Clinical Experience with Intraoperative Ultrasonographic Image in Microsurgical Resection of Cerebral Arteriovenous Malformations

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■ BACKGROUND: **Intraoperative ultrasonography is widely used in neurosurgery for the management of intracerebral hematoma and brain tumor. However, the clinical value of this method in the surgery of cerebral arteriovenous malformations (AVMs) has not been reported. In this study, the application of intraoperative ultrasonography for AVM surgery was evaluated prospectively.**

■ METHODS: **This prospective clinical study comprised 41 patients who underwent microsurgical resection of cerebral AVMs at our institute. After routine craniotomy, ultrasonographic imaging with color Doppler ultrasonography and real-time contrast-enhanced ultrasonographic angiography if necessary were applied as navigated images on the monitor during the operation.**

■ RESULTS: **Ultrasonographic imaging made it easier to understand the vascular architecture during the operation. Color Doppler flow imaging clearly delineated the shape and margin of the AVMs. Intraoperative real-time contrast-enhanced ultrasonographic angiography enabled the surgeons to categorically identify AVM feeders both on the surface and deep in the tissue.**

■ CONCLUSIONS: **Microneurosurgery with intraoperative ultrasonographic image guidance was a safe, effective, and reliable method for identifying the afferent and efferent vessels and for confirming the complete resection of AVMs. These benefits of image-guided microsurgery were mostly apparent for deep-seated AVMs that were not visible on the surface of the brain.**

INTRODUCTION

Cerebral arteriovenous malformations (AVMs) are a relatively rare condition encountered in neurosurgical practice. Although the last 20 years have witnessed remarkable developments in microneurosurgery and imaging techniques,[1-3] intracranial AVM remains one of the most challenging lesions for neurosurgeons.[4] Image guidance has dramatically improved the safety and efficacy of many cranial operations. Imaging techniques using cerebral digital subtraction angiography (DSA), magnetic resonance imaging (MRI), or navigated three-dimensional (3D) ultrasonographic angiography offer perfect visualization of the vascular anatomy, but mainly for preoperative planning.[5-7] Vascular anatomic information cannot be transferred to the intraoperative situation directly. Therefore, real-time intraoperative ultrasonography would be more helpful in the surgical resection of brain lesions.[8]

Microsurgical treatment of AVMs is based on identification of the pathologic vessels, followed by careful dissection of feeding arteries.[9] In this study, we applied color Doppler ultrasonography and ultrasonographic contrast agent—specific imaging to identify the afferent and efferent vessels and to confirm the complete resection of AVMs. The advantages of image-guided resection of cerebrovascular lesions have been previously reported.[10-12] Shorter time for operation, smaller craniotomies, and smaller amounts of intraoperative blood loss have been discussed as benefits of computer-assisted microsurgical treatment of AVMs. In this article, we describe our experiences of intraoperative ultrasonographic image-guided microsurgery for cerebral AVMs and test the benefits and limitations of this technology.

PATIENTS AND METHODS

Patients

We recruited 41 patients, who presented with clinical symptoms and/or computed tomography or MRI findings that were

Key words
- Arteriovenous malformation
- Intraoperative ultrasonography
- Neuronavigation

Abbreviations and Acronyms
3D: Three-dimensional
AVM: Arteriovenous malformation
DSA: Digital subtraction angiography
MRA: Magnetic resonance angiography
MRI: Magnetic resonance imaging

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suggestive of cerebral AVMs and subsequently confirmed by cerebral DSA between September 2003 and December 2012. There were 21 males and 20 females with age range from 16 to 55 years (average, 34 years). The clinical signs and symptoms included seizures ($n = 13$), neurologic deficits ($n = 11$), headache ($n = 10$), and intracranial hemorrhage ($n = 5$). The other 2 patients were asymptomatic, but the diagnosis of AVM was made incidentally. Five of them had undergone preoperative endovascular embolization. The Spetzler-Martin AVM grading system indicated grade II for 20 patients, grade III for 18 patients, and grade IV for 3 patients. Informed consent was obtained from each patient.

Imaging Technique

The incision sites were planned by classic neuronavigation in 26 patients, whereas bone flaps in the other 15 patients were outlined based on the information obtained from MRI and magnetic resonance angiography (MRA). The MRI and MRA scans were transferred to the neuronavigation workstation for processing by data transfer via intranet. Image-to-patient registration was performed using anatomic landmarks. In the workstation, magnetization-prepared rapid gradient-echo was processed to create 3D reconstructed images for surgical planning and intraoperative image guidance. After the craniotomy, a color Doppler ultrasonographic (Siemens Acuson Sequoia 512, Germany) angiogram was acquired before and after opening the dura, which was achieved by tilting and moving the probe over the area of interest. Depth of focus, pulse repetition frequency, color gain, and image persistence in each patient were obtained. The depth, size, and flow characters of the AVMs could be generally determined using this technique combined with preoperative imaging studies, including DSA and MRI. In some cases, it was challenging to locate deep feeders of the large or deep-seated AVMs. Real-time contrast-enhanced ultrasonographic angiography was applied to the virtual indicator to find the direction and the distance of the deep-seated feeders in 25 patients. The contrast agent SonoVue (Bracco, Milan) was injected intravenously. The Doppler settings were switched to contrast agent—specific imaging mode by using the pulse-inversion harmonic imaging technique (frequency, 1.5 MHz; mechanical index, 0.20). The real-time microbubble perfusion process was observed to identify the feeding arteries and draining veins of the AVM in a single cross section. The so-called burst-refill technique was used to sweep the lesion in multiple sections and orientations to obtain information on the surrounding vascular anatomy.[13] All intraoperative ultrasonography examinations were performed by 1 of 3 radiologists using high-resolution sonographic equipment (Acuson Sequoia 512).

RESULTS

Intraoperative ultrasonography produced high-quality images in all patients (Figure 1). Color Doppler flow imaging clearly delineated the shape and margin of the AVMs. Approximate positions of feeding arteries and draining veins could be determined from information obtained using intraoperative color Doppler ultrasonography and preoperative imaging (Figure 2). However, it was sometimes difficult to differentiate between feeding arteries and surrounding normal arteries by using this method alone. Contrast agent—specific imaging with secondary harmonic imaging showed blood flow and the perfusion process in vessels in real time. Using contrast-enhanced intraoperative Doppler sonography to generate ultrasonographic images, the perfused parts of an angiography-confirmed AVM were observed as a hyperechoic area. The main feeder and its relationship with the nidus were well detected by sonography (Figure 3). The arterial pulsation of the feeder was visible. Compared with preoperative DSA and MRI, the main feeding arteries of the AVMs were depicted more clearly. This feature was particularly helpful, because the intraoperative navigational identification of surgical planes leads to minimal exploration into the nidus or dissection at a greater distance from the malformation. After dissection, identification, and clipping of the feeders, the nidus was dissected, the veins were clipped, and the whole AVM was removed from the operation cavity. Intraoperative ultrasonographic angiography was also helpful to detect residual AVM. In 2 patients, intraoperative ultrasonographic angiography showed residual AVM, which was subsequently removed. The exact numbers and proportion of the patients in which ultrasonography allowed identification were as follows: 1) shapes of the AVM were clearly indicated in each patient; 2) in 25 patients who underwent contrast-enhanced ultrasonography, feeders were found in 23, which was confirmed by DSA; among them, 2 feeders were indicated by DSA in 6 patients, whereas only 1 feeder was found during operation; 3) the normal arteries were confirmed during surgery and kept; 4) there were 1 or 2 draining veins in each patient; 5) a residual portion was found in 2 patients who underwent ultrasonography.

Postoperatively, systolic arterial blood pressure was kept less than 120—140 mm Hg for 48 hours to decrease the risk of perfusion breakthrough phenomena. No surgical complications occurred and clinical outcomes were excellent. A postoperative angiogram was obtained after 6 months for all patients. All AVMs were radically removed without new permanent morbidity.

DISCUSSION

Although endovascular embolization and stereotactic radiosurgery were used to treat AVMs,[14,15] microsurgery remains the mainstay of AVM treatment.[16] AVM surgery, which is often more complex than expected, has benefited from neuroimaging guidance and intraoperative monitoring techniques. Although navigation technology has revolutionized many aspects of neurosurgery, brain shifts that occur when opening the patient's cranium and during the resection of AVMs remain a serious limitation.[17] Intraoperative imaging is therefore important to allow for navigation based on updated images and to offer the possibility of observing the immediate effects of surgery for quality control.[18] Neurosurgeons require key anatomic details of AVMs seated within the brain parenchyma to facilitate surgical excision and minimize surgery risks. These details include location of the main body of the AVM in relation to the craniotomy, the size of the AVM, its relation with the brain parenchyma, perilesional changes, location of feeding arteries, and any accompanying lesions related to the AVM. The advantage of using updated ultrasonographic images for navigation is the topicality of the data. By recording real-time imaging data intraoperatively, AVMs and additional findings are localized directly and are ready for