Frameless neuronavigation based only on 3D digital subtraction angiography using surface-based facial registration

Laboratory investigation

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Object. Cerebrovascular lesions can have complicated abnormal anatomy that is not completely characterized by CT or MR angiography. Although 3D rotational angiography provides superior spatial and temporal resolution, catheter angiograms are not easily registered to the patient, limiting the use of these images as a source for neuronavigation. However, 3D digital subtraction angiography (DSA) contains not only vascular anatomy but also facial surface anatomy data. The authors report a novel technique to register 3D DSA images by using only the surface anatomy contained within the data set without having to fuse the DSA image set to other imaging modalities or use fiducial markers.

Methods. A cadaver model was first created to assess the accuracy of neuronavigation based on 3D DSA images registered by facial surface anatomy. A 3D DSA scan was obtained of a formalin-fixed cadaver head, with acquisitions of mask and contrast runs. The right common carotid artery was injected prior to the contrast run with a 45% contrast solution diluted with water-soluble red liquid latex. One week later, the head was registered to a neuronavigation system loaded with the 3D DSA images acquired earlier using facial surface anatomy. A right pterional craniotomy was performed and 10 different vascular landmarks were identified and measured for accuracy using the neuronavigation system. Neuronavigation based only on 3D DSA was then used to guide an open clipping procedure for a patient who presented with a ruptured distal lenticulostriate aneurysm.

Results. The accuracy of the measurements for the cadaver model was 0.71 ± 0.25 mm (mean ± SE), which is superior to the 1.8–5 mm reported for neuronavigation. The 3D DSA–based navigation-assisted surgery for the distal lenticulostriate aneurysm aided in localization, resulting in a small craniotomy and minimal brain dissection.

Conclusions. This is the first example of frameless neuronavigation based on 3D catheter angiography registered by only the surface anatomy data contained within the 3D DSA image set. This is an easily applied technique that is beneficial for accurately locating vascular pathological entities and reducing the dissection burden of vascular lesions.

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Key Words • digital subtraction angiography, cadaver model • distal lenticulostriate aneurysm • neuronavigation • rotational angiography • 3D laser surface registration • surgical technique

PARALLELING the rapid development of neuroimaging technology, the introduction of neuronavigation in the 1980s has revolutionized the surgery of intracranial diseases.2,11 Neuronavigation based on CT or MRI studies has tailored surgical interventions to individual anatomy and pathology, with minimal disruption to the physical and functional architecture of the brain. Vascular anatomy is best appreciated with digital subtraction angiography (DSA), which remains the gold standard for imaging of cerebrovascular pathology. Both CT angiography (CTA) and MR angiography (MRA) have lower detection sensitivity and inferior spatial resolution relative to DSA for aneurysms smaller than 3 mm.1,19,20 The use of DS angiograms as source images for neuronavigation, however, has been limited because DSA studies typically lack the soft-tissue information necessary to register the radiographic image space to the head in the physical space. Images from DSA typically require fusion with CT or MR images for coregistration.

Abbreviations used in this paper: AVM = arteriovenous malformation; BA = basilar artery; CCA = common carotid artery; CTA = CT angiography; DSA = digital subtraction angiography; FDCT = flat-panel detector CT; ICA = internal carotid artery; LSA = lenticulostriate artery; MRA = MR angiography; PCA = posterior cerebral artery; VA = vertebral artery.
We report a novel technique to register 3D DSA images in the endovascular suite without the need to fuse to other imaging modalities. Soft-tissue information obtained during the acquisition of the 3D DSA studies can be used to reconstruct facial surface anatomy in radiographic image space. Registration of a patient to the 3D DSA with facial surface recognition can then be accomplished in the operating theater without using CT or MR images for coregistration. This technique was validated using a cadaver model. The 3D DSA registration technique was also successfully used for precise localization of a distal lenticulostriate aneurysm during an open surgical procedure, permitting a smaller craniotomy, less extensive transsylvian dissection, and, consequently, less manipulation of the surrounding vasculature and parenchyma.

**Methods**

**Acquisition of 3D DSA Images and Neuronavigation**

All 3D DSA data sets were acquired as 5-second rotational runs on a biplane AXIOM Artis zee angiography system (Siemens) with the following parameters: 90 kV, 0.36 μGy per frame, 200° rotation, 1.50° angulation step per frame, and projection on 30 × 40–cm flat-panel detector. A mask run was first acquired, followed by a contrast run acquisition. For the cadaver model, 50 ml of a 45% Isovue 250 (Bracco Diagnostics, Inc.) diluted with water-soluble red liquid latex (Ward’s Natural Science) was injected directly into the right common carotid artery (CCA) just prior to the contrast run acquisition. For the illustrative case, 21 ml of Isovue 250 was injected through a catheter navigated into the left internal carotid artery (ICA) via a transfemoral approach by using a power injector at a rate of 3 ml/sec, and images were acquired after a 2-second delay.

Both the mask and contrast run data sets were reformatted in a DICOM image protocol and transferred to a StealthStation S7 Surgical Navigation System (Medtronic). The cadaver model in the laboratory or the patient’s head in the operating room were fixed in a head frame to which a navigation reference frame was secured. The facial surface anatomy was then reconstructed on the neuronavigation platform from the loaded 3D DSA mask run DICOM data set by using the software algorithm intrinsic to the neuronavigation system, as would be standard for other loaded neuroimaging modalities, namely CT or MRI DICOM data sets. Registration to the neuronavigation system was performed in the usual manner with a surface face tracing using the loaded mask run. The accuracy of the registration was confirmed with external landmarks. On the neuronavigation system, a 3D object of the vascular anatomy was constructed using the contrast run and overlaid onto the registered mask run data set.

**Cadaver Model**

A cadaver model was created by irrigating a fresh cadaver head with saline separately through the great vessels of the neck until the returned fluid was clear. The head was fixed for 1 week in a 10% formalin solution. One hour before acquiring 3D DSA images, the head was removed from the 10% formalin solution and again irrigated with saline through the CCAs. The 3D DSA images were then obtained as described, and the latex-injected head was stored in a 10% formalin solution for a period of 2 weeks to allow the latex vascular cast to set. Afterward, the head was fixed to a stationary head frame, and a navigation reference frame was secured to the head frame. A standard left pterional craniotomy was performed and the sylvian fissure was dissected using the microsurgical technique. When vascular landmarks were encountered, including turns and bifurcations of the large latex-filled vessels, a navigation probe was used to mark the landmark, and the corresponding difference in the image space as shown on the navigation computer system was recorded as the navigation error. The error is reported as the mean ± SE.

**Illustrative Case**

This study and imaging protocol was reviewed and approved by the university’s institutional review board.

**Results**

**Cadaver Study**

Acquisition of the 3D DSA images of the cadaver model was uncomplicated (Fig. 1 left). Both the mask and contrast runs contained detailed soft-tissue information sufficient to construct face surface anatomy. The contrast-latex injection into the right CCA not only filled the ipsilateral ICA vascular distribution, but also the posterior circulation including the bilateral vertebral arteries (VAs) and the contralateral left ICA distribution. The surface rendering of the vascular anatomy (Fig. 1 right) was very detailed, showing a right fetal origin of the posterior cerebral artery (PCA) and a small 2.2-mm aneurysm at the right M1 bifurcation.

At the time of the cadaver model dissection, the 3D DSA data set previously obtained for the model was loaded onto a neuronavigation system as DICOM images. The data set contained both the mask and contrast runs. The model was registered to the neuronavigation system without difficulty by using a map of the facial surface anatomy constructed from the mask run on the neuronavigation system (Fig. 2). Accurate registration was confirmed using external landmarks. A total of 10 different vascular landmarks were identified after a standard left pterional craniotomy (Table 1), and the error of the neuronavigation system to the anatomy was measured for each landmark (Fig. 3). The mean accuracy measured was 0.71 ± 0.25 mm.

**Illustrative Case**

An 83-year-old man with a history of hypertension and aortic valve replacement who was maintained on warfarin therapy presented with acute onset of slurred speech while walking in a park. On examination he was extremely dysarthric, with a left facial droop and left hemiparesis. He was otherwise following commands. An initial CT scan of the head revealed a large intraparenchymal hemorrhage within the right basal ganglia (Fig.
4A and B). The international normalized ratio on presentation was 2.5 and the patient was administered 4 U of fresh-frozen plasma and 10 mg of vitamin K. A CTA study of the head (Fig. 4C and D) and later an MRA study of the head depicted a small lesion at the medial border of the right intraparenchymal hemorrhage that was associated with a small linear vascular structure, a matter of concern for a possible aneurysm. A distal lenticulostriate aneurysm was found during a cerebral angiogram obtained to further characterize the lesion (Fig. 5). An attempt to cannulate the lenticulostriate artery (LSA), with the goal of sacrificing the vessel with liquid embolization, was unsuccessful due to the very small vessel size and the acute angle made by the LSA with respect to the M1 parent vessel. As described above, 3D DSA images were obtained of the head in preparation for an open neurosurgical repair of the aneurysm.

In the operating theater, the patient’s head was secured in a Mayfield head frame. The 3D DSA data set was loaded onto the neuronavigation station as DICOM images as 2 sets of data: a mask run and a contrast run. After securing a neuronavigation reference frame to the Mayfield, the patient was registered to the neuronavigation system by using the mask run, with excellent precision as confirmed with external landmarks. As with the cadaver study, a separate 3D volume object of the vascular anatomy was constructed on the neuronavigation system by using the mask run, with excellent precision as confirmed with external landmarks. As with the cadaver study, a separate 3D volume object of the vascular anatomy was constructed on the neuronavigation system by using the contrast run and overlaid onto the mask run images. Using the navigation system, a minimal right frontal craniotomy was made and a small 16-mm corticotomy was created in the right frontal lobe (Fig. 6). The neuronavigation system was linked to a Zeiss Pentero 900 microscope (Carl Zeiss AG), and image guidance was used to dissect a trajectory through the frontal lobe brain substance, through the intraparenchymal hematoma, and directly to the distal lenticulostriate aneurysm. The aneurysm was carefully inspected and 2 clips were placed at its base. The dome of the aneurysm was perforated with a needle to ensure that the lesion was completely excluded from circulation. The head wound was closed in the usual fashion and the patient was admitted to the intensive care unit for standard postoperative care.

### Table 1: Measured neuronavigation errors for the cadaver model

<table>
<thead>
<tr>
<th>Anatomical Location</th>
<th>Measured Error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 branch point</td>
<td>0.0</td>
</tr>
<tr>
<td>M1–M2 junction</td>
<td>0.9</td>
</tr>
<tr>
<td>M2 bifurcation</td>
<td>2.2</td>
</tr>
<tr>
<td>M3 branch</td>
<td>0.0</td>
</tr>
<tr>
<td>aneurysm dome at M1 bifurcation</td>
<td>0.0</td>
</tr>
<tr>
<td>ICA bifurcation</td>
<td>0.6</td>
</tr>
<tr>
<td>AC0A</td>
<td>0.0</td>
</tr>
<tr>
<td>PCoA at ICA origin</td>
<td>1.3</td>
</tr>
<tr>
<td>BA bifurcation</td>
<td>0.4</td>
</tr>
<tr>
<td>OphA origin</td>
<td>1.7</td>
</tr>
</tbody>
</table>

*ACoA = anterior communicating artery; OphA = ophthalmic artery; PCoA = posterior communicating artery.*

### Discussion

The use of angiography as a source for frameless neuronavigation is not a novel concept. Frameless neuronavigation based on CTA or MRA has been used to tailor the most direct trajectory to a vascular lesion and to characterize complex anatomy during the treatment of cerebral aneurysms.\(^7,9,14,15\) This in turn minimizes the cosmetic burden, craniotomy size, and unnecessary brain manipulation without compromising exposure of the pathological lesion. Magnetic resonance angiography–based neuronavigation is also an important adjuvant to the operative management.
of an arteriovenous malformation (AVM). The elucidation of the complex anatomy of AVMs by neuronavigation provides a more reliable verification of the resection margins with minimal disruption to the normal brain architecture, reducing the duration of brain retraction and the morbidity related to the surgical approach.12

Conventional DSA provides superior spatial and temporal resolution of fine vascular anatomy less than 3 mm, relative to both CTA and MRA.1,19,20 Imaging of

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**Fig. 3.** Examples of error measurements during the cadaver model dissection using the neuronavigation system. A navigation probe was placed at the origin of the right ophthalmic artery after the anterior clinoid process was drilled, and is displayed as axial (A) and inline probe view (B) projections on the navigation system. The tip of the probe is indicated by the red crosshairs at the center of each projection, and the measured error was 1.7 mm. The axial (C) and coronal (D) navigation projections of the probe placed at the bifurcation of the basilar artery (BA) are shown, and the measured error was 0.4 mm. Relevant anatomy is labeled. CN = cranial nerve; O. Ch. = optic chiasm; Ophth. A. = ophthalmic artery; PCoA = posterior communicating artery; Temp. Lobe = temporal lobe.

**Fig. 4.** Axial (A) and coronal (B) projections of a noncontrast CT scan of the head depicting a large acute hematoma within the right basal ganglia. Axial (C) and coronal (D) projections of a CT angiogram showing a hyperdense lesion at the medial border of the intraparenchymal hematoma (arrows); the lesion was suspected of being an aneurysm.

**Fig. 5.** Right M1 segment anterior-posterior (left) and lateral (right) projections of an arterial phase angiogram. An intravascular balloon has been inflated within the mid–M1 segment to accentuate the opacification of the distal aneurysm (arrowheads) and its parent LSA (arrows). The abrupt acute angle of the LSA at its origin and its small caliber prevented canalization of the artery with a microcatheter for liquid embolization.
Registration of 3D DSA using facial surface anatomy

vascular anatomy by DSA is not degraded by surrounding bony structures or metallic implants as it would be for CTA. The image resolution for MRA may be limited by slow flow that is not fully visualized by the time of flight technique. However, DSA is more challenging to use as a source of neuronavigation because this imaging modality does not contain extravascular data needed for registration. Different strategies have been instituted for the use of conventional DSA for neuronavigation. For example, DSA has been successfully fused with CT or MRI studies, with favorable results.4 A portable vascular C-arm has also been used to create an angiographic road map by using DSA to guide open cerebrovascular procedures as a form of neuronavigation.3

Rotational 3D DSA provides more information about complex cerebrovascular anatomical detail than conventional DSA.1,3,17,19,22 The 3D DSA images are reconstructed from 2 separate rotational angiography acquisitions: a mask run and a contrast run. These rotational angiography acquisitions are volume data sets analogous to flat-panel detector CT (FDCT) scans that contain bony and soft-tissue information similar to conventional multidetector CT. In a hybrid operative suite containing a fixed C-arm, FDCT can be directly used for frameless neuronavigation because the patient’s head is fixed in space throughout the procedure.5,8,33 Hybrid operative suites, however, require considerable technical and engineering resources, which can be costly. The 3D DSA images have been fused and coregistered with CT or MRI scans for neuronavigation during surgery for complex aneurysms and AVMs.16 Also, 3D DSA has been successfully used as source imaging for neuronavigation alone without fusion to other imaging modalities or the use of fiducials. The soft-tissue information captured during the rotational angiography runs of the 3D DSA acquisition is sufficient to reconstruct facial surface anatomy. This facial surface anatomy can then be registered in the usual manner to a neuronavigation platform. The measured neuronavigation accuracy of the cadaver model was 0.71 ± 0.25 mm, which is superior to the mean accuracy of 1.8–5 mm reported for neuronavigation.46 This is probably attributable to the fact that the cadaver model was formalin fixed and the vasculature was injected with latex, rendering the cerebrovascular and brain tissue relatively immobile. Although for the illustrative case presented here the CT angiograms may have been used as the source images for navigation, the 3D DSA images obtained in the endovascular suite were used without difficulty. Once the 3D DSA data set is transferred to the neuronavigation platform as DICOM images, registration is standard and thus there is no learning curve for the experienced surgeon. The 3D DSA images provide exquisite detail of vascular anatomy as well as soft-tissue anatomy contained within the FDCT overlay. Neuronavigation was particularly helpful in the illustrative case, in which the lesion was located deep within the brain substance, and would be useful for other types of cerebrovascular pathologies including anterior circulation distal aneurysms or micro-AVMs not well visualized on CTA or MRA.

Neuronavigation based on any static image set does have limitations. For aneurysms in particular, accuracy is lost by brain shift caused by releasing CSF. Accuracy for AVMs is lost as the lesion cavity begins to collapse, resulting in brain shift. In a hybrid suite, these limitations can potentially be overcome with subsequent 3D DSA acquisitions.

Fig. 6. Illustrative case. Open surgical treatment of the distal LSA aneurysm. A: The neuronavigation system was used to minimize the size of the right frontal craniotomy and corticotomy. B: Intraoperative microscopic view of the aneurysm visible just below and to the right of the crosshairs. C and D: Orthogonal inline probe view neuronavigation projections based only on 3D DSA, showing a probe at the aneurysm.
Conclusions

Frameless neuronavigation based on 3D DSA images provides detailed anatomical information about cerebrovascular pathology that is easily used in the operating room. The accuracy of neuronavigation based on 3D DSA is equivalent to neuronavigation based on other imaging modalities.

Disclosure

Drs. Moftakhar and Lopes are consultants for Covidien and Penumbra. Heike Theessen is a full-time employee of Siemens Medical Solutions.

Author contributions to the study and manuscript preparation include the following. Conception and design: Lopes, Stidd, Theessen. Acquisition of data: Stidd, Serici, Theessen. Analysis and interpretation of data: Stidd. Drafting the article: Stidd, Wewel, Ghods, Munich, Serici. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Lopes. Administrative/technical/material support: Theessen. Study supervision: Lopes, Stidd.

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