ORIGIINAL RESEARCH

Evaluation of cerebral arteriovenous malformation using ‘dual vessel fusion’ technology

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ABSTRACT

Aim This study explored the value of using a vessel fusion technique for visualizing and evaluating the vessel structure of patients diagnosed with arteriovenous malformations (AVMs).

Materials and methods Ten patients with AVMs supplied by multiple cerebral arteries were investigated. The three-dimensional structure of the AVM nidus, feeding arteries, and draining veins were reconstructed from rotational angiographic images and then displayed on a single image in a fused manner.

Results In the vessel fusion image, the tangled cluster of vessels surrounding the AVMs could be clearly visualized in three-dimensional space from a selected optimal viewing angle. Each AVM nidus component with its specific feeding arteries and venous drainage could be accurately identified.

Conclusions The vessel fusion technique offered detailed anatomical information that enabled clinicians to better understand the AVM structure, which helped with treatment planning.

INTRODUCTION

Arteriovenous malformations (AVMs) are a type of congenital cerebral vascular disease in which arteries are connected to veins without the intervening capillary networks. Due to the absence of a capillary bed, high pressure arterial blood flows directly into the low pressure venous system, which may result in brain hemorrhage.1–3

There are currently several imaging techniques for diagnosing AVMs in clinics, such as CT, MRI, noninvasive CT, and MR angiograms. However, these techniques are limited either by providing inadequate imaging information or by their low spatial resolution.4–8 Cerebral DSA, with a resolution of 0.1–0.2 mm,8 is considered the ‘gold standard’ for diagnosing AVMs. This technique involves placing a catheter through a large artery, such as the femoral artery, and then moving it to the neck. Next, radio-opaque contrast medium (CM) is injected via a catheter to highlight the cerebral arteries of interest. At the same time, two-dimensional x-ray images are acquired for clinical observation. Conventionally, the two-dimensional DSA images provide structural information of the AVM nidus component supplied by one feeding artery each time (eg, carotid or vertebral artery). Larger and more complex AVMs may derive their blood supply from multiple arteries. In these cases, several DSA sequences are required in order to visualize each component of the AVM nidus. Attempts have been made to achieve an entirely two-dimensional visualization of the large AVM nidus with multiple feeding arteries simultaneously.9

However, the AVM nidus is composed of a complex tangled cluster of vessels varying in three-dimensional space. Therefore, with only limited projection angles and the nature of being unable to extract mutual relationships of the vasculature in three dimensions, accurate assessment of AVMs via two-dimensional DSA images alone is not guaranteed, which potentially results in treatment failure.11–13 It has been suggested that three-dimensional AVM volume reconstructions have overcome the limitations of two-dimensional imaging, including false vessel foreshortening due to inappropriate projection angle and vessel obscuration due to overlying vessels. Attempts have been successfully made to combine the advantages by merging the images from different imaging modalities (eg, CT and three-dimensional angiography) for navigating surgical resection of AVMs.14

In this study, the feasibility of using the vessel fusion technique for assisting AVM diagnosis was investigated. This technique offered more comprehensive information and enabled a better understanding of the AVM anatomy, leading to a more accurate diagnosis and reliable treatment planning.

MATERIALS AND METHODS

Patient selection

Ten consecutive patients (nine men and one woman) with cerebral AVMs were included in the study. Detailed diagnostic information on each patient is listed in table 1. This study was approved by the hospital ethics committee.

Image acquisition

During the imaging procedure, patients were stabilized under local anesthesia, and selective cerebral angiography with a transfemoral approach was performed for the bilateral internal carotid arteries (ICAs) and vertebral arteries (VAs) in a sequential manner. To obtain three-dimensional vasculature of the AVMs, dual rotational x-ray angiography (Artis zee Biplane, VC14, 30 cm×40 cm flat panel detector, Siemens Healthcare, Germany) was performed. To this aim, a three-dimensional mask image was acquired first. CM (300 mgI/mL) was then injected into each detected AVM feeding artery by a power injector (150 psi) at injection rates of 3 mL/s and 2.5 mL/s for the ICAs and VAs,
respectively, for a duration of 6 s. The x-ray was delayed for 1 s after CM injection was started in order to ensure that the vessels were fully contrasted during image acquisition. The C arm rotated by 200° in 5 s at a speed of 1.5°/frame and with an x-ray dose of 0.36 μGy/frame. As an output, a total of 133 projection images were generated for each three-dimensional acquisition.

Vessel fusion technique

As the first step of vessel fusion, all of the raw projection image data in Dicom format were transferred to a dedicated commercial workstation (syngo Leonardo XWP, VB15, Siemens Healthcare). Advanced techniques (‘dual volume reconstruction’ and ‘syngo inspace 3D/3D fusion’, Siemens Healthcare) have made the workstation capable of automatically reconstructing three-dimensional volume and producing fusion images by combining each volume dataset. Fusion of two image datasets involved using either intensity based automatic registration or visual matching based on manual registration of two sets of three-dimensional angiography pixel data. If the automatic registration result was unsatisfactory, manual registration could be selected as the landmark, and then manual adjustment was performed until the two volumes were superimposed. Once the images were successfully registered, volume rendered fusion images with each individual volume depicted in a different color were generated and displayed to provide intraoperative image guidance.

With this method, the AVM components from different origins and with different drainage patterns could be displayed at the same time. Moreover, the skull could also be integrated by reconstructing one unsubtracted angiographic image dataset and fused with the other subtracted angiographic vessel dataset. The fusion image could be rotated, magnified, and the window and level settings adjusted to achieve optimized visualization.

Correct vessel fusion was determined by evaluating the anatomical relationships of the vasculature. For instance, match of the anterior/posterior communicating artery and draining veins in three-dimensional space could be visually examined. In all cases, an experienced radiologist evaluated the accuracy of the image registration and vessel fusion results.

### RESULTS

Successful vessel fusion was achieved for all patients enrolled in the study. The AVM nidus structure with associated aneurysm, feeding arteries, and draining veins were clearly identified through the generated fusion image. These results and treatment options for each patient are detailed in table 2.

Imaging results from a representative AVM patient (patient No 7) prior to surgical treatment are discussed in this section. Maximum intensity two-dimensional DSA images from two orthogonal projection angles (anteroposterior and lateral) of the left ICA and VA are shown in figure 1. A large AVM with a compact nidus formed at the left temporal parietal occipital lobes was seen. Major arterial feeders from the left middle cerebral artery and posterior cerebral artery (PCA) were identified. The AVM drained into the superior longitudinal sinus through several draining veins. However, small arteries and veins around the nidus were difficult to assess.

Vessel fusion images are able to depict detailed AVM vascular components either individually (figure 2A) or as a combination in one image, including feeding arteries, draining veins, and AVM nidus (figure 2B,C). The fused vessels can also be manipulated to visualize from multiple angles. A perfect docking of the posterior communicating artery and PCA is shown in figure 2B, demonstrating successful fusion of the vessels. It can be seen

### Table 1  Patient diagnostic information

<table>
<thead>
<tr>
<th>Patient No</th>
<th>Age (years)</th>
<th>Clinical symptoms</th>
<th>AVM location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30s</td>
<td>Headache, limb weakness, and numbness</td>
<td>R frontal parietal</td>
</tr>
<tr>
<td>2</td>
<td>30s</td>
<td>Headache and vomiting</td>
<td>L cerebellum</td>
</tr>
<tr>
<td>3</td>
<td>20s</td>
<td>Headache and vomiting</td>
<td>L temporal</td>
</tr>
<tr>
<td>4</td>
<td>50s</td>
<td>Headache and vomiting</td>
<td>R superior cerebellum</td>
</tr>
<tr>
<td>5</td>
<td>50s</td>
<td>Headache, vomiting, and limb weakness</td>
<td>L frontal</td>
</tr>
<tr>
<td>6</td>
<td>20s</td>
<td>Unconsciousness</td>
<td>L temporal parietal</td>
</tr>
<tr>
<td>7</td>
<td>10s</td>
<td>Intermittent headache</td>
<td>L temporal parietal occipital</td>
</tr>
<tr>
<td>8</td>
<td>50s</td>
<td>Headache, vomiting, and unconsciousness</td>
<td>L anterior inferior cerebellum</td>
</tr>
<tr>
<td>9</td>
<td>20s</td>
<td>Seizure and unconsciousness</td>
<td>L frontal parietal</td>
</tr>
<tr>
<td>10</td>
<td>40s</td>
<td>Syncope, headache, and vomiting</td>
<td>L temporal parietal</td>
</tr>
</tbody>
</table>

AVM, arteriovenous malformation.

### Table 2  Clinical findings from fusion images and patients’ treatment options

<table>
<thead>
<tr>
<th>Patient No</th>
<th>Feeding artery</th>
<th>Draining vein</th>
<th>Combined with aneurysm</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R pericallosal and callosomarginal, R PCA and MCA lenticulostriate branches</td>
<td>Straight sinus, longitudinal sinus,</td>
<td>No</td>
<td>Intervention</td>
</tr>
<tr>
<td>2</td>
<td>L SCA</td>
<td>L transverse sinus</td>
<td>Yes</td>
<td>Craniotomy</td>
</tr>
<tr>
<td>3</td>
<td>L MCA</td>
<td>Superior longitudinal sinus, sigmoid sinus</td>
<td>No</td>
<td>Medication</td>
</tr>
<tr>
<td>4</td>
<td>R SCA, AICA and ICA tentorial branch</td>
<td>Transverse sinus</td>
<td>Yes</td>
<td>Craniotomy</td>
</tr>
<tr>
<td>5</td>
<td>L FPA</td>
<td>Longitudinal sinus</td>
<td>Yes</td>
<td>Craniotomy</td>
</tr>
<tr>
<td>6</td>
<td>L ACA and MCA</td>
<td>Superior longitudinal sinus</td>
<td>No</td>
<td>Craniotomy</td>
</tr>
<tr>
<td>7</td>
<td>L PCA and MCA</td>
<td>Superior longitudinal sinus</td>
<td>Yes</td>
<td>Gamma knife</td>
</tr>
<tr>
<td>8</td>
<td>L AICA</td>
<td>Transverse sinus</td>
<td>Yes</td>
<td>Intervention</td>
</tr>
<tr>
<td>9</td>
<td>L MCA and ACA, R ACA</td>
<td>Longitudinal sinus</td>
<td>Yes</td>
<td>Intervention</td>
</tr>
<tr>
<td>10</td>
<td>L MCA artery of central sulcus</td>
<td>Longitudinal sinus</td>
<td>No</td>
<td>Intervention</td>
</tr>
</tbody>
</table>

ACA, anterior cerebral artery; AICA, anterior inferior cerebella artery; FPA, frontopolar artery; ICA, internal carotid artery; MCA, middle cerebral artery; PCA, posterior cerebral artery; SCA, superior cerebella artery.

that the blood supply of the AVM originates from the left ICA and VA, and extends to the left middle cerebral artery and PCA. Blood flow from two different arterial systems join at the AVM nidus and blood is then collected into the superior longitudinal sinus (figure 2B,C). Also, the AVM is associated with an aneurysm located at the top of the nidus. In contrast with two-dimensional DSA images, the complex structure of the AVM nidus with the surrounding small arteries and veins, and their three-dimensional mutual relationships, were clearly and faithfully represented by the fusion images. Thus different blood supplies to the nidus can be easily differentiated. In addition, the skull was fused with the vessels (figure 2D), which offer a comprehensive representation of the AVM anatomy and provides guidance for surgical resection, such as planning for surgical access, and localization of feeding arteries and draining veins during operation.

DISCUSSION
Accurate imaging information on volume, location, arterial feedings, as well as venous drainage is essential in the diagnostic assessment of AVMs. In most cases, AVMs have multiple feeding arteries and draining veins, and the inner structure of the nidus is divided into several subregions, communicating and fusing with each other. Conventionally, clinicians evaluate the complex structure of the AVM based on two-dimensional DSA findings, which provide only limited anatomic information.

In this study, we proved that an accurate presentation of the AVM could be achieved using a vessel fusion technique, which essentially eliminates the inherent limitations of using two-dimensional DSA to evaluate the complex three-dimensional structure of AVMs. During rotational angiography, dual volumes of image datasets were obtained by the C arm rotating around the patient twice to acquire the projection images, including a mask run without CM followed by the angiographic run with CM in the vessel. The volumes of mask comprised primarily of bones and subtracted angiographic vessel can be then reconstructed, registered, fused, and displayed in different colors simultaneously for visualization on one working window using a volume rendering technique.17

The successful vessel fusion results and its advantages over conventional two-dimensional DSA images were demonstrated by the representative patient case. The resulting reconstructed three-dimensional vasculature consists of volumetric representations of two different feeding arteries, AVM nidus, and small arteries and veins, with detailed structures clearly identified. This helps to minimize the inaccuracies induced by visually examining several separate two-dimensional DSA sequences in an effort to obtain a whole image of the AVM structure. The

Figure 1  DSA presentation with anteroposterior view and lateral view for AVM from left ICA (A, B), and for AVM from left VA, showing that feeding vessel originates from left PCA (C, D).
skull is also presented in the fused image, which provides sufficient confidence to plan a surgical or interventional treatment. The limitation of this technique should also be mentioned. With local anesthesia, there could be an element of patient motion artifact which limits the use of three-dimensional registration. Therefore, during the imaging procedure, a standardized three-dimensional image acquisition protocol is the key factor for generating an accurate vessel fusion image. All parameters of the rotational angiographic system should be kept as consistent as possible, such as the source image distance, volume of interest position, and zoom format, etc. Throughout multiple three-dimensional image acquisitions for different arteries, the patient should be stabilized to minimize motion induced inaccuracies, such as motion artifacts, and volume misalignment during registration. For post-processing, the window setting should also be selected in the same range. Otherwise, accurate fusion of vessels from different origins can be technically challenging.

CONCLUSION
The vessel fusion image can depict AVM components in three-dimensional space, and thus provides a comprehensive presentation of AVM anatomy, delineates the number and origins of different feeding arteries and draining veins, and displays the complex vessel interconnections. The vessel fusion technique has the potential to make a significant contribution towards facilitating a better understanding of the pathological characteristics for clinicians, which is essential for successful treatment planning as well as helping to improve treatment effects and efficacy.


Competing interests None.

Ethics approval The study was approved by the Wuhan General Hospital of Guangzhou Military Command, PLA.

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