Magnetic resonance imaging/magnetic resonance angiography fusion technique for intraoperative navigation during microsurgical resection of cerebral arteriovenous malformations

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Object. Microsurgical resection of arteriovenous malformations (AVMs) is facilitated by real-time image guidance that demonstrates the precise size and location of the AVM nidus. Magnetic resonance images have routinely been used for intraoperative navigation, but there is no single MRI sequence that can provide all the details needed for characterization of the AVM. Additional information detailing the specific location of the feeding arteries and draining veins would be valuable during surgery, and this detail may be provided by fusing MR images and MR angiography (MRA) sequences. The current study describes the use of a technique that fuses contrast-enhanced MR images and 3D time-of-flight MR angiograms for intraoperative navigation in AVM resection.

Methods. All patients undergoing microsurgical resection of AVMs at the Dartmouth Cerebrovascular Surgery Program were evaluated from the surgical database. Between 2009 and 2011, 15 patients underwent surgery in which this contrast-enhanced MRI and MRA fusion technique was used, and these patients form the population of the present study.

Results. Image fusion was successful in all 15 cases. The additional data manipulation required to fuse the image sets was performed on the morning of surgery with minimal added setup time. The navigation system accurately identified feeding arteries and draining veins during resection in all cases. There was minimal imaging-related artifact produced by embolic materials in AVMs that had been preoperatively embolized. Complete AVM obliteration was demonstrated on intraoperative angiography in all cases.

Conclusions. Precise anatomical localization, as well as the ability to differentiate between arteries and veins during AVM microsurgery, is feasible with the aforementioned MRI/MRA fusion technique. The technique provides important information that is beneficial to preoperative planning, intraoperative navigation, and successful AVM resection.

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Key Words • magnetic resonance imaging/magnetic resonance angiography fusion • arteriovenous malformation • intraoperative navigation • microsurgery

Treatment of cerebral AVMs involves a combination of microsurgical resection, stereotactic radiosurgery, and endovascular embolization.10 Accurate interventions require an understanding of the lesion’s intricate anatomy. In the setting of microsurgery, it is ideal to have real-time navigational capacity demonstrating the angioarchitecture of the feeding arteries, draining veins, and precise size and location of the nidus. Imaging options for treatment planning include conventional catheter angiography, CTA, high-resolution MRI, and MRA.10 Conventional DSA visualizes all 3 components of the AVM (feeding arteries, draining veins, and nidus) and provides superior spatial resolution, information about the flow dynamics of the lesion, and it has the significant advantage of time resolution.3,15,16 However, DSA cannot be used for intraoperative navigation, as it provides minimal information on the location of the AVM within the brain. On the other hand, CTA demonstrates detailed vascular anatomy that can be used for navigation,6,15 but lacks dynamic information that is crucial for treating AVMs and does not readily differentiate between arteries and veins, making surgical planning difficult. In addition, AVMs that have been embolized preoperatively have significant artifact, which makes CT scans difficult to use for precise intraoperative navigation.

Magnetic resonance angiography allows for the con-
struction of images of cerebral vessels within the brain, avoiding radiation and contrast injection. There have been prior reports on the use of MRA sequences to depict AVMs and improve the accuracy of AVM treatment with radiosurgery when combined with catheter angiography. The development of an MRA sequence that would offer good distinction of vessel anatomy and dynamic real-time information would improve intraoperative navigation and possibly simplify AVM microsurgery.

Different MRI protocols can provide complementary information. Specifically, 3D TOF MRA demonstrates the luminal aspects of cerebral vessels in which there is high-velocity flow, and it is useful in identifying the feeding arteries and high-flow vascular components of AVMs. On the other hand, CE MRI scans can show the enhancement of slower-flowing intracranial vessels, be obtained in any plane, and demonstrate excellent anatomical detail. It can be used for visualization of the nidus and, more importantly, may be used to identify draining veins. Neither modality alone can provide the structural and temporal information necessary to appreciate the complete anatomy of an AVM. Fusion of MRA and MRI sequences, however, can create a hybrid volume that allows more complete visualization of the AVM's angiography, which is achieved by utilizing the MRA identification of arterial components and the CE MRI identification of the venous components. In addition, liquid embolic materials, such as Onyx, create little artifact on MRI/MRA and provide useful navigation information in preoperatively embolized AVMs. In the current study we evaluated an imaging fusion technique in which volumetric 3D TOF MRA and CE MRI were used for intraoperative navigation during microsurgical resection of AVMs.

Methods

Patient Population

We retrospectively identified all patients from the Dartmouth Cerebrovascular Surgery Program in whom an AVM was microsurgically resected using neuronavigation based on MRI/MRA fusion. Between 2009 and 2011, this group included 15 patients. The study received approval from the Committee for the Protection of Human Subjects.

Imaging

Contrast-enhanced MRI and 3D TOF MRA scans were used for the planning of AVM microsurgery. Contrast-enhanced MRI and 3D TOF MRA studies, with fiducial markers in place, were obtained in 15 patients on the day of their AVM surgery. Magnetic resonance imaging examinations were performed on a 1.5-T Signa HDxt scanner (GE Healthcare). Axial MRA images were acquired using a 3D TOF gradient-echo acquisition sequence (FOV 22 cm, TR/TE 30/6.9 msec, flip angle 20°, slice thickness 1.2 mm, pixel size 0.47 × 0.47 mm). Following intravenous administration of the contrast agent Magnevist (Gd-diethylenetriamine pentaacetic acid, Berlex Labs), a 3D T1-weighted gradient-echo sequence was obtained (FOV 22 cm, TR/TE 11/4.5 msec, flip angle 13°, slice thickness 1.5 mm, pixel size 0.47 × 0.47 mm). Following the transfer of both files in DICOM (Digital Imaging and Communications in Medicine) format to the Brainlab Workstation, the AVM nidus was outlined on the axial MRI study. Subsequently, the data from the CE MRI and 3D TOF MRA scans were fused, and the 2 different modalities were represented with different colors (amber for 3D TOF MRA and blue for CE MRI) on a single image. In the fused images, arteries (amber) and veins (blue) were overlaid on each other and in anatomical location on the CE MRI images of the brain. After appropriate positioning and 3-point head stabilization on the Mayfield head holder, the CE MRI study was coregistered with the fiducial markers placed on the patient’s head, allowing navigation of the arteries, nidus, and veins. These fused images then were used during microsurgical resection of the AVMs.

Results

Demographics

Between 2009 and 2011, 15 patients in whom AVM microsurgical resection was performed had undergone preoperative planning with MRI/MRA fusion. The mean age of the group was 42.6 years (range 21–72 years) and consisted of 40% males. The patients had 11 supratentorial AVMs (3 frontal, 3 occipital, 3 parietal, and 2 temporal) and 4 infratentorial AVMs (3 cerebellar and 1 brainstem). Four patients initially presented with a hemorrhage, 3 with seizures, and 8 with headaches.

Outcomes

Image fusion was successful in all 15 cases. Data manipulation required to fuse the image sets was performed on the morning of surgery; the added setup time was minimal. The navigation system accurately identified feeding arteries and draining veins during resection in all cases. There was minimal artifact from embolic materials in the AVMs that had preoperative embolization. Complete obliteration of the AVM was demonstrated on intraoperative angiography in all cases.

Illustrative Cases

Case 1

This 21-year-old woman presented to the emergency department after a tonic-clonic seizure preceded by a few minutes of expressive aphasia. Magnetic resonance imaging demonstrated a 3 × 3 × 2.5–cm left frontal AVM bordering the anterior aspect of the pars triangularis. There was no evidence of an intracranial hemorrhage. Conventional angiography demonstrated that the lesion was supplied by branches of the left anterior and middle cerebral arteries, lenticulostriate arteries, and the left ophthalmic artery (Fig. 1A). The venous outflow of the AVM was to the transverse sinus, superior sagittal sinus, and vein of Galen. Functional MRI revealed left-sided language dominance, and diffusion tensor imaging demonstrated that the arcuate fasciculus passed posterior to the lesion.
The AVM was subjected to staged Onyx embolization in 3 sessions, and the patient subsequently was taken to the operating room for microsurgical resection of the lesion. Stereotactic navigation was based on CE MRI/3D TOF MRA fusion. The feeding arteries (Fig. 1C) and draining veins (Fig. 1D) were successfully identified intraoperatively. This facilitated precise resection of the lesion in eloquent cortex. The patient tolerated the procedure well and recovered without deficits. She remained seizure free at her 2-year follow-up.

Case 2

This 53-year-old man underwent MRI during workup for progressively worsening headaches. The study demonstrated a 3-cm left parietal AVM. There was no evidence of an intracranial hemorrhage. Conventional angiography revealed that the lesion was supplied by branches of the left pericallosal artery, left middle cerebral artery, and left posterior cerebral artery (Fig. 2A). The venous outflow from the AVM was to the superior sagittal sinus. Staged Onyx embolization was performed in 3 sessions, and the patient was subsequently taken to the operating room for resection of the lesion. Stereotactic navigation was based on CE MRI/3D TOF MRA fusion. Real-time identification of the feeding arteries (Fig. 2C) and draining veins (Fig. 2D) of the AVM was successful intraoperatively. The patient tolerated the procedure well and recovered without deficits.

Discussion

Treatment planning for microsurgical resection of cerebral AVMs currently includes both standard MRI and conventional angiography. High-resolution CE MRI and 3D TOF MRA are often used to study fine anatomical detail. While angiographic MRA techniques (3D TOF MRA) visualize luminal aspects of vessels, brain and nidus anatomy are better demonstrated with conventional MRI (CE MRI). The image fusion technique described in the current series used 3D TOF MRA data merged with high-resolution CE MRI images to comprehensively represent all pertinent anatomical structures required for accurate vessel and nidus identification and intraoperative navigation.

Although conventional angiograms are necessary to define AVM vascular anatomy, including the characterization of nidus, feeding arteries, draining veins, venous varices, and intranidal or feeding vessel aneurysms, they

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**Fig. 1.** Case 1. Left frontal AVM.  **A:** Digital subtraction angiogram with left internal carotid artery injection (lateral projection) demonstrating that the lesion is supplied by branches of the left anterior and middle cerebral arteries, the lenticulostriate arteries, and the left ophthalmic artery and is draining to the transverse sinus, superior sagittal sinus, and vein of Galen.  **B:** Axial CE MRI study demonstrating the blood vessels in the nidus of the AVM.  **C and D:** Axial CE MRI/3D TOF MRA fusion images with the arteries in amber and the veins in blue demonstrating a feeding artery (arrow, C) and a draining vein (arrow, D). The large central region of low signal in the MR image is an embolized nidus, thus accounting for the paucity of amber vessels in that region.

**Fig. 2.** Case 2. Left parietal AVM.  **A:** Digital subtraction angiogram with left internal carotid artery injection (lateral projection) demonstrating that the lesion is supplied by branches of the left pericallosal artery, the left middle cerebral artery, and the left posterior cerebral artery and is draining to the superior sagittal sinus.  **B:** Axial CE MR image demonstrating the blood vessels in the nidus of the AVM.  **C and D:** Axial CE MRI/3D TOF MRA fusion images with the arteries in amber and the veins in blue demonstrating a feeding artery (arrow, C) and a draining vein (arrow, D). The large central region of low signal in the MR image is an embolized nidus, thus accounting for the paucity of amber vessels in that region.
cannot be used for coregistration with stereotactic neuronavigational software. Recent advances in 3D angiography permit the construction of 3D data sets that may allow for the incorporation of these data into modern neuronavigational systems; however, the time required for image acquisition results in mixed arterial and venous opacification.

Magnetic resonance angiography has been shown to be a noninvasive alternative to conventional angiography in some applications, with a high degree of diagnostic accuracy. The use of MRA for targeting and subsequent follow-up of microneurosurgically treated AVMs has been reported by a number of investigators. Others have confirmed the value of MRA in defining vascular and parenchymal anatomy for AVM radiosurgery, particularly in patients who have not had prior embolization or surgery and who have compact, medium-size nidus. Bednarz et al. have demonstrated that combining 3D TOF MRA and stereotactic angiography increased the accuracy of AVM radiosurgery and allowed for optimal dose planning. In addition, Peteret et al. prospectively evaluated 21 AVMs using TOF and phase-contrast MRA and angiography. They concluded that MRA was equal or superior to angiography for flow velocity quantification and visualization of the nidus, with a failure rate of 9.5%. Kondziolka et al. compared stereotactic angiography and stereotactic MRA in 28 patients with AVMs. They reported that in 16 cases MRA revealed 3D features that were not apparent on 2D angiograms alone.

The value of MRI-based techniques can be enhanced by harnessing the power of image fusion to combine different sequences. Several groups have used this method to improve the diagnostic and targeting accuracy of MRI-based techniques. Nasel has described fusing 3D TOF MRA and T2-weighted MRI scans in 10 consecutive patients with cerebrovascular pathology. He achieved excellent visualization of wall and luminal aspects of the intracranial segments of the internal carotid artery; the vertebrobasilar system; and the anterior, middle, and posterior cerebral arteries. In addition, McGee and associates fused 3D TOF MRA and CE MRI studies in the treatment planning for cerebral AVMs with Gamma Knife surgery. They demonstrated spatial distortion of less than 1 mm when fusing the image sets and thus supported the feasibility of this technique in radiotherapy planning. However, prior to this study, there had not been a study demonstrating the feasibility and utility of fusing different MRI sequences in stereotactic intraoperative navigation during AVM microsurgery. In the current study, we demonstrated the feasibility of using images acquired in a single preoperative setting to show all 3 vascular components of an AVM, while allowing real-time correlation and intraoperative navigation. Differentiation between the feeding arteries and draining veins is possible using this MRI fusion technique and is invaluable during microsurgical resection. The use of different colors for the arteries and veins allows the surgeon to easily recognize the vessels and correlate their location in the tissue in real time.

In addition, embolic materials used in preoperative embolization of AVMs (for example, Onyx and N-butyl cyanoacrylate) contain tantalum or Ethiodol, and these materials create significant artifact on CTA studies. Such studies often are too distorted by artifact to use in intraoperative navigation for precise localization. Magnetic resonance images demonstrate minimal artifact from embolic material and appear to be an optimal technique for intraoperative navigation.

Intraoperative navigation relying on this technique has some limitations. The MRI acquisition of images is at risk for distortion, related to susceptibility differences at tissue-air interfaces, patient movement, and the presence of metallic objects or chemical shift effects. The use of high-bandwidth pulse sequences and fat-suppression techniques can at times reduce these effects. Long scanning times may be another relative disadvantage.

Conclusions

Precise anatomical localization, as well as the ability to differentiate between arteries and veins during AVM microsurgery, is feasible with the described MRI/MRA fusion technique, which provides important information that benefits preoperative planning, intraoperative navigation, and successful resection of AVMs. The proposed overlay technique offers high-resolution imaging with 3D evaluation of cerebral vessels and appears to be a promising aid to AVM microsurgery.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Erkmen, Bekelis. Acquisition of data: Erkmen, Bekelis, Desai, Eskey. Analysis and interpretation of data: Erkmen, Bekelis, Missios, Desai. Drafting the article: Bekelis, Missios. Critically revising the article: all authors. Study supervision: Erkmen.

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