Application of 4-Dimensional Digital Subtraction Angiography for Dural Arteriovenous Fistulas

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■ BACKGROUND: **Three-dimensional reconstruction of digital subtraction angiography (3D-DSA) is a useful imaging modality for assessing complex cerebrovascular lesions. However, due to the importance of flow over time in certain vascular lesions, 3D-DSA is of less value as it lacks the temporal resolution. Dural arteriovenous fistulas (AVFs) are complex lesions in which an arteriovenous shunt exists between meningeal arteries and a dural venous sinus or cortical vein. Traditional 2D-DSA, especially with superselective injections of feeding arteries, is currently the gold standard for assessment, but overlapping of opacified vessels can complicate interpretation. A novel imaging technique, 4D-DSA, merges 3D reconstructions of multiple temporal series. It offers a unique perspective on complex cerebrovascular lesions and may offer several advantages in the assessment of dural AVF.**

■ METHODS: **4D-DSA images were acquired in 5 patients who presented with dural AVFs. All relevant clinical data, imaging, and procedural/operative reports were reviewed retrospectively. 4D-DSA images were reconstructed on a separate 3D workstation and compared to 2D and 3D-DSA images in an offline fashion.**

■ RESULTS: **In all 5 cases, 4D-DSA proved to be useful in lesion assessment and treatment planning. This included observation ($n = 2$), microsurgery ($n = 1$), and endovascular embolization ($n = 2$).**

■ CONCLUSIONS: **In the small series of patients in which it has been evaluated, 4D-DSA offers several advantages in assessing dural AVFs. The ability to see and manipulate feeding arteries in 3D combined with temporal resolution was useful in assessment and treatment planning. Continued experience with this imaging technique will be needed to identify its optimal use.**

INTRODUCTION

Dural arteriovenous fistulas (AVFs) are the second most common cerebrovascular malformation with arteriovenous shunting. They are acquired lesions and arise most commonly near dural venous sinuses, especially near the transverse-sigmoid sinus junction. The abnormal arteriovenous shunt connects dural arteries to dural venous sinuses and/or cortical veins. They can commonly present with pulsatile tinnitus due to their proximity to the middle ear, if not initially with hemorrhage or seizures. The natural history of AVFs is the largely dependent on the presence of cortical venous reflux, as incorporated into the Borden et al[1] and the Cognard et al[2] classifications.[3-5] Dural arteries flow through a fistula pouch and arterialized vein, all of which must be fully addressed in treatment. Cross-sectional imaging, such as computerized tomography angiogram or magnetic resonance angiogram, is useful in understanding the surrounding parenchyma or relationship to the skull base, but provides little to no information about the flow characteristics of the lesion or its angioarchitecture. Thus, DSA has been the imaging modality of choice to evaluate these lesions.[6]

The utility of 3-dimensional (3D) reconstruction of cerebral digital subtractionangiography (DSA) for assessment of cerebrovascular

Key words
- 3D angiography
- 4D
- Digital subtraction angiogram
- Dural arteriovenous fistula

Abbreviations and Acronyms
2D: 2-dimensional
3D: 3-dimensional
4D: 4-dimensional
AVF: Arteriovenous fistula
CT: Computerized tomography
DSA: Digital subtraction angiography
MRI: Magnetic resonance imaging
OA: Occipital artery
VA: Vertebral artery

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pathologies has been substantial.[7,8] Although 3D-DSA provides useful volumetric anatomic information, it does not show the variability of flow over time and thus is of lesser utility in lesions where the time phase (early arterial to late venous) is important, notably AVFs and arteriovenous malformations. These lesions, often with feeders from multiple arterial distributions, can also benefit from dual-volume 3D-DSA.[7] As noted by Davis et al,[9] the need for multiple 2-dimensional (2D) temporal series or multiple 3D-DSA images increases procedural morbidity due to increased radiation exposure and contrast load.

Recently, Sandoval-Garcia et al.[10,11] presented the 4-dimensional (4D) DSA[9] technique and established its utility in the management of arteriovenous malformations, a pathology in which the time "dimension" of angiography is paramount in evaluation. This 4D-DSA imaging technique allows for visualization of a series of volumetric anatomic images (3D-DSA) across time as the contrast bolus is opacifying the vessels. The 4D-DSA imaging technique is similar to conventional 3D-DSA image acquisition and can be acquired without additional contrast administration or radiation exposure. Furthermore, the 4D reconstruction technique encodes temporal information into volumetric data using the information from individual projection images during acquisition and can create a series of fully time-resolved 3D-DSA images with a frame rate of $\leq$30 frames per second.[11]

In the present study we investigate the use of 4D-DSA as an adjunct in the evaluation of AVFs. The high flow nature of AVFs make them ideally suited for resolving the temporal aspects of the vasculature proximal to, within, and distal to the lesion. 3D-DSA, on the other hand, consists of arterial and venous structures in the same post-processed image, making it of less utility and requiring increased reliance on 2D-DSA images.

METHODS

4D-DSA images were acquired in 5 consecutive patients with AVFs under an institution-approved protocol. All relevant clinical data, imaging, and procedural/operative reports were reviewed retrospectively.

Procedures

All cerebral angiographic studies and cerebrovascular interventions were performed at Baylor St. Luke's Medical Center in Houston, TX, after obtaining appropriate consents. Cerebrovascular surgical procedures, as well as angiography procedures, were performed using established techniques.

Image Acquisition

Routine 2D and 3D-DSA images were acquired in all 5 patients. Three-dimensional DSA images were acquired using a 5-second DSA Head protocol on a Siemens flat-panel C-arm angiography system (Artis Zee bi-plane, VC21, Siemens Angiography, Forchheim, Germany). During the 200-degree rotation, projection X-ray images were acquired before (mask acquisition) and after contrast injection (fill acquisition). 3D digitally subtracted images were automatically reconstructed and visualized as volume-rendered images using a dedicated clinical 3D workstation. Where needed, a 3D subtraction reconstruction algorithm with motion correction was applied to correct for misalignments between mask and fill acquisitions. For the 3D-DSA acquisition, 18 mL of undiluted contrast agent (Omnipaque 300 mg/mL; GE Healthcare, Little Chalfont, Buckinghamshire, UK) was power-injected at a rate of 2.5 mL/sec at a maximum of 800 psi with a 2-second X-ray delay. In cases where evaluation of a lesion with dual vascular supply was required (those highlighted in this report), separate 3D-DSA images were acquired with selective injection of contrast into each parent vessel.

4D-DSA images in this article were acquired using a 6-second DSA 260-degree Head protocol (Siemens Angiography). During the 260-degree acquisition, both mask and fill acquisitions were acquired, each consisting of 172 projection images. For 4D-DSA image acquisition, we used 14–17 mL of undiluted contrast agent at a rate of 2.5–3 mL/sec at 800 psi with 0 second X-ray delay and 0.5-second injector delay. The primary differences between 4D-DSA and 3D-DSA acquisitions are: 1) 4D-DSA acquisition uses a longer acquisition protocol (1 second longer) and larger angular coverage (260 degrees vs. 200 degrees) to capture temporal information, 2) 4D-DSA acquisition captures contrast arrival into the arteries and veins (0-second X-ray delay) as opposed to steady state imaging in 3D-DSA acquisition (2-second X-ray delay).

Post-Processing Image Reconstruction

3D-DSA images were reconstructed on the clinical workstation during the study. 4D-DSA acquisitions were transferred to a research 3D workstation (*syngo* X-workplace VB21, Siemens Angiography, Forchheim, Germany) and reconstructed offline at a later time using a 4D-DSA reconstruction prototype software. With this prototype, an initial 3D volume known as constraint volume depicting the geometry of the vessels is reconstructed first. The temporal information for any pixel in the constraint volume is derived from the individual projection image in the original acquisition and is encoded into the constraint volume to create several time-resolved 3D-DSA volumes. These time-resolved 3D volumes constitute 4D DSA reconstruction data and can be viewed and manipulated like 3D-DSA images at any time point or can be visualized along time axis to depict the flow information like in 2D-DSA images. This final set of time-resolved 3D images (4D-DSA) was then used for evaluation. The software used is commercially available for purchase.

RESULTS

Angiographic and treatment data were available for 5 patients, mean age 57.2 years (range, 50–64 years). Four patients were women and 1 was a man. Of the 5 patients diagnosed, 2 received endovascular Onyx embolization and 1 was treated surgically. Endovascular embolization was attempted and aborted in 1 other patient. Dural AVFs were categorized according to the Cognard classification: 1 type I, 1 type 2a, 3 type IV were diagnosed. Two lesions had hemorrhaged on presentation.

Illustrative Cases

Case 1. A right-handed patient with a past medical history of hypertension presented with severe headache. Computerized tomography (CT) of the brain showed left parietal intraparenchymal hemorrhage with intraventricular and subdural extension. Follow-up magnetic resonance imaging (MRI) revealed