Overview of multimodal MRI of intracranial Dural arteriovenous fistulas

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ABSTRACT

Dural arteriovenous fistulas (DAVFs) include a wide range of pathological conditions that are associated with intracranial vessel abnormalities. While some types of DAVFs present with typical neuroimaging characteristics, others share overlapping pathological and neuroimaging features that can hinder accurate differentiation. Hence, misclassification of the various types of DAVFs is common. Thorough knowledge of DAVF imaging findings is essential to avoid such misinterpretations. Traditional digital subtraction angiography (DSA) is considered the gold standard for diagnosing and evaluating DAVFs. However, angiography cannot detect changes in a patient’s brain structure. Conventional magnetic resonance imaging (MRI) sequences, including MR angiography (MRA), allow the evaluation of DAVFs without ionizing radiation or invasiveness. Advanced MRI techniques, such as susceptibility-weighted imaging (SWI) and dynamic contrast-enhanced MRA, provide added value to real-time physio-pathological data regarding the hemodynamics of DAVFs. Beyond these techniques, new insights using high-resolution vascular wall MRI are incorporated for the noninvasive evaluation of DAVFs. This article reviews the pathophysiology of DAVFs, focusing on the specifics of MRI findings that facilitate their classification. The role of conventional and advanced MRI sequences for DAVFs was assessed using insights derived from the data provided by structured reports of multimodal MRIs to evaluate DAVFs.

1. Introduction

Dural arteriovenous fistulas (DAVFs) are complex intracranial vascular malformations with a population detection rate of less than 1/100,000.¹ The most common manifestation is a pathological anastomosis between the dural artery and venous sinus or cortical vein. This accounts for approximately 10–15% of intracranial vascular malformations.²³ DAVFs usually occur in the dural lobes surrounding the venous sinuses. They can be located at the transverse-sigmoid sinus, cavernous sinus, superior sagittal sinus, anterior cranial fossa, tentorium of cerebellum, or other locations.³⁴ DAVFs may be benign lesions. However, due to cortical venous reflux or cortical venous obstacles, these lesions may possess aggressive manifestations. This condition can potentially result in intracranial hemorrhage or neurological damage and can also be fatal.⁵⁻⁷ Benign symptoms include intracranial murmurs, tinnitus, headache, dizziness, conjunctival edema, and orbital congestion. Aggressive manifestations may be related to intracranial hemorrhage (ICH) or a non-hemorrhagic neurological deficit (NHND). These deficits include vascular edema and cytotoxicity, mainly dementia, epilepsy, cranial nerve injury, intracranial hypertension syndrome, focal defect, transient ischemic attack, or venous stroke.¹¹⁻¹³ A DAVF diagnosis primarily depends on typical clinical symptoms and digital subtraction angiography (DSA) results. Computed tomography and magnetic resonance imaging (MRI) prove to be beneficial for an accurate diagnosis. While traditional DSA is the gold standard for diagnosing and evaluating DAVFs, angiography is invasive and cannot be used to observe brain tissue or structure. With the development of MRI technology, especially the application of high-resolution MRI and dynamic contrast-enhanced MRI (DCE-MRI) imaging sensitivity and specificity, DAVF diagnostics are continuously improving. High-resolution MRI and DCE-MRI can be used as alternatives to DSA for a preoperative diagnosis.¹⁴ Endovascular therapy is usually the first-line treatment for DAVFs. Both transarterial and transvenous pathways represent viable options. Treatment choice depends on many factors, such as the location of a DAVF, direction of venous drainage, distribution of involved vessels, structure of venous sinuses, and pathological brain changes.¹⁵⁻¹⁸

Further development of MRI technology should endeavor to address the following issues: (1) clarifying the DAVF diagnosis and fistula location, (2) verifying the venous drainage direction and DAVF grade, (3)
identifying the feeding arteries and drainage veins, (4) observing the venous sinus structure, and (5) determining brain pathology.

2. Conventional MRI for DAVFs

Conventional MRI sequences, including MR angiography (MRA), permit non-invasive evaluation of DAVFs without ionizing radiation, while revealing changes in the brain and vascular structures.

2.1. T2WI, FLAIR, and DWI

A conventional MRI can detect the specific anatomical features of a DAVF. These include dilated feeding arteries, dilated draining veins, venous sinuses, and the related venous system.\textsuperscript{18–21} High-grade DAVFs with venous hypertension, focal angiogenic edema, cytotoxic edema, intracranial hemorrhage, and/or venous obstruction can be detected using T2 weighted imaging (T2WI), fluid attenuated inversion recovery (FLAIR), and diffusion weighted imaging (DWI).\textsuperscript{19,21,22}

In addition, MRI perfusion studies have shown that, in high-grade DAVFs with venous reflux, the cerebral blood volume of the affected hemisphere secondary to venous drainage disorders increases.\textsuperscript{23}

T2/FLAIR hyperintensity in the DAVF venous drainage area is closely associated with the presence of cortical venous reflux, cortical venous obstacles, and aggressive symptoms. After effective DAVF treatment, the high signal usually gradually disappears.\textsuperscript{24,25} T2/FLAIR hyperintensity symbolizes the reversible clinical process of vasogenic edema. This phenomenon is consistent with the clinical findings at our center (Fig. 1). We observed that T2/FLAIR hyperintensity is an independent indicator of increased neurological risk over time. If further studies corroborate this finding, even patients who occasionally appear with mild symptoms such as tinnitus may require urgent treatment.\textsuperscript{24} Although DWI is usually considered to have limited application in the case of a DAVF, it is worth exploring whether DWI can provide additional valuable information. DWI hyperintensity, usually caused by limited diffusion or the T2 penetration effect, can be combined with apparent diffusion coefficient (ADC) hypointensity to identify the limited diffusion between them.\textsuperscript{21} For high-grade DAVFs with venous stasis or venous reflux, normal brain tissue blood drainage is restricted. This leads to vasogenic edema, which manifests as a high T2/FLAIR signal. If venous stasis and venous reflux cannot be rectified in a timely manner, vasogenic edema in the affected area will gradually progress to cytotoxic edema,\textsuperscript{26,27} resulting in a high DWI signal (Fig. 1).\textsuperscript{26,27} Whether cytotoxic brain edema with hyperintensity on DWI is clinically reversible is currently unknown. Future studies should explore whether brain tissue with limited diffusion and DWI hyperintensity can be restored to normal levels.

2.2. Non-enhanced MRA

The morphological and hemodynamic characteristics of DAVFs constitute independent risk factors for DAVF progression. These include characteristics of the arterial blood supply, location and drainage of the fistula, intracranial venous thrombosis along with the venous sinus, and deep vein or cortical venous return disorder, with or without reflux.\textsuperscript{4,17,26,29} Recognizing the above characteristics of DAVFs has important practical value for guiding clinical treatment. MRA is the most useful tool for screening and diagnosing patients with suspected DAVFs. It is also useful for evaluating the patient’s prognosis after treatment.\textsuperscript{15,19} Although most cranial MRAs, such as time-of-flight (TOF) or phase-contrast MRA (PC-MRA), are performed without contrast agents, artifacts or abnormal signals caused by slow blood flow or turbulence can

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**Fig. 1.** T2-Flair and DWI with DSA for DAVF with venous reflux located in the left lateral sinus, T2-Flair (A) and DWI (B) showed hyperintensity in the left occipital lobe, basal ganglia and radiation crown. DSA confirmed a complex DAVF in the superior sagittal sinus (C, D large arrow). The superior sagittal sinus lost its drainage capability due to a supratentorial venous obstruction (E).
interfere with their effectiveness. Therefore, dynamic contrast-enhanced MRA (DCE-MRA) has become an important alternative diagnostic method.\textsuperscript{30} DCE-MRA provides more hemodynamic details than TOF or PC-MRA.\textsuperscript{31,32}

Studies have reported that the sensitivity of TOF-MRA in diagnosing DAVF is 79.49\% (95\% confidence interval CI: 66.81\%–92.16\%), with a specificity of 100\% (95\% CI: 100.00\%–100.00\%).\textsuperscript{33} The main diagnostic key is the identification of the feeding artery (middle meningeal artery). Original TOF-MRA images with high spatial resolution have proven to be useful screening tools for DAVFs. They detect and track abnormal vessels, including arteriovenous malformations and aneurysms.\textsuperscript{34–36} TOF-MRA can distinguish various DAVF characteristics (Fig. 2), including asymmetrically dilated feeding arteries, structural characteristics of vessels surrounding fistulas, abnormal draining veins, dilated cortical veins, and reverse flow with venous thrombosis. These characteristics form the basis of our research on TOF-MRA.\textsuperscript{37}

3. Advanced MRI for DAVFs

Advanced MRI techniques, such as DCE-MRA, susceptibility-weighted imaging (SWI), and vascular wall MRI (VW-MRI), provide enhanced and further valuable diagnostic information compared to conventional MRIs. Specifically, they provide the added value of real-time pathophysiological data regarding DAVF hemodynamics and vascular structure.

3.1. Dynamic Contrast Enhanced MRA (DCE-MRA)

DCE-MRA can provide temporal resolution and identify intracranial hemodynamics and venous drainage, thus determining Borden or Cognard classifications.\textsuperscript{38–40} Venous drainage patterns can predict the risk of ICH and NHND, such as vascular edema and cytotoxic edema.\textsuperscript{28,32,41,42} The gold standard for clarifying the direction of DAVF venous drainage remains cerebral angiography based on selective catheter intubation. However, when evaluating DAVF drainage direction, non-invasive methods should be the preferred choice. Certain studies comparing DCE-MRA with DSA have demonstrated that DCE-MRA can diagnose DAVFs and identify the direction of venous drainage.\textsuperscript{38,39} Therefore, DCE-MRA can be used as a preliminary diagnostic pre-surgical tool.\textsuperscript{39,40,42,44} In terms of DAVF treatment, the individual needs of specific patients must be analyzed in detail. This includes identifying the feeding arteries, assessing fistula complexity, determining venous drainage, exploring the patency of the venous sinus, and confirming the

![Fig. 2. TOF-MRA and DSA for left transverse sinus complex DAVF. The feeding arteries were posterior and middle meningeal arteries along with the occipital artery (A, B arrowheads). The fistula was concentrated in the dura mater of the left middle posterior cranial fossa (C, D, E arrows), including the petrous surface of the temporal bone and sigmoid sinus. Corporate drainage vein and left transverse sinus (C, F bold arrows). DSA confirmed the fistula was concentrated in the dura mater of the left middle posterior cranial fossa (G, H arrows), common drainage vein and left transverse sinus (G, H large arrows).]
condition of the neck vessels.\textsuperscript{39,45}

DCE-MRA has high spatial resolution and high accuracy in assessing the anatomical relationship between a DAVF and surrounding structures (Fig. 3), delineating the feeding arteries and fistula in detail, and facilitating the formulation of a treatment strategy.\textsuperscript{39} DCE-MRA also provides significant advantages in evaluating the DAVFs venous condition, which can distinguish between true and false occlusions caused by abnormal hemodynamic effects. DCE-MRA supersedes DSA in displaying the overall intracranial drainage pattern.\textsuperscript{39} This allows for an improved assessment of the feasibility of intravenous interventional therapy and/or combined methods.\textsuperscript{39,46,47}

3.2. Susceptibility-weighted imaging (SWI)

Aggressive manifestations of DAVF include ICH, which often leads to severe neurological impairment with high disability and fatality rates. Studies have suggested that cortical venous hypertension and reflux may lead to arterialization of fragile cortical veins, leading to ICH.\textsuperscript{10,48} SWI can detect hemorrhage and calcification due to slight changes in the magnetic susceptibility of brain structures. Research has indicated that SWI can assess hemorrhage in the ischemic penumbra of acute ischemic stroke.\textsuperscript{49} Mainly oxygenated arterial hemoglobin, a diamagnetic substance, presents as hyperintensity on SWI. Paramagnetic deoxygenated venous hemoglobin in the venous system displays as hypointense on SWI. Post-DAVF, deoxygenated venous hemoglobin is replaced by oxygenated hemoglobin and is expressed as intravenous hyperintensity on SWI.\textsuperscript{50-52}

The characteristics of hemosiderin hypointensity on SWI can be used to assess whether cerebral hemorrhage has occurred because of DAVFs. A DAVF causes drainage of arterial blood into nearby tortuous and dilated veins. SWI can be used to determine whether the responsible vein drains arterial blood from the fistula or whether the stasis vein is draining venous blood. SWI can also identify the fistula location.\textsuperscript{22} Inchoate SWI research has certain limitations.\textsuperscript{50} SWI can assess the presence of ICH related to arteriovenous shunts; however, it cannot assess the risk of subsequent ICH. Because of the pronounced SWI artifacts, evaluating the effect of DAVFs near the skull base, sinuses, and mastoid is difficult. Furthermore, SWI fails to measure the magnetic susceptibility value, which is helpful for assessing whether arterial blood resides in the draining vein. Further research with a larger sample size is required to determine ICH risk in follow-up cases.

Yamaguchi et al.\textsuperscript{21} reported that drainage veins with hypointensity have a lower risk of ICH, whereas drainage veins with hyperintensity/isointensity have an increased risk of bleeding. This phenomenon is consistent with our evaluation. SWI hypointensity indicates venous stasis caused by drainage obstacles with relatively low venous pressure and rupture risk. SWI hyperintensity indicates that the vein is fragile with high intravenous pressure. The SWI intensity of the draining vein can be used to assess the venous blood flow status and ICH risk. Future SWI research should include determining the location of the fistula and condition of the primary involved vein (the vein responsible for draining arterial blood or the stasis vein for draining venous blood) (Fig. 4). A greater emphasis on sensitivity and specificity of SWI in DAVF diagnosis can aid in estimating whether arteriovenous blood is present in the draining vein.

3.3. Vascular Wall MRI (VW-MRI)

Intracranial high-resolution VW-MRI, termed black blood sequences, can be used to identify the rupture site of spontaneous subarachnoid hemorrhage in intracranial aneurysm patients.\textsuperscript{53-55} Few case reports describe its application in complex ruptured DAVFs\textsuperscript{56} and cerebral arteriovenous malformations.\textsuperscript{57,58} Ruptured vascular structures have specific manifestations on VW-MRI. They appear tortuous and dilated with obvious vein wall enhancement.\textsuperscript{56} This finding is consistent with the observation of intracranial aneurysms with spontaneous subarachnoid hemorrhage. VW-MRI can also be used to assess whether arterial blood resides in the draining vein. Further research with a larger sample size is required to determine ICH risk in follow-up cases.
hemorrhage (SAH). Vascular wall enhancement helps to determine the risk of spontaneous SAH and the specific site of likely aneurysm rupture. VW-MRI data suggest that all spontaneously ruptured vessels harbor an obviously enhanced wall. However, this hypothesis requires further support. DAVF research should focus on the enhancement of characteristics in spontaneously ruptured vessels on VW-MRI. Bleeding and enhancement are strongly correlated because enhancement leads to inflammatory changes that affect the fragility of the local vessel wall. This results in an elevated risk of rupture and bleeding.

Currently, endovascular therapy (EVT) is the preferred treatment for DAVFs, and can be divided into transarterial or transvenous treatment. Transarterial EVT is the first choice of treatment for high-grade DAVFs with cortical venous drainage or limited transvenous access. The main strategy is to embolize the supplying artery, block the fistula and drainage vein, limit blood flow, maintain the functional venous system, and reduce the complications associated with commonly used transvenous methods. The transvenous route is greatly affected by the venous sinus structure and venous sinus thrombosis, sometimes

Fig. 4. SWI and DSA for a lateral sinus DAVF with the straight sinus and Gallen vein reflux. SWI hyperintensity implied that the fistula is located in the lateral sinus with the straight sinus and Gallen vein reflux (A, B arrow). DSA confirmed this via external carotid angiography (E, F large arrow and F, G arrow). SWI banding hypointensity indicated venous obstruction (B dotted oval). Punctuated SWI hypointensity indicated micro-hemorrhage (C narrow arrow). Flake hypointensity distributed along the gyrus was the manifestation of iron deposition (D white wax line). DSA confirmed venous obstruction (H dotted oval).

![Image](https://via.placeholder.com/150)

Fig. 5. Normal and DAVF lateral sinus. The lateral sinus wall was uniformly strengthened, with no abnormal structure in the sinus (A, B). The lateral sinus wall was strengthened inconsistently, chordae Willisi (CW) in the sinus (C arrow). 3D hybrid DSA confirmed the existence of CW, which divided the sigmoid sinus into an upper part responsible for the normal drainage function (D narrow arrow) and a lower region draining the DAVF (D large arrow). A stent was implanted in the DAVF transverse-sigmoid sinus post-recanalization. Sigmoid sinus recanalization (E, F large arrows) and transverse-sigmoid junction thrombosis (G, H arrows) were detected by VW-MRI and DSA.
making it difficult to access the target area. To achieve complete occlusion and avoid complications, an appropriate strategy must be tailored to each patient. The selected venous sinus or cortical vein should fully participate in fistula drainage without normal cerebral venous drainage. It should be blocked for therapeutic purposes, thereby allowing for occlusion.1,12,14,15,66,67 VW-MRI can be used to evaluate the structure of the venous sinus and optimize the choice of the transvenous route (Fig. 5). DAVFs can be secondary to cerebral venous thrombosis.6,67 Blood turbulence and stasis in the DAVF vein may also lead to cerebral venous thrombosis.14,15 DAVF progression leads to a relative increase in intracranial venous flow, reactive venous sinus stenosis, and intracranial venous drainage disorder.1,12,14 Therefore, preserving venous sinus function is more attractive than the previous method of occlusion of the venous sinus. This method maintains the physiological drainage of intracranial circulation. Venous sinus angioplasty and stenting, methods for restoring venous drainage function, can be used to treat high-level DAVF with sinus stenosis or occlusion.6,66 Thus, the preoperative analysis of venous sinus classification, venous sinus structure, and venous sinus thrombosis is particularly important (Fig. 5). Intracranial high-resolution VW-MRI can be used to identify the above-mentioned sinus characteristics, which is its primary value. Identifying the structure of the venous sinus and vein can guide the selection of interventional methods and transvenous treatments.

The anatomical structure, variation, and relationship with the surrounding structures of the venous sinus vary significantly. The venous sinus is divided into three types: Type I - the superior sagittal sinus, straight sinus, and bilateral transverse sinus; Type II - the superior sagittal sinus, straight sinus, and bilateral transverse sinus meet in pairs before converging into the sinus confluence; and Type III - the superior sagittal sinus, straight sinus, and bilateral transverse sinus converge directly, without direct communication between the confluens sinuum.66,67 Based on the presence of venous sinus stenosis and any difference in confluence between the left and right sides, the classification can be refined.66,67 As MR venography (MRV) cannot recognize the structure of the venous sinus lumen, such as the chordae Willisi (CW) or thrombosis, VW-MRI analysis of the venous sinus structure and thrombosis is particularly important. Various treatment strategies should be formulated according to the classification of the venous sinus anatomy. In recent years, autopsies have been conducted to determine the structural characteristics of the venous sinus and anatomical characteristics of the wall and CW. This provides a basis for future studies of the structural characteristics of the venous sinus with a VW-MRI focus.68 VW-MRI can distinguish in detail the anatomical and structural characteristics of the venous sinus and identify the specific manifestations of a DAVF venous sinus, permitting personalized clinical treatment.

4. Summary

An in-depth knowledge of DAVFs from a histological, hemodynamic, and neuroimaging perspective is necessary for accurate interpretation of conventional and advanced MRI sequences. MRI sequences, such as DCE-MRA, display the overall intracranial drainage pattern. SWI is useful for estimating arteriovenous blood in the draining vein, and VW-MRI can determine the structural characteristics of the venous sinus. These sequences provide valuable information that enables increased accuracy for DAVF detection, classification, and characterization. Familiarity with the strengths and limitations of each technical adjustment technique to acquire advanced MRI sequences is important for optimizing their usefulness. A structured and functional neuroimaging report can help systematize the evaluation of DAVFs, rendering correct classification and description. Advanced MRI techniques for DAVF evaluation have demonstrated promising results not only for diagnostic purposes, but also for planning therapeutic options. However, further studies are required to validate these approaches and to incorporate them into routine MRI protocols.

Declaration of competing interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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