen can be the display of a neurosurgical exoscope. Indeed, if further development of augmented reality proves itself relevant for neurosurgical applications, and if interest in this technology does not stagnate in the years to come, this might translate into a possible paradigm shift from operating microscope to exoscope.

In addition to the previously discussed hardware and software constraints, the optimal form of visual augmentation may also be task-dependent. For example, while aneurysm and AVM surgery can both be performed using the augmented microscope setup, full anatomic segmentations of the vascular segments of interest have been found to be useful in aneurysms,[29] but less systemically so for AVMs.[30] Indeed, as discussed in a previous section, pinpoint markings in the location of an AVM's feeder vessels are likely more useful than confusing full-vessel segmentations, no matter the level of software sophistication these may reach.[41] This example illustrates how the same information can produce different results when presented in different forms. Consideration must therefore not only be given to which information to augment and which setup to rely on, but also which augmented rendering to use for the surgical task at hand.

Future Applications

Future applications will focus on the integration of additional relevant and customized anatomic and functional information in the visual field of the surgeon. This information will obviously vary depending on the procedure, and will not be standardized for the whole of the neurosurgical spectrum. For example, data from brain perfusion studies could be integrated into the augmented surgical field for EC-IC bypass surgery to guide the choice of the site of anastomosis.[33,145] However, surgical augmentation does not need to limit itself to radiologic information. It is imaginable that nonvisual information can be visually augmented. For example, a system integrating image guidance and continuous intraoperative neurophysiologic monitoring during transpedicular instrumentation could be devised to tint the surgeon's augmented view in green, orange, or red hues, to provide real-time indications of the safety of the chosen transpedicular route as the screw advances.

Nor does augmentation necessarily need to be visual in nature: The tonalities heard when using a suction device for continuous mapping of the corticospinal tract[60] acoustically convey neurophysiologic information to the surgeon. Augmenting an operation with acoustic information has been named *audiotactic surgery*.[121] Indeed, augmented reality could conceptually apply to all senses, and not only vision.[1] Similarly, in the context of the nascent interest in robotic neurosurgery, haptic feedback could augment the surgeon's perceptions during teleoperated robot manipulation.[1]

CONCLUSION

The intraoperative use of augmented reality technology overcomes the setbacks of traditional neuronavigation by translating the three-dimensionality of preoperative imaging to the three dimensions of the surgical field. The surgeon's understanding, required for the successful completion of the task at hand, is thereby enhanced. The integration of neuronavigational data directly into the operative field also improves the surgical workflow, obviating the need for frequent stops in order to consult the neuronavigation station. Moreover, it provides a means of continuous intuitive monitoring of the system's accuracy and reliability through direct visual assessment of the overlap of the virtual segmentations with the physical world.

It has found applications in diverse neurosurgical procedures where its "see-through" abilities allow foresight of relevant anatomic features. It can play a role in the avoidance of complications during the surgical approach, for example, through the direct preview of the location of the venous sinuses during the retrosigmoid approach or of air sinuses during frontal craniotomies. In addition, it can play a role in guidance once upon the pathology, illustrated during the drilling at the skull base around the labyrinth, during the targeted dissection around an AVM in search of its feeder vessels, or during the apposition of a clip around the hidden portions of an aneurysm's neck. From reports of its use in the literature so far, it appears particularly indicated in cases with challenging anatomy or for unconventional surgical routes.

Yet more generally, augmented reality in neurosurgery holds an even broader, possibly more consequential potential: because it allows customizing standardized procedures to the unique anatomy and pathology of an individual patient, it represents a significant aid in the current paradigm shift toward more personalized, minimally invasive surgeries.[32]

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