Augmented Reality in the Surgery of Cerebral Aneurysms: A Technical Report

BACKGROUND: Augmented reality is the overlay of computer-generated images on real-world structures. It has previously been used for image guidance during surgical procedures, but it has never been used in the surgery of cerebral aneurysms.

OBJECTIVE: To report our experience of cerebral aneurysm surgery aided by augmented reality.

METHODS: Twenty-eight patients with 39 unruptured aneurysms were operated on in a prospective manner with augmented reality. Preoperative 3-dimensional image data sets (angio-magnetic resonance imaging, angio-computed tomography, and 3-dimensional digital subtraction angiography) were used to create virtual segmentations of patients’ vessels, aneurysms, aneurysm necks, skulls, and heads. These images were injected intraoperatively into the eyepiece of the operating microscope. An example case of an unruptured posterior communicating artery aneurysm clipping is illustrated in a video.

RESULTS: The described operating procedure allowed continuous monitoring of the accuracy of patient registration with neuronavigation data and assisted in the performance of tailored surgical approaches and optimal clipping with minimized exposition.

CONCLUSION: Augmented reality may add to the performance of a minimally invasive approach, although further studies need to be performed to evaluate whether certain groups of aneurysms are more likely to benefit from it. Further technological development is required to improve its user friendliness.

KEY WORDS: Aneurysms, Augmented reality, Image-guided surgery, Minimal invasiveness, Neuronavigation

Augmented reality refers to the integration of computer-generated images with the real-world environment.¹–³ It is synonymous with the term semi-immersive environment and is therefore distinct from virtual reality, in which the environment is wholly unreal.¹ Applied to the field of neurosurgery, it implies projecting segmented structures of interest from computed tomography (CT) or magnetic resonance imaging onto the real operating field. The augmented image can be visualized using various display technologies: via heads-up display,⁴ via head-mounted display,⁵ through image injection into the operating microscope,⁶–⁹ or even using mirror reflection onto the patient’s body.¹⁰ The injected images can be visualized in 2 or 3 dimensions (2-D or 3-D). Augmented reality thus represents a form of interactive image-guided surgery, aiding the surgeon in intraoperative orientation by showing what cannot directly be seen. Furthermore, it allows the surgeon to integrate multimodal information without the need to direct attention away from the operating field (eg, to the neuronavigation workstation and the bayonet probe).

To date, most publications concerning augmented reality describe its various technological developments; only a few actually illustrate its clinical applications in neurosurgery. Intraoperative use of augmented reality has been reported for the surgery of meningiomas, gliomas, pituitary tumors, cerebral cavernomas, and arteriovenous malformations.⁷,¹¹–¹⁵ To the best of our knowledge, it has never been discussed for aneurysm surgery. Our aim was to develop a standard operating procedure and to evaluate the benefits and drawbacks of using...
augmented reality for cerebral aneurysm surgery, from patient positioning to the act of clipping itself.

**METHODS**

**Patients**

From January 1, 2012, to October 31, 2013, 39 unruptured aneurysms were clipped with the use of augmented reality in 28 patients during 30 operations of a total of 68 aneurysms clipped. All 39 aneurysms were clipped by the same surgeon in a hybrid neurointerventional suite allowing intraoperative angiographic (3-D digital subtraction angiography) control of clipping. The surgeon had experience with > 300 clipping procedures. Data concerning the patients’ clinical conditions, cerebrovascular anatomy, and aneurysm geometry, as well as the course of surgery and the use of augmented reality, were recorded prospectively. The usefulness of augmented reality in each case was assessed using 3 Boolean parameters: whether the virtual images had an impact on the size and shape of the craniotomy, whether the virtual images helped in minimal dissection and exposition, and whether the virtual projection of the aneurysm neck aided in clip placement.

Furthermore, rates of clip corrections based on intraoperative angiography were compared between patients operated on with augmented reality and 136 unruptured aneurysms previously clipped without augmented reality. The rate of clip corrections is defined as the ratio of the number of corrections to the total number of clip placements. Clinical outcome was reported as the difference between clinical status before surgery and 3 months after, measured with the modified Rankin Scale.

**Preoperative Image Acquisition and Image Segmentation**

Angiographic imaging (3-D angio-magnetic resonance imaging, 3-D angio-CT, 3-D digital subtraction angiography) was acquired during routine preoperative diagnostic workup (Figure 1C). DICOM (digital imaging and communication in medicine) images were stored on a PACS system. In some cases, a preoperative flat-panel CT (Allura Xper FD20; Philips, Best, the Netherlands) and 3-D angiography were obtained in the hybrid suite with the patient already positioned for surgery. The data sets were loaded and fused for segmentation of the skin, bone, and cerebral vessels in a single 3-D matrix (BrainLAB iPlan platform; BrainLAB, Feldkirchen, Germany). For each case, the intracranial vessels of interest, the aneurysm, the neck of the aneurysm, the skull, and the head of the patient were segmented. Segmentation was performed with the automated segmentation function in which the user determines the region of interest and the desired range of intensity or density on the uploaded radiological examination. Time-of-flight MR sequences and 3-D angiography were preferentially used for the segmentation of vascular structures (Figure 1A and 1B); high-resolution CT was used for the segmentation of the skull; both 3-D magnetic resonance imaging and 3-D CT were used for the segmentation of patients’ heads. Because all different modality sequences were fused into a single 3-D matrix, the user toggled from 1 sequence to the next, depending on the nature of the structure that needed segmenting. The neck of the aneurysm was segmented on the 3-D segmented reconstruction of the aneurysm.

**Patient and Operating Microscope Registration**

Patients were positioned on the operating table with their heads immobilized in a radiolucent head holder (Mayfield; Integra LifeScience, Plainsboro, New Jersey). The neuronavigation reference star was fixed to the head holder. The location of the patient was registered with face surface-matching systems (Z-touch or Softouch, Kolibri; BrainLAB). The operating microscope (Zeiss Penetero 900; Zeiss, Oberkochen, Germany) was connected to the neuronavigation station (Kolibri; BrainLAB) through its dedicated neuronavigation interface; it was then calibrated by registration at full magnification of 2 focal points centered on the reference star.

**Preincision Image Injection**

A 3-D stereoscopic volume-rendered model of the patient’s head was injected into the eyepiece of the neuronavigated microscope, and this virtual image was superposed on the real head. The accuracy of the registration was evaluated visually, using in particular the nose and auricular concha superposition (Figure 2A and 2B). The segmented vessels and aneurysm (Figure 3A and Video 1, Supplemental Digital Content 1, http://youtu.be/r-ZlwH5iQJM [at 20 seconds]) were then injected for orientation and optimal head positioning. The surgical field and operating microscope were draped; the reference stars were replaced by identical sterile ones; and the microscope calibration repeated.

**Intraoperative Image Injection**

After incision, the virtual model of the skull was injected, and registration precision was reassessed at a millimetric scale by evaluation of the overlap of the model with the real skull at medium magnification (Figure 3B and 3C). The orbital rim, orbitozygomatic suture, and zygoma were used for millimetric verification (Video 1 [44 seconds]). The segmented vascular structures were then injected to help plan the craniotomy (Figure 2C). After opening of the dura mater, a 3-D semitransparent model of the arteries of interest was injected, and registration once more reassessed at a submillimetric scale by evaluation of the overlap between the model and visible arterial segments at high magnification. Image injection of vascular structures was then used for orientation (Video 1 [1 minute 7 seconds]) and Figure 3D and 3E) and clip placement (Video 1 [1 minute 51 seconds-2 minutes 2 seconds] and Figure 3F). Intraoperative angiography was performed to confirm optimal clipping (Figure 1E).

**RESULTS**

**General**

Among the 39 clipped aneurysms, 17 were located at the MCA bifurcation, 8 on the anterior communicating artery, 5 on a posterior communicating artery, 3 on the M1 segment of the MCA, 2 on the choroidal segment of the internal carotid artery, 1 on the ophthalmic segment of the carotid artery, 1 distal to the MCA bifurcation, 1 on a superior cerebellar artery, and 1 on an interoposterior cerebellar artery. Aneurysm diameter ranged from 2 to 19.3 mm, and the average diameter was 5.9 mm (Table 1).

**Functionalities of Augmented Reality**

Virtual images were visualized as a 3-D volume (Figures 2B and 3B) or as 2-D sections (Figure 2A and 3C). Transparency of the virtual images could be adjusted (Video 1 [36-43 seconds]). In 3-D volume images, 2 different levels of transparency attempt to bestow a sense of depth between what is above or below the point of focus (Video 1 [1 minute 27 seconds]). In 2-D image segments, structures in the plane of focus appear in full lines, slightly deeper structures appear dotted, and superficial structures are omitted (Video 1 [1 minute 3 seconds]), section through the left orbit and left frontal sinus). The intensity of injected images could be
FIGURE 1. **A**, preoperative vascular segmentation of the aneurysm and surrounding vessels using the iPlan platform (BrainLAB, Feldkirchen, Germany) extracted from **C** preoperative 3-dimensional digital subtraction angiography showing a 4-mm aneurysm of the left posterior communicating artery in the patient shown in Figure 3. **B**, surgical angle of the same segmentation. **D**, preoperative and **E** intraoperative angiography confirming optimal aneurysm clipping. The thin arrow indicates the anterior choroidal artery; the thick arrow indicates the clip.
adjusted by the assistant, and image injection could be turned on and off by the surgeon by pushing a button on the handle of the microscope. The objects to inject were selected through the neuronavigation workstation.

**Utility of Augmented Reality**

Visual evaluation of the accuracy of patient coregistration was performed in all patients, and the coregistrations were in all cases < 3 mm off target. Patients’ heads were repositioned in 3 cases (10%). The craniotomy was tailored to the injected images of the aneurysm and of underlying bony structures (Figure 2C) in the last 19 of the 30 operations (63.3%). The first 11 operations were required to design the operating procedure, to perform accuracy controls, and to build confidence in the procedure. Dissection and exposition were considered to be minimal, ie, less than under normal conditions, owing to image injection of the aneurysm in 26 of the 39 aneurysms (66.7%). Image injection of the aneurysm neck was found to be useful in clip positioning in 33 cases (92.3%). Augmented reality was considered to have had a major impact in 5 surgeries (16.7%) in that it was estimated by the surgeon that clipping would have been significantly more laborious had image injection not been used (Table 2).

On average, microscope calibration took 10 minutes; verification of accuracy took an additional 10 minutes. Manipulation of the neuronavigation station was performed entirely by the assistant throughout the duration of the operation and did not disturb the surgeon or interfere with the surgical workflow.

Video 1 shows augmented reality-aided clipping of an unruptured, 4-mm, growing left posterior communicating artery aneurysm in a patient with a medical history significant for clipping of a ruptured left middle cerebral artery (MCA) aneurysm 5 years earlier and for the placement of a Pipeline stent because of neck regrowth. Before incision (6-34 seconds), the patient is settled in the supine position, and her head is turned to the right. During skull exposition (35 seconds-1 minute 5 seconds), the superior orbital rim, zygoma, and titanium plate from a previous intervention are seen. The segmented skull images are superposed. After the craniotomy (1 minute 6 seconds-2 minutes 8 seconds), arachnoid dissection, identification of the anterior choroidal artery, choice of clip, and clip placement are guided by image injection. Note the presence of an intravascular stent in the M1 segment of the MCA from a previous endovascular intervention.

**Clinical Outcome and Intraoperative Angiography Control**

In the augmented reality patient cohort, differential modified Rankin Scale scores at 3 months indicated clinical stability after 25 interventions (83.3%) and a difference of 1, 2, and 3 after 3 operations (10.0%), 1 operation (3.3%), and 1 operation (3.3%), respectively. Outcome analysis at 3 months in a cohort of 81
patients with 136 aneurysms clipped without augmented reality during 87 operations showed clinical stability after 60 operations (69.0%) and a difference of 1, 2, and 3 after 17 (19.5%), 5 (5.7%), and 2 (2.3%) operations, respectively. Two patients (2.3%) died of coronary disease 3 days after surgery and as a result of an acute subdural hematoma 1 month after surgery. One patient (1.1%) was lost to follow-up.

Intraoperative control of clipping through angiography led to 4 clip adjustments; the rate of clip corrections was 9.3% [4 / (39 + 4)]. On final intraoperative angiography, all aneurysms were clipped without neck remnants or vessel compromise (Table 2). In comparison, the rate of clip corrections was 11.7% [18 / (136 + 18)] in 136 unruptured aneurysms previously clipped without augmented reality.
Finally, if the surgeon indeed

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TABLE 1. Augmented Reality-Assisted Cerebral Aneurysm Surgery: Patients and Aneurysmsa

<table>
<thead>
<tr>
<th>Patients, n (%)</th>
<th>28 (100)</th>
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<tbody>
<tr>
<td>Male</td>
<td>8 (29)</td>
</tr>
<tr>
<td>Female</td>
<td>20 (71)</td>
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<tr>
<td>Patient age, y</td>
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<tr>
<td>Age range</td>
<td>36-76</td>
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<tr>
<td>Median</td>
<td>54</td>
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<tr>
<td>Interventions, n</td>
<td>30</td>
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<tr>
<td>Aneurysms, n (%)</td>
<td>39 (100)</td>
</tr>
<tr>
<td>Aneurysm status, n (%)</td>
<td>39 (100)</td>
</tr>
<tr>
<td>Unruptured</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Ruptured</td>
<td>39 (100)</td>
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<tr>
<td>Aneurysm and craniotomy sites, n</td>
<td></td>
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<tr>
<td>IC Opht</td>
<td>1 (Pterional)</td>
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<tr>
<td>IC Ach</td>
<td>2 (Pterional)</td>
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<tr>
<td>Acom</td>
<td>8 (Pterional)</td>
</tr>
<tr>
<td>M1</td>
<td>3 (Pterional)</td>
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<tr>
<td>MCA bif</td>
<td>17 (Pterional)</td>
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<tr>
<td>MCA bif dis</td>
<td>1 (Pterional)</td>
</tr>
<tr>
<td>Pcom</td>
<td>5 (Pterional)</td>
</tr>
<tr>
<td>PICA</td>
<td>1 (Lateral suboccipital)</td>
</tr>
<tr>
<td>SCA</td>
<td>1 (Pterional)</td>
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<tr>
<td>Maximum aneurysm diameter, mm</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>2-19.3</td>
</tr>
<tr>
<td>Average</td>
<td>5.9</td>
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<tr>
<td>Differential modified Rankin Scale score at 3 mo, n (%)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>25 (83.3)</td>
</tr>
<tr>
<td>1</td>
<td>3 (10.0)</td>
</tr>
<tr>
<td>2</td>
<td>1 (3.3)</td>
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<tr>
<td>3</td>
<td>1 (3.3)</td>
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</tbody>
</table>

aAcom, anterior communicating artery; IC Opht, ophthalmic segment of internal carotid artery; IC Ach, choroidal segment of internal carotid artery; MCA bif, bifurcation of middle cerebral artery; MCA bif dis, distal to bifurcation of middle cerebral artery; Pcom, posterior communicating artery; PICA, posteriorinferior cerebellar artery; SCA, superior cerebellar artery. Differential modified Rankin Scale score is the difference between postoperative and preoperative modified Rankin Scale scores.

TABLE 2. Augmented Reality-Assisted Cerebral Aneurysm Surgery: Usefulness

| Evaluation of accuracy of patient neuronavigation coregistration (total of 30 operations), n (%) | 30 (100) |
| Impact on craniotomy of image injection of aneurysm (s) (total of 30 operations), n (%) | 5 (16.7) |
| Impact on exposition of image injection of aneurysm (total of 39 aneurysms), n (%) | 26 (66.7) |
| Impact on coregistration (total of 30 operations), n (%) | 19 (63.3) |
| Impact on clip placement of image injection of aneurysm neck (total of 39 aneurysms), n (%) | 36 (92.3) |
| Major impact of augmented reality on surgery (total of 30 operations), n (%) | 5 (16.7) |
| Rate of clip corrections from intraoperative angiography |          |
| N               | 4        |
| Rate, %         | 9.3      |

aRate of clip corrections is the number of clip corrections divided by the total number of clip placements.

DISCUSSION

We present our experience with cerebral aneurysm surgery assisted by augmented reality. The described setup does not need additional hardware in the operating theater other than the neuronavigation workstation and the operating microscope, which are already present in most neurosurgery centers, and it is operated entirely by the surgical team. Although it adds time to the operation, it does not significantly disrupt the surgical workflow, but at the same time, it provides useful information on intraoperative orientation directly into the eyepiece of the microscope. Although standard neuronavigation is point based, augmented reality immerses the 3-D image data in the real-world 3-D surgical field, greatly aiding the surgeon in the mental task of processing these 2 image data sets. Furthermore, the surgeon does not need to look away from the operating field to the neuronavigation screen and strain his/her vision, which is already accommodated to the binocular of the microscope.\textsuperscript{1,17,18} Finally, if the surgeon indeed wishes to correlate the surgical field seen through the microscope with the complete 3-D images on the neuronavigation workstation, the microscope, once calibrated, also serves as a virtual pointer, where the tip corresponds to the point of focus.

When applied to aneurysm surgery, we view augmented reality as useful in several ways. First, the position of the patient’s head can be optimized for the best surgical trajectory before draping using the projection of the virtual aneurysm (Figure 3A). As mentioned by others,\textsuperscript{2,8,11,15,18} augmented reality assisted with craniotomy planning in 19 of the 30 surgeries in this case series.

Second, augmented reality allows intraoperative orientation. We found that subarachnoid dissection could be minimized using image guidance in approximately 65\% of cases.

Third, image injection of the segmented aneurysm and of neighboring vessels can remind the surgeon of the angioarchitecture while dissecting around them. Injecting a segmented image of the aneurysm neck allows in situ confirmation of the clip to be used and how to place it. This parameter might be of particular interest during clipping of complex aneurysms, although we found it useful in nearly all cases (92\%). Figure 4 is an illustrative example of this in a patient presenting to our institution with a left MCA bifurcation aneurysm treated during the same operation with augmented reality. A left pterional approach was performed, and the contralateral posterior communicating artery aneurysm was viewed through an angle between the optic nerves. Image injection of the neck allowed the surgeon to appreciate its sellar shape, and a curved clip was accordingly placed after minimal dissection behind the aneurysm. The intraoperative angiography revealed complete exclusion of the lesion and the absence of stenosis of neighboring vessels. It is important to note that when a thorough visual
inspection of the neck cannot be performed to exclude perforator trapping or a neck remnant, as was the case in this clipping procedure, immediate 3-D angiography should be carried out to assess the quality of clipping; neither indocyanine green nor endoscopic exploration was an adequate means of assessing this in this case.

Finally, in line with considerations from Kockro et al, image injection allows direct evaluation of the accuracy of neuro-navigation registration and can show how reliable the augmented images actually are from the very start. This can be done before skin incision with superposition of a virtual image of the patient’s head over the real head (Figure 2A and 2B) and after incision with superposition of the virtual skull over the real one (Figure 3B and 3C and Video 1 [43 seconds-1 minute 6 seconds]). For this, we used surface facial features such as the nasal contour; the frontal, orbital, infraorbital, and zygomatic regions; and the auricular conchae. Although the skull surface provides sparse intraoperatively identifiable landmarks, we found the zygoma, the frontozygomatic suture, and, when prominent enough, the processus marginalis (the posteriorly pointing sharp edge below the frontozygomatic suture) to be reliable structures for the evaluation of accuracy during pterional approaches; the mastoid fissure and rim of the foramen magnum were used for the retromastoid approach. In our experience, 3-D volume images are adequate for the global evaluation of the superposition of virtual and real-life structures, whereas 2-D sections allow finer evaluation at a point of interest.

Surface-matching patient registration or combined methods using surface-matching and paired-point registration are considered to provide acceptable registration results, with an error of < 4 mm. However, augmented reality technology could intuitively also be used to correct this mismatch through
“intelligent” fusion between the injected image and the real structure using information from the field of the microscope. This correction could be performed at every stage of surgery, ie, using the skin surface, using bone, and using sulci, veins, and arteries. It requires the identification of unequivocal “signature shapes” in each of these structures and then a comparison of the observed shape in the microscope with the calculated contours generated from neuronavigational data; the difference between these 2 data sets could allow calculation of a convolution function that would correct for shifts and deformations. Although we tested several techniques to correct for shift, current software applications do not allow easy intraoperative corrections. Of note, brain shift was less an issue in our augmented clipping case series because the craniotomies were small and dissections were minimal; the injected image always led us to the aneurysm. Slight translation of the virtual aneurysm was actually even appreciated during clipping.

Although augmented reality was useful in the majority of cases for craniotomies, dissection, and clip placement, we considered that it actually had a major impact in 5 surgeries (16.7%) in that it was estimated by the surgeon that clipping would have been significantly more laborious had image injection not been used. The characteristic feature that seems to render image injection of major impact is an unusual operating trajectory or a limited exposition. It remains to be seen whether this parameter is reproducible in a larger case series and whether aneurysm size, aneurysm neck features, and particular vascular sites are also of predictive value. Smaller craniotomies and minimal dissection have been reported to have a positive impact on postoperative morbidity.21,22 Our comparative outcome data between patients clipped with and without augmented reality seem to indicate better results in the former group, although the cohort is still too small to be able to underline a real effect.

Notably, Rohde et al23 considered the idea of using neuronavigational data to aid the surgeon in appreciating the aneurysm environment and angioarchitecture during clipping procedures, thereby limiting complications. In line with our considerations and results, neuronavigation was viewed as a useful adjunct in their series and allowed tailored fissure openings targeting the aneurysm, as well as visualizing its hidden aspects. However, the described setup consisted of a separate display screen containing both 2-D and 3-D vascular and bone segmentations, requiring the surgeon to look away from the microscope while inserting a neuronavigation pointer into the depth of the craniotomy to be able to rotate around the 3-D vascular tree. Our system, on the other hand, integrates the 3-D neuronavigational data directly into the surgical view; more important, as the operating microscope itself is navigated, the surgical experience is further augmented because the virtual images take into account the position of the microscope and its point of focus and magnification, thereby at all times matching the true real-world structure in both scale and angle of view. Furthermore, the resolution of the segmentations in the series by Rohde et al23 was limited, and bony structures had to be manually cut away, with the risk of “indenting” the vessel reconstructions. Our system combines fused multimodal images, allowing automatized selective structure segmentation (Figure 1B and 1C), which can be selectively used during the operation. The possibility of segmenting vascular structures from 3-D angiography further heightens the resolution of injected images. In this way, even small aneurysms and small perforators in the vicinity of bony structures, otherwise difficult to visualize on CT, can be seen clearly.

Kockro et al24 used a handheld probe mounted with a video camera subsequently augmented by 3-D segmentations and visualized on a separate screen. Although this setup truly uses augmented reality, it is still not integrated into the surgical view of the microscope, as the authors themselves point out. Furthermore, the display is monoscopic. Stereoscopic 3-D image injection into the operating microscope, as used in our system, is described in several previous reports and allows the surgeon to directly appreciate the volumetric rendering of the segmented structure.7,9,17 However, as Kockro et al24 rightly state, despite these advances, the human brain does not readily perceive the virtual structures as being below the visible surface. In our experience, this effect can be tapered by intraoperatively diminishing the contrast of the injected images; the latter become less salient in contrast to the real-world structures and more readily accepted. Moreover, as described earlier and as depicted in Video 1, when a segmented structure is actually reached, a difference in transparency bestows a sense of depth between the part of the structure above and below the point of focus.

Because intraoperative angiography is used routinely in our institution for clip control in all aneurysm cases clipped in the hybrid operating theater, a more objective measure of the utility of augmented reality is the rate of clip corrections. Our unpublished data indicate this rate to be 11.7% in a cohort of 136 unruptured aneurysms clipped without the assistance of augmented reality. This rate is 9.3% in the case series presented here with augmented reality. Although it is in any case not worse than the rate of clip corrections without augmented reality, as mentioned above concerning comparative clinical outcomes, our cohort is still too small to determine whether augmented reality actually has an impact on it. Nevertheless, augmented reality represents a natural progression toward increasing the surgeon’s comfort, which intuitively and undoubtedly has an impact on surgical quality. However, despite a better understanding of the hidden aspects of the aneurysm neck, vascular wall irregularities (wall hyperplasia, calcifications) remain a significant limiting factor for perfect clipping.

The intraoperative use of augmented reality is in line with new thinking and efforts to render microsurgical clipping less invasive and could be an alternative to other minimally invasive techniques such as endoscopy-assisted surgery, which can itself be augmented, as reported by Kawamata et al.16

CONCLUSION

Augmented reality could be another useful adjunct to the concept of minimally invasive surgery of cerebral aneurysms. Furthermore, future development should allow complete automation of this technique for any form of neurosurgery to allow
immediate use by the surgeon when needed without any preparation or special skills.

Disclosure

The authors have no personal financial or institutional interest in any of the drugs, materials, or devices described in this article.

REFERENCES


Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal Web site (www.neurosurgery-online.com).

COMMENTS

The authors of this article report their initial experience with augmented reality in the surgery of aneurysm clipping. The principle of augmented reality is not a new one, but the current application in aneurysm surgery is innovative. This application of augmented reality involves acquisition of high-resolution vascular imaging, brain imaging (including parenchyma and bone), image segmentation, and fusion before any surgical planning is made. Once this is available, then the rest of its application is similar to neuronavigation in terms of projecting anatomic landmarks on locations in space. The angiographic virtual imaging is projected into the operating microscope. This will give the surgeon a virtual image that should superimpose with the real location of the structures being projected (bones, vessels, etc). The benefit of such technology would be more evident in aneurysms located in the pericallosal, distal middle cerebral, or posterior superior cerebellar artery, where it can help minimize the craniotomy site and predict the aneurysm clip size and projection. As this application become widely available and an integral part of the neuronavigation, it theoretically can lead to making minimal invasive aneurysm clipping surgery a standard in unruptured aneurysms.

Ali Alaraj
Fady Charbel
Chicago, Illinois

This is a very interesting technical note reporting the authors experience using augmented reality in the clipping of cerebral aneurysms. The authors report their experience of cerebral aneurysm surgery aided by augmented reality in 28 patients with 39 aneurysms. They also report their experiences in optimizing their craniotomy during the progression of this series by using navigational information. The method presented here seems to be an interesting tool not only in helping the surgeon during aneurysm clipping but also in evolving the surgeon’s surgical technique. First, it is an additional tool helping surgeons position an aneurysm clip accurately. Second, by allowing the surgeon to tailor an individual craniotomy, it help optimize the surgical trauma. According to the principle Primum non nocere, all steps that bring us surgeons closer to the goal of performing surgery with a minimum amount of surgical trauma are welcome. Even though further studies with larger numbers of participants are of course needed before ultimate conclusions can be drawn, in my opinion, the technology presented here has the potential to be useful in making complex cerebralvascular operations safer and less traumatizing.

Axel Thomas Stadie
Mannheim, Germany

This study provides valuable experiences with the 3-dimensional image segmentation and injection features of a commercially available navigation system. Although the theoretical technical possibilities of the current navigation systems are somehow familiar to most of us, only a few actually make full use of them. This group has gone all the way by
segmenting the essential anatomic structures of aneurysm surgery, planning the ideal surgical strategy, and subsequently injecting the 3-dimensional data into the operating microscope to facilitate dissection and clip application. Having used the same technical features for vascular and tumor surgery numerous times, I fully agree with the group’s findings: Intraoperative guesswork is reduced; anatomic orientation is improved; and surgery becomes easier. For the sake of safe surgery, it is well worth going through the additional hassle of segmentation, multimodal image preparation, and intraoperative overlay, and I am convinced that these features will be used more widely once their preoperative and intraoperative implementation becomes a little easier to handle and the graphics and image injection quality improve. One day, we will have reached a point when operating on brain tissue will no longer be dependent on anatomic approximation and exploration but rather be guided by a precise computer-graphic synthetic environment that surrounds the surgical field and adapts to it by continuous processing of intraoperative imaging data. This article shows that we are on the right path towards this.

Ralf A. Kockro
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In this article, the authors describe a technique in which the surgeon can combine preoperative 3-dimensional image sets and neuronavigation to provide an augmented reality view of the cerebral blood vessels during aneurysm clipping procedures. The images are injected into the operating microscope to allow superimposition onto the microscopic view to help with the surgeon’s understanding of the relevant vascular anatomy, as well as the adjacent bony structures, and to assist with aneurysm clipping.

The authors compare their experience of 39 aneurysms clipped using augmented reality with a historical cohort of 136 aneurysms previously clipped without augmented reality. They determine that the use of augmented reality assisted with patient positioning, reduced dissection and exposure, and assisted with clip positioning.

In a study such as this, it is clearly difficult to obtain objective data on the usefulness of the augmented reality technique. Outcome measures such as the rates of clip reposisioning were not significantly different between the current and historical cohorts (9.3% vs 11.7%, respectively), despite the surgeon feeling that image injection of the aneurysm neck assisted with clip positioning in 92.3% of cases. Furthermore, the clinical outcome data between the cohorts are difficult to interpret.

Nevertheless, for any surgeon who clips intracranial aneurysms, it is hard to imagine that having more information about the vascular and adjacent bony anatomy would not be useful. Although some aneurysms are straightforward to clip, others are much more challenging, and having this additional information without even having to move one’s eyes away from the operating microscope is, without question, an advantage. I hope that someday in the near future this technique becomes routinely incorporated into all cerebrovascular procedures.

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