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Advanced noninvasive imaging of spinal vascular malformations

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Abstract

Spinal vascular malformations (SVMs) are an uncommon, heterogeneous group of vascular anomalies that can render devastating neurological consequences if they are not diagnosed and treated in a timely fashion. Imaging SVMs has always presented a formidable challenge because their clinical and imaging presentations resemble those of neoplasms, demyelination diseases, and infection. Advancements in noninvasive imaging modalities (MR and CT angiography) have increased during the last decade and have improved the ability to accurately diagnose spinal vascular anomalies. In addition, intraoperative imaging techniques have been developed that aid in the intraoperative assessment before, during, and after resection of these lesions with minimal and/or optimal use of spinal digital subtraction angiography. In this report, the authors review recent advancements in the imaging of SVMs that will likely lead to more timely diagnoses and treatment while reducing procedural risk exposure to the patients who harbor these uncommon spinal lesions.

Keywords

indocyanine green video angiography; magnetic resonance angiography; spinal arteriovenous malformation; vascular malformation

Spinal vascular malformations are an uncommon, heterogeneous group of vascular anomalies that can render devastating neurological consequences if they are not diagnosed and treated in a timely fashion. The most common classification system separates SVMs into the following 4 types: spinal DAVFs (Type I), intramedullary glomus malformations (Type II), extensive juvenile or metameric malformations (Type III), and perimedullary spinal cord AVFs (Type IV).^{2,4-6,14} However, Kim and Spetzler⁹ recently proposed a new classification system based on the anatomical description of SVMs, namely, extradural, intradural dorsal/ventral, intraduralintramedullary, extradural-intradural, and conus medullaris vascular malformations. Pathophysiologically, the shunting of arterial blood through dorsal and/or medullary veins can lead to either vascular steal, particularly from high-flow lesions, or venous hypertension and congestion, reducing intramedullary blood flow; both processes often lead to spinal cord ischemia and dysfunction.^{2,4,9,14} Timely diagnosis and a precise understanding of the angioarchitecture of these lesions can open therapeutic corridors and determine treatment strategies.

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Imaging of SVMs has always presented a formidable challenge because their clinical and imaging presentations are similar to neoplasms, demyelination diseases, and infection.^{4–6,8,10,14,17,21} The gold standard of imaging of SVMs has traditionally been catheter-based 2D angiography because of its ability to produce images with superior temporal and spatial resolution.^{2,8–10,14} However, spinal 2D DS angiography is not without risks. Selective catheterization of arteries supplying an SVM can often be time consuming, require multiple catheterizations, involve long radiation exposure times, and use large volumes of potentially nephrotoxic contrast agents. Furthermore, selective catheterization of segmental arteries can lead to spinal cord infarction due to their embolization or occlusion. Therefore, advancements in noninvasive imaging modalities (MR and CT angiography) have increased during the last decade and have improved the ability to accurately diagnose spinal vascular anomalies.^{10–12,19,20,23} In addition, intraoperative imaging techniques have been developed that aid in the intraoperative assessment before, during, and after resection of these lesions with minimal and/or optimal use of spinal DS angiography.

The purpose of this report was to review recent advancements in the imaging of SVMs that will likely lead to more timely diagnoses and treatment while reducing procedural risk exposure to the patients who harbor these uncommon spinal lesions.

Diagnostic Imaging of SVMs

Patients with SVMs often present with symptoms of progressive myelopathy and neurological compromise.^{6,10,14,17,21} Noninvasive imaging of the spine, such as MR imaging or CT with contrast (myelography), is often done to evaluate the spinal column, cord, vasculature and supporting structures. Although the imaging hallmarks of SVMs are typically less apparent when CT is used, they are similar to those seen on MR imaging, namely prominent or enlarged subarachnoid vessels. Magnetic resonance imaging, however, has the distinct advantage of examining the spinal cord tissue and supporting structures in detail which, on T2-weighted images, often demonstrates increased signal intensity, representing spinal cord edema and/or periradicular hematoma spanning 1 or more vertebral segments (Fig. 1). These imaging characteristics, however, are nonspecific and static; they do not provide any hemodynamic information regarding the vasculature of the spinal column. Noninvasive angiography techniques (CT and MR angiography) have recently allowed the acquisition of dynamic information, which has greatly assisted in not only the diagnoses of SVMs, but also the localization of the fistulous connection(s).^{1,11–13,19,20,23} The anatomical localization of the fistulous connection(s) is not only imperative for definitive therapy but can also complement spinal DS angiography, possibly leading to a reduction in the number of selective catheterizations and amount of radiation and contrast used, as well as procedural complications, thus greatly benefitting the patient.

Multidetector spiral CT angiography has improved over the past several years in the reduction of acquisition time for each image and increased spatial resolution. Using a 16-detector row spiral CT angiography, Lai et al.¹² reported 8 cases of spinal DAVFs in which the fistulous connection, feeding arteries, and draining veins were localized with great consistency when compared with spinal DS angiography. Recently, Si-Jia et al.,²⁰ using a 64-detector row spiral CT, reported the same good results in 17 patients with improved spatial and temporal resolution. However, the spatial and temporal resolution was still inferior to spinal DS angiography and made the angioarchitecture of complicated SVMs very difficult to characterize. Si-Jia et al. also reported that fistulous connections involving the anterior or posterior spinal arteries were often not visualized because of the limitations of CT angiography spatial resolution. Furthermore, the distinct arterial and venous phases of SVMs often cannot be separated using CT angiography, and cine review of the entire spine cannot be done due to the limitations of acquisition time and the limited FOV, respectively. Computed tomography

angiography also has the added disadvantage of exposing patients to radiation and potentially nephrotoxic contrast agents.

To overcome the limitation of temporal resolution of noninvasive imaging, rapid multiphase dynamic MR angiography with parallel imaging has been developed with a temporal resolution of 3–6 seconds and a spatial resolution of ~ 1 mm (Fig. 2). The advantages of rapid time-resolved MR angiography of the spine are the improvement of temporal resolution through parallel imaging while maintaining a high spatial resolution, allowing hemodynamic visualization of the SVM, acquiring a large FOV, allowing a wide survey of possible fistulous connections, and eliminating patient exposure to radiation and iodinated-contrast agents.¹ The disadvantages of rapid time-resolved MR angiography are the reductions in the signal-to-noise ratio when increasing the temporal resolution, the limitation of spatial resolution, the difficulty in detecting and preserving normal intramedullary arteries and specific subclassification of SVMs, and the need for sophisticated and time-consuming postprocessing efforts. However, many groups have reported the successful use of spinal MR angiography in the diagnoses of SVMs.^{1,10,13,18,19} Ali et al.¹ recently reported on 11 patients who were suspected of harboring SVMs based on suspicious spinal MR angiography findings. In 6 cases in which arteriovenous shunting was identified on spinal MR angiography, SVMs were confirmed using spinal DS angiography; therefore, the MR angiography had correctly predicted the vertebral level of the fistulous shunt. In 5 cases of negative spinal MR angiography, no SVM was found on subsequent spinal DS angiography. Posttreatment spinal MR angiography was done in 3 patients and accurately assessed the success or failure of SVM treatment as confirmed by spinal DS angiography. However, Sharma and Westesson¹⁹ reported a case in which spinal MR angiography demonstrated an SVM; subsequent spinal DS angiography altered the type and site of malformation and prevented failed surgery. It is clear that spinal MR angiography offers an additional and useful tool in the diagnosis of SVMs and can be used to complement, not supplant, spinal DS angiography.

Intraoperative Imaging of SVMs

Once the fistulous connection(s) of an SVM is localized and surgery has been selected as the definitive therapeutic option, primarily for intradural dorsal/ventral AVFs, intradural-intramedullary AVMs, conus medullaris AVMs, and extradural-intradural AVMs with significant mass effect, the fistulous connections are located intraoperatively, ligated, and the lesion resected, if possible.^{2,9,14} Some centers use intraoperative spinal DS angiography to reconfirm the anatomical location of the SVM or to determine either the extent of fistula disconnection or resection of the SVM.^{3,22} The advantage of intraoperative spinal DS angiography is the definitive knowledge of lesion location, ligation, and extent of resection with high spatial and temporal resolution.^{3,22} The disadvantages are the requirement of extra personnel for completion of the spinal angiogram, exposure of the patient to radiation and iodinated contrast, and the lack of images from the surgical point of view. A new method of intraoperative video angiography using ICG dye has been developed that allows fast imaging of vascular flow with integration into the surgical microscope.^{15,16} Indocyanine green dye, a near-infrared fluorescent tricarboxyanine dye, is injected peripherally as a bolus. Within seconds, and with the appropriate optical filters attached to the surgical microscope, the vasculature is illuminated in the surgical FOV, resulting in arterial and venous angiographic images, which can be viewed on an external video screen (Fig. 3). The advantages of ICG video angiography are ease of use, fast results, high spatial resolution, an ability to repeat multiple injections, the absence of radiation and iodinated contrast agents, and relative low cost.^{15,16} Multiple injections can be made safely during the surgical procedure so that the remaining malformation can be examined during the resection (Fig. 3). The disadvantages of such a technique are that the fluorescent signal cannot be observed through tissue or hematoma, that is, the surgical FOV must include the vessels or lesion in question and the requirement of

a relative wide FOV such that an adequate amount of light can excite and be detected by the surgical microscope infrared detector. Although ICG video angiography is a promising method for observing intraoperative vascular hemodynamics and has several advantages over spinal DS angiography, it is not meant as a replacement but rather as an adjunct to the currently available techniques. It will always be at the discretion of the operating surgeon to determine which imaging techniques will provide adequate knowledge to assess SVM localization, ligation, and extent of resection.

Future Developments

Improved noninvasive imaging techniques for SVMs will enable more exact localization of these lesions, which will minimize the procedural time needed for spinal DS angiography in cases of questionable diagnoses, endovascular therapy, and intraoperative assessment. Furthermore, improved follow-up imaging may not have to involve patient exposure to the procedural risks of spinal DS angiography. To achieve such a goal, several improvements are on the horizon and are sure to impact noninvasive imaging of SVMs. One of the most important aspects of imaging of SVMs is temporal resolution. Although increasing the number of detectors used in CT angiography will not significantly improve the acquisition speed, alternative MR angiography techniques have improved the temporal resolution without sacrificing spatial resolution. Cashen et al.⁷ reported the development of a 4D radial contrast-enhanced MR angiography sequence capable of obtaining ≥ 3 frames per second using 3D cylindrical k-space sampling, angular undersampling, asymmetric sampling, sliding window reconstruction, pseudorandom view ordering, and a sliding subtraction mask. This technique has recently been used to examine intracranial AVMs with a temporal resolution of 6 frames per second. The application of such an MR angiography sequence to the spine will greatly improve the ability to examine and characterize the hemodynamics of SVMs. Another area of rapid imaging improvement is happening within the operating room. As more and more centers use intraoperative imaging, be it CT, MR imaging, or ICG video angiography, the improvement of the current and development of new techniques will surely follow, such as the ability to use intraoperative CT or MR angiography, techniques that will certainly complement if not supplant intraoperative spinal DS angiography. Finally, the development of new-generation fluorochromes will certainly improve the detection of intravascular fluorescence such that the hemodynamics of SVMs can be visualized within tissue or through hematoma. All of these potential developments are not only geared to improve noninvasive SVM imaging, but also to significantly reduce the exposure of patients to procedural risks and potentially nephrotoxic contrast agents.

Conclusions

Although the gold standard of SVM imaging currently remains 2D DS angiography because of its superior ability to acquire images with better spatial and temporal resolution, noninvasive techniques continue to improve. Rapid time-resolved MR angiography can establish the vertebral level of most SVMs noninvasively and assist in optimizing spinal DS angiography if endovascular treatment is chosen or the appropriate surgical levels need to be explored. Indocyanine green video angiography is also a very helpful perioperative imaging modality when used to assist in the determination of retained fistulous connections during the resection of an SVM. As technology continues to develop, noninvasive imaging methods will continue to improve but will complement, not supplant, spinal DS angiography in the diagnosis and treatment of SVMs.

Abbreviations used in this paper

AVM arteriovenous malformation

DAVF	dural arteriovenous fistula
DS	digital subtraction
FOV	field of view
ICG	indocyanine green
SVM	spinal vascular malformation

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FIG. 1.

A and B: Midline thoracic sagittal T2-weighted MR images demonstrating characteristic MR imaging findings of a T-8 intradural-intramedullary SVM, including the spinal AVM nidus (A, *arrowhead*) with associated T2 signal changes (A, *arrow*) and draining intradural veins (B, *arrow*). C and D: Axial T2-weighted MR images demonstrating increased perinidal T2 signal changes (C, *arrow*) and prominent subarachnoid vessels (D, *arrow*).

FIG. 2.

A–E: Progressive rapid time-resolved MR angiography time sequence of images demonstrating the filling of the spinal AVM nidus (C, *arrow*) and the draining vessels (E, *arrow*). The time interval between the images is ~ 2 seconds. F: Spinal DS angiogram of same SVM showing filling of the SVM nidus (*arrow*).

FIG. 3.

Intraoperative photographs (A, C, and E) and corresponding ICG video angiograms (B, D, and F) of a dorsal intradural SVM before, during, and after surgical treatment. A: Intraoperative photograph of the SVM before clip ligation. B: Corresponding ICG fluorescence image to panel A demonstrating the spinal AVM fistulous connections (*arrows*). C: Intraoperative photograph of the SVM after clip ligation of a single fistulous connection (*arrow*) and demonstration of another fistulous connection (*arrowhead*). D: Corresponding ICG fluorescence image to panel C demonstrating the residual spinal AVM (*arrowhead*) after initial clip ligation of one fistulous connection (*arrow*). E: Intraoperative photograph of the SVM after complete surgical treatment including clip ligation (*arrows*). F: Corresponding ICG fluorescence image to panel E demonstrating no apparent residual spinal AVM after surgical treatment including clip ligation (*arrows*) with maintenance of parent artery blood flow.