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Evaluation of Intracranial Dural Arteriovenous Fistulas: Comparison of Unenhanced 3T 3D Time-of-flight MR Angiography with Digital Subtraction Angiography

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Purpose: We compared gross characterization of intracranial dural arteriovenous fistulas (DAVFs) between unenhanced 3-tesla 3-dimensional (3D) time-of-flight (TOF) magnetic resonance angiography (MRA) and digital subtraction angiography (DSA).

Methods: We subjected 26 consecutive patients with intracranial DAVF to unenhanced 3T 3D TOF MRA and to DSA. Two independent sets of observers inspected the main arterial feeders, fistula site, and venous drainage pattern on MRA and DSA images. Inter-observer and intermodality agreements were assessed by κ statistics.

Results: Interobserver agreement was excellent for fistula site ($\kappa = 0.919$; 95% confidence interval [CI], 0.805 to 1.000), good for main arterial feeders ($\kappa = 0.711$; 95% CI, 0.483 to 0.984), and very good for venous drainage ($\kappa = 0.900$; 95% CI, 0.766 to 1.000). Intermodality agreement was excellent for fistula site ($\kappa = 0.968$; 95% CI, 0.906 to 1.000) and good for main arterial feeder ($\kappa = 0.809$; 95% CI, 0.598 to 1.000) and venous drainage ($\kappa = 0.837$; 95% CI, 0.660 to 1.000).

Conclusion: Gross characterization of intracranial DAVF was similar for both imaging modalities, but unenhanced 3T 3D TOF MRA cannot replace DSA.

Keywords: *digital subtraction angiography, intracranial dural arteriovenous fistula, magnetic resonance angiography, 3T*

Introduction

Intracranial dural arteriovenous fistulas (DAVFs) are abnormal shunts between dural arteries and the dural venous sinus and meningeal or cortical veins. They comprise about 10 to 15% of all intracranial vascular malformations.^{1,2} Their pathogenesis has been explained variously,²⁻⁴ and they are thought to be sequelae of venous thrombosis or occlusion that leads to venous hypertension.^{3,4} Although DAVFs can arise anywhere within the dura mater, the most frequent sites are the transverse-sigmoid

and cavernous sinuses. DAVFs with cortical venous drainage carry an increased annual mortality risk of 10.4%; the risk is increased 8.1% for intracranial hemorrhage and 6.9% for non-hemorrhagic neurologic deficits.⁵ Risk factors for intracranial hemorrhage include shunt location (e.g., transverse-sigmoid sinus, superior sagittal sinus, tentorium, anterior cranial fossa, and craniocervical junction), cortical venous drainage, and varix.⁶ On the other hand, the disease course of a cranial DAVF without cortical venous drainage is benign. Observation or palliative treatment has resulted in a benign and tolerable level of disease in 98.5% of cases.⁷

Intra-arterial digital subtraction angiography (DSA) is the standard of reference for the diagnosis

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of DAVFs. Its high spatial and temporal resolution facilitate the accurate analysis of feeders, venous drainage, and fistula sites. However, DSA is invasive and not without possible complications; morbidity of 0.03% and mortality of 0.06% have been reported for patients undergoing diagnostic cerebral angiography.^{8,9} The requirement of injection of iodinated contrast material for DSA exposes patients and medical staff to radiation and precludes its use in patients allergic to these materials. Therefore, a noninvasive, reliable method is needed for the appropriate selection of patients with DAVF with high risk (aggressive symptoms) and the exclusion of patients with DAVF considered benign.

Unenhanced 3-dimensional (3D) time-of-flight (TOF) magnetic resonance angiography (MRA) is a noninvasive technique that does not require contrast material and that is useful for the diagnosis of intracranial DAVFs.^{1,10–14} Its source images yield flow and anatomic information at high spatial resolution. However, the diagnostic ability of unenhanced 3D TOF MRA at 1.5T for intracranial DAVFs is limited compared with that of DSA.^{1,10–14} Potential advantages of 3D TOF MRA at 3T compared to 1.5T^{15–19} include high signal-to-noise ratio (SNR) and prolonged T_1 -weighted relaxation times that improve contrast between vessel and tissue and acquisition of MRA images of high quality and high spatial resolution. Consequently, 3T 3D TOF MRA can be expected to provide precise information regarding the fistula site, arterial feeders, and venous drainage of DAVFs.

To our knowledge, there are no systematic studies on the reliability of unenhanced 3T 3D TOF MRA for assessing feeders, fistula sites, and venous drainage of DAVFs. In this study, we compared gross characterization of intracranial DAVFs between unenhanced 3T 3D TOF MRA and DSA.

Materials and Methods

Study population

Our institutional review board approved this study, and written informed consent was obtained from all patients or their legal representatives prior to imaging studies. Our study included 26 consecutive patients (12 women, 14 men) aged 35 to 76 years (mean, 60 years) with intracranial DAVF who underwent 3T 3D TOF MRA and intra-arterial DSA between 1 July 2007 and 29 February 2012.

MR imaging

All patients were scanned with a 3T scanner (Achieva 3T; Philips Medical Systems, Best, The Netherlands) using 8-channel head coils. Imaging

included 3-plane scout localizers, axial spin-echo T_1 -weighted images (repetition time [TR]/echo time [TE]/number of signal-intensity acquisitions [NSA], 450 ms/10 ms/one; matrix, 320×320), turbo spin-echo T_2 -weighted images (TR/TE/NSA, 4060 ms/80 ms/one; turbo factor, 9; matrix, 512×512), fluid-attenuated inversion recovery (FLAIR) images (TR/TE/NSA/inversion time [TI], 9000 ms/120 ms/one/2500 ms; turbo factor, 15; matrix, 352×352), and 3D TOF MRA images.

We first identified 5 slabs for 3D TOF MRA on a sagittal scout image. Parameters were TR/TE/NSA, 20 ms/3.5 ms/one; 20° flip angle; field of view (FOV), 20×20 cm, matrix, 512×512 ; voxel size, $0.39 \times 0.39 \times 1.0$ mm (reconstructed voxel size $0.25 \times 0.25 \times 0.5$ mm); parallel imaging factor, 2; and acquisition time, 4 minutes 48 seconds. Cephalad saturation pulses were applied to eliminate signals of venous blood. When the DAVF was located at the top of the head, we added another MRA slab using the same parameters. To create 3D displays of the MRA images, we used maximum-intensity-projection (MIP) and partial MIP techniques.

DSA technique

An experienced neuroradiologist and/or a neurosurgeon performed diagnostic biplanar intra-arterial DSA (Allura Xper FD; Philips Medical Systems, Best, The Netherlands) after catheterization of the internal and external carotid and vertebral arteries via a femoral artery approach. The images were obtained with a matrix of 2048×2048 and FOV of 17 cm. The temporal resolution of the images was 3 frames/second. We manually injected a 6- to 10-mL bolus of undiluted iodinated contrast material with an iodine concentration of 300 mg/mL (Iopamidol, Iopamiron 300; Bayer-Schering, Berlin, Germany) for each projection. As a rule, DSA was performed within 7 days of 3D TOF MRA.

Image analysis

By consensus, 2 readers with 21 and 23 years of experience in neuroangiography (Readers 1 and 2) evaluated the entire series of DSA images on a PACS workstation. Two different readers with 18 and 19 years of experience in diagnostic MR neuroimaging, who were blinded to clinical information and DSA results, independently evaluated the 3T MRA data on a PACS workstation. The 3D, MPR, and MRA source images were displayed with all regions visible in each case. The use of software permitted the readers to arrange the regions of special interest at will in any given spatial orientation.

We assessed data of 3T MRA and DSA for fistula

Table 1. Summary of Patients and Dural Arteriovenous Fistulas (DAVFs)

Case No.	Age	Sex	Symptom	Fistula site	Main feeder	Venous drainage*
1	57	F	Exophthalmos	CS	MMA	Type 1
2	70	F	Diplopia	CS	MMA	Type 1
3	75	F	Diplopia	CS	MMA	Type 1
4	60	F	Headache	CS	FRA	Type 1
5	71	M	Diplopia	CS	FRA	Type 1
6	62	F	Chemosis	CS	AMA	Type 1
7	37	F	Headache	CS	AMA	Type 1
8	60	F	Headache	CS	AphA	Type 1
9	71	F	Diplopia	CS	MMA	Type 2
10	76	M	Chemosis	CS	MMA	Type 2
11	49	F	Chemosis	CS	MMA	Type 2
12	72	F	Chemosis	CS	FRA	Type 2
13	55	F	Chemosis	CS	AphA	Type 2
14	63	M	Bruit	TS	OA	Type 1
15	64	M	Cerebral hemorrhage	TS	OA	Type 2
16	64	M	Chemosis	TS	OA	Type 2
17	53	M	Diplopia	TS	OA	Type 2
18	69	M	Cerebral hemorrhage	TS	OA	Type 2
19	35	M	Diplopia	TS	OA	Type 2
20	55	M	Chemosis	FM	AphA	Type 1
21	59	M	Cerebral hemorrhage	FM	AphA	Type 2
22	64	M	Aphasia	SSS	MMA	Type 2
23	57	F	Cerebral hemorrhage	SSS	MMA	Type 2
24	51	M	Headache	SPS	MMA	Type 3
25	72	M	Dementia	Front	OphA	Type 3
26	45	M	Seizure	Convex	MMA	Type 3

AMA, accessory meningeal artery; AphA, ascending pharyngeal artery; Convex, convexity; CS, cavernous sinus; F, female; FM, sinuses around the foramen magnum; FRA, foramen rotundum artery; Front, frontal skull base; M, male; MMA, middle meningeal artery; OA, occipital artery; OphA, ophthalmic artery; SPS, superior petrosal sinus; SSS, superior sigmoid sinus; TS, transverse-sigmoid sinus junction

*Venous drainage of DAVFs directly into the dural venous sinus was recorded as Type 1; drainage into the dural venous sinus with cortical venous reflux as Type 2; and drainage directly into subarachnoid veins (cortical venous reflux only) as Type 3.¹⁸

site, main arterial feeder, and venous drainage of the DAVF. Recorded fistula sites included the cavernous sinus (CS), transverse-sigmoid sinus (T-S), sinuses around the foramen magnum (FM), superior sigmoid sinus (SSS), and other sites. Main arterial feeders were defined as arterial branches deriving from the middle meningeal artery (MMA), accessory meningeal artery (AMA), foramen rotundum artery (FRA), ascending pharyngeal artery (AphA), occipital artery (OA), or other arteries. When the main feeder among multiple feeders was identified, its vessel caliber was recorded. Venous drainage directly into the dural venous sinus was recorded as Type 1, into the dural venous sinus with cortical venous reflux, as Type 2, and directly

into the subarachnoid veins (cortical venous reflux only), as Type 3, according to the classification of Borden and associates.²⁰ The readers were cognizant of the possibility of false-positive intracranial MRA findings.^{14,21} Inconsistent individual assessments were re-evaluated until a consensus was reached. After the blinded study, the observers, by consensus, looked for the reason(s) for any incorrect interpretations on MRA images, using DSA findings as the gold standard.

Statistical analysis

We determined interobserver agreement between Readers 1 and 2 of the DSA and the MRA images and intermodality agreement between the consen-

sus readings for the MRA and the DSA images with respect to the fistula site, main arterial feeder, and venous drainage by calculating the κ coefficient ($\kappa < 0.20$ = poor; $\kappa = 0.21$ to 0.40 , fair; $\kappa = 0.41$ to 0.60 , moderate; $\kappa = 0.61$ to 0.80 , good; $\kappa = 0.81$ to 0.90 , very good; and $\kappa > 0.90$, excellent agreement). We also recorded the exact number and the percentage of times when the results from the 2 readers and the 2 modalities were in exact agreement, including the 95% CI. A statistical package, MedCalc for Windows (MedCalc Software, Mariakerke, Belgium), was used for all analyses.

Results

Table 1 presents clinical data and summarizes

the DSA and MRA findings of the 26 patients with DAVF. On DSA images, 13 fistulae were located at the CS, six at the T-S, two at the FM, two at the SSS, and three at other sites (Figs. 1–3). In the analysis of fistula site on MRA images, the readers agreed on 24 of the 26 (92%) cases; interobserver agreement was excellent ($\kappa = 0.919$; 95% CI, 0.805 to 1.000) (Table 2). MRA interpretations reached by consensus reading and DSA findings were in agreement in 25 of 26 (96%) cases. Intermodality agreement between DSA and MRA was also excellent ($\kappa = 0.968$; 95% CI, 0.906 to 1.000) (Table 3, Figs. 1–3).

On DSA images, 10 DAVFs were primarily supplied by the MMA, six by the OA, four by the AphA, three by the FRA, two by the AMA, and

Table 2. Interobserver and intermodality agreement for the identification of fistula site, main feeders, and venous drainers

	MRA		Interobserver agreement	MRA*	DSA	Intermodality agreement
	Reader 1	Reader 2				
Fistula site			24/26 (92%)			25/26 (96%)
CS	13	12		12	13	
T-S	6	6		6	6	
FM	2	2		2	2	
SSS	2	2		2	2	
Other sites	3	4		4	3	
Main feeders			21/26 (81%)			23/26 (88%)
MMA	7	8		9	9	
AMA	4	1		2	2	
FRA	3	4		3	4	
AphA	5	6		5	4	
OA	5	4		5	6	
Other feeders	2	3		2	1	
Venous drainers			24/26 (92%)			23/26 (88%)
Type 1	10	11		10	10	
Type 2	12	10		12	13	
Type 3	4	5		4	3	

AMA, accessory meningeal artery; AphA, ascending pharyngeal artery; CS, cavernous sinus; F, female; FM, sinuses around foramen magnum; FRA, foramen rotundum artery; M, male; MMA, middle meningeal artery; MRA, magnetic resonance angiography; OA, occipital artery; SSS, superior sigmoid sinus; TS, transverse-sigmoid sinus

*Consensus reading of the 2 observers

Table 3. Interobserver and intermodality agreement for dural arteriovenous fistulas (DAVF)

	Fistula site	Main feeders	Venous drainage
Interobserver agreement	0.919 (0.805–1.000) ^a	0.711 (0.483–0.984) ^a	0.900 (0.766–1.000) ^a
Intermodality agreement	0.968 (0.906–1.000) ^a	0.809 (0.598–1.000) ^a	0.837 (0.660–1.000) ^a

^aData are κ statistics; 95% confidence intervals (CIs) are in parentheses.

Fig. 1. A 57-year-old woman with a dural arteriovenous fistula (DAVF) at the left cavernous sinus. (A) Digital subtraction angiography (DSA; lateral projection from the left external carotid artery) shows an arteriovenous shunt (arrow) at the left cavernous sinus primarily supplied by branches from the middle meningeal artery (dotted arrow) and draining into the superior orbital vein (arrowheads). The foramen rotundum and accessory meningeal arteries (small arrows) also feed the fistula. Venous drainage is Borden Type 1. (B) Sagittal partial maximum-intensity-projection (MIP) magnetic resonance angiography (MRA) image shows a dilated superior ophthalmic vein (arrowheads) and multiple feeders, including the middle meningeal artery (dotted arrow), and the foramen rotundum and accessory meningeal arteries (small arrows). (C) Axial source image from MRA shows hyperintense spots (arrows), indicating feeders in and around the left cavernous sinus. Hyperintensity is seen in the left cavernous sinus (arrowhead). (D) The axial source image caudal to Fig. 1C reveals apparent dilation of the left middle meningeal artery (arrow) deriving from the foramen spinosum and the left accessory meningeal artery (small arrow) in the foramen ovale. Both readers judged that the main feeder as the middle meningeal artery, the fistula site as the cavernous sinus, and venous drainage as Borden Type 1.

one by another vessel (Table 1, Figs. 1–3). Both readers inspecting 3T MRA images agreed on the main arterial feeder of the DAVF in 21 of 26 (81%) cases; interobserver agreement was recorded as good ($\kappa = 0.711$; 95% CI, 0.483 to 0.984) (Table 2). In 23 of 26 (88%) instances, the findings of 3T MRA reached by consensus and the DSA findings reached independently by the other 2 readers coincided with respect to the main arterial DAVF feeder. Intermodality agreement (3T MRA vs DSA) was very good ($\kappa = 0.809$; 95% CI, 0.598 to 1.000) (Table 3, Figs. 1–3).

On DSA images, venous drainage was recorded as Type 1 in 10 (38%) DAVFs, as Type 2 in 13 (50%), and as Type 3 in three (12%) (Table 1). On

3T MRA images, the readers agreed in 24 of 26 (92%) cases; interobserver agreement was also very good ($\kappa = 0.900$; CI, 0.766 to 1.000) (Table 2). MRA and DSA findings were in agreement in 23 of 26 (88%) cases. Intermodality agreement for venous drainage was very good ($\kappa = 0.837$; 95% CI, 0.660 to 1.000) (Table 3, Figs. 1–3).

Retrospective consensus reviews showed one (4%) incorrect interpretation regarding fistula site, three (12%) regarding main feeder, and three (12%) regarding venous drainage. The misinterpreted fistula site was a small shunt at an unusual location, i.e. the most anterior part of the cavernous sinus. Two feeders were incorrectly interpreted due to their small caliber and a third, because of a selec-

Fig. 2. A 53-year-old man with a dural arteriovenous fistula (DAVF) at the right transverse-sigmoid sinus. (A) Digital subtraction angiography (DSA; lateral projection from the right occipital artery) shows an arteriovenous shunt (arrowhead) at the right transverse-sigmoid sinus primarily supplied by branches from the right occipital artery (arrow) and draining into the cortical veins (circle). The venous drainage is Borden Type 2. (B) Lateral view of maximum-intensity-projection (MIP) magnetic resonance angiography (MRA) shows findings similar to the DSA image in Fig. 2A. An arteriovenous shunt (arrowhead) at the right transverse-sigmoid sinus is mainly fed by branches from the right occipital artery (arrow). Cortical venous drainage is well visualized (circle). (C) Axial source image from MRA shows hyperintense structures (small arrows), indicating feeders in and around the right sigmoid sinus. A dilatation of the right occipital artery (arrow) is observed. (D) The axial source image cranial to Fig. 1C reveals dilated cortical veins (circle) in the right cerebral sulci, indicating cortical venous drainage. Both readers judged that the main feeder was the occipital artery, the fistula site was the transverse-sigmoid sinus, and venous drainage was Borden Type 2.

tion error of the main feeder from among multiple feeders. Venous drainage was incorrectly interpreted due to retrograde cortical venous drainage far distant from the fistula site in 2 cases and as a result of overlapping of the drainage by normal venous structures in a third case.

Discussion

Very good to excellent agreement between 3T MRA and DSA for the diagnosis of DAVF (fistula sites 0.968, 95% CI, 0.906 to 1.000; main feeders 0.809, 95% CI, 0.598 to 1.000; venous drainage 0.837, 95% CI, 0.660 to 1.000) indicated the reliability of unenhanced 3T MRA for gross characterization of DAVFs.

Our 3T MRA protocol offers some benefits over that with 1.5T. The SNR of 3T scanners is approxi-

mately twice that of 1.5T instruments, and the spatial resolution is higher. The increased T_1 relaxation time at 3T facilitates background suppression, further enhances inflow, and yields improved contrast-to-noise ratios.^{16,22} In addition, our MRA sequence combines the multi-slab technique and short TE. Phase dispersions from turbulence or flow saturation from slow flow tend to limit the sensitivity of MRA. Because the multi-slab technique features small voxels and short TEs to minimize intra-voxel phase dispersion, its use minimizes losses in signal intensity due to spin saturation and permits larger imaging volumes.^{23,24} In combination, these techniques yielded high spatial resolution (reconstructed voxel size $0.25 \times 0.25 \times 0.5$ mm), which allowed the depiction of small feeders and venous drainages.

Two of our readers used axial source, MIP, and

Fig. 3. A 72-year-old man with a dural arteriovenous fistula (DAVF) at the right frontal base. (A) Digital subtraction angiography (DSA; lateral projection from the right internal carotid artery) shows an arteriovenous shunt (small arrow) at the frontal base primarily supplied by branches from the right ophthalmic artery (arrow) and draining into the cortical veins (arrowheads). The venous drainage is Borden Type 3. (B) Lateral view of maximum-intensity-projection (MIP) magnetic resonance angiography (MRA) shows dilated cortical veins (arrowheads) contiguous with the right ophthalmic artery (arrow). (C) Axial source image from MRA shows the dilated ophthalmic artery (arrow). A hyperintense structure (small arrow) is seen at the cribriform plate. (D) The axial source image cranial to Fig. 1C reveals dilated cortical veins (circle) in the right frontal sulci, indicating cortical venous drainage. Both readers judged that the main feeder was the ophthalmic artery, the fistula site was the frontal base, and venous drainage was Borden Type 3.

partial MIP MRA images to evaluate vessel structures. Although angiogram-like images are derived from the MIP algorithm, vessels exhibiting lower signal intensity may be lost and small or slow-flowing vessels may not be visualized.²⁵ MRA source images contain both flow and anatomic information. We posit that our display method contributed to the identification of vessel structures on 3T MRA images.

Not all arteries usually visible on DSA were visualized on 3T MRA images. Vessel diameter can be small compared with the voxel size of MRA images, and their spatial resolution is insufficient for their depiction. Our retrospective review with respect to the main feeder indicated that this was true in 2 of 3 incorrectly interpreted cases. On unenhanced 3T MRA images, visualization of vessel structures depends on their orientation relative to

the scan plane. If it is parallel to flowing blood, enhancement may be lost as spins are exposed to saturating radiofrequency pulses. In addition, specific acquisition parameters, e.g., TE and spatial resolution, and vendor specifications of the pulse sequence may have affected our findings. Technical advances, such as the development of 7T MR imaging systems, have led to an increase in the signal-to-noise ratio^{26,27} and may improve visualization of vessel structures on MRA images.

Recent 3T 4-dimensional (4D) MRA techniques, i.e., 4D contrast-enhanced MRA and 4D arterial spin labeling-based MRA, can provide hemodynamic information regarding intracranial DAVFs,^{28–30} but these techniques are not so reliable for assessing arterial feeders of DAVFs.^{28,29} Our current study demonstrated very good agreement between 3D TOF MRA and DSA findings for the main arte-

rial feeders. In assessing main arterial feeders, intermodality agreement is better for 3D TOF MRA than for these 4D MRA techniques.^{28,29} This is probably due to the difference in spatial resolution of these techniques, i.e., $0.25 \times 0.25 \times 0.5 \text{ mm}^3$ for 3D TOF MRA and 0.5 to 1.0×0.5 to 1.0×0.6 to 1.5 mm^3 for 4D MRA techniques.^{28,29} With regard to venous drainage, intermodality agreement is worse for 3D TOF MRA than for these 4D MRA techniques,^{28,29} probably because 3D TOF MRA does not provide hemodynamic information for intracranial DAVFs. We believe that 3D TOF MRA and 4D MRA techniques are complementary for assessing intracranial DAVFs.

The planning of interventional procedures in patients with intracranial DAVF requires accurate information regarding vessel structures, especially fistulous points.³¹ Spatial resolution is lower on images of 3T TOF MRA than DSA, and 3T TOF MRA does not provide the temporal resolution of the vascular flow dynamics. Consequently, information of 3T TOF MRA regarding venous anatomy is inferior to that of DSA, and 3T TOF MRA cannot replace DSA at the treatment planning stage. On the other hand, 3T TOF MRA yields vascular and anatomic information that is not available on DSA images alone. Three-tesla TOF MRA might provide similar information to that of cone-beam CT regarding fistulous points of DAVF. Further studies are required to clarify the role of 3T TOF MRA in assessing fistulous points of DAVF.

Our study has some limitations. First, we did not compare data of unenhanced 3T MRA and contrast-enhanced 3D MRA. By combining the T_1 shortening effect of gadolinium-based contrast agents, contrast-enhanced 3D MRA might yield more information than unenhanced 3T MRA on vessel structure. Further studies are needed to clarify this issue. Second, we only evaluated gross characterization of DAVF—the main arterial feeder, venous drainage pattern from the Borden classification, and 4 types of shunt location. However, most fistulas have multiple feeders. Venous drainage stenosis/occlusion and/or venous collaterals with pseudophlebitic pattern are important details for prognosis as well as for planning transvenous access routes. Single shunt-versus-multishunt points (extensive sinus involvement) are also important factors for prognosis and treatment planning, and we did not consider them in this comparative analysis. Third, experienced neuroradiologists evaluated the MRA images, and their experience evaluating MR images may have affected their performance in detecting and describing DAVF.³² Finally, our data were based on a single-center study, and the num-

ber of patients was small.

In conclusion, the gross characterization of intracranial DAVF is similar on unenhanced 3T 3D TOF-MRA and DSA. However, adequate treatment planning requires detailed angiographic characterization by DSA.

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