Rotational angiography for diagnosis and surgical planning in the management of spinal vascular lesions


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Object. The management of spinal vascular malformations has undergone significant evolution with the advent of advanced endovascular and angiographic technology. Three-dimensional rotational spinal angiography is an advanced tool that allows the surgeon to gain a better appreciation of the anatomy of these spinal vascular lesions and their relation to surrounding structures. This article describes the use of rotational angiography and 3D reconstructions in the diagnosis and management of spinal vascular malformations.

Methods. The authors present representative cases involving surgical treatment planning for spinal vascular malformations with focus on the utility and technique of rotational spinal angiography. They report the use of rotational spinal angiography for a heterogeneous collection of vascular pathological conditions.

Results. Eight patients underwent rotational spinal angiography in addition to digital subtraction angiography (DSA) for the diagnosis and characterization of various spinal vascular lesions. Postprocessed images were used to characterize the lesion in relation to surrounding bone and to enhance the surgeon’s ability to precisely localize and obliterate the abnormality. The reconstructions provided superior anatomical detail compared with traditional DSA. No associated complications from the rotational angiography were noted, and there was no statistically significant difference in the amount of radiation exposure to patients undergoing rotational angiography relative to traditional angiography.

Conclusions. The use of rotational spinal angiography provides a rapid and powerful diagnostic tool, superior to conventional DSA in the diagnosis and preoperative planning of a variety of spinal vascular pathology. A more detailed understanding of the anatomy of such lesions provided by this technique may improve the safety of the surgical approach.

(http://thejns.org/doi/abs/10.3171/2012.1.FOCUS11254)

Key Words • spinal angiography • spinal artery aneurysm • spinal dural arteriovenous fistula • 3D rotational angiography

vascular lesions of the spine are rare and difficult to diagnose by means of noninvasive imaging modalities.2,6,7,26 Spinal dural arteriovenous fistulas are the most common type of SVM; patients with SDAVFs usually present with progressive myelopathy and weakness,21,25 and the lesions require prompt diagnosis and treatment.3 Spinal AVMs are less common than SDAVF, and the classification of these lesions has been a subject of considerable debate.17,29 Aneurysms also occur in the spinal arterial circulation and are commonly associated with fistulas. Spinal aneurysm rupture may lead to acute neurological deficits. Over the last 2 decades, imaging techniques have evolved to better visualize these heterogeneous lesions that may occur in the spinal vasculature.

Multiple case series8,23,28 and meta-analysis27 have underscored the utility and benefits of microsurgical treatment for spinal vascular lesions. Precise localization and detailed knowledge of the vascular architecture is essential for preoperative planning. Multiple imaging modalities have been used for the diagnosis of vascular malformation of the spine including CTA, MRI, and catheter-based DSA. Although traditional DSA is the most sensitive methodology for detecting SVMs, it is limited...
by its planar nature, and anatomical correlation with the surrounding soft tissue and bony anatomy can be difficult. The combination of high-resolution vascular images from selective transarterial DSA with the tomographic images of a cross-sectional modality such as CT or MRI provides greater anatomical detail for localization of vascular pathology and for preoperative planning of either endovascular or surgical treatments. The use of 3D RA has become routine in the management of intracranial aneurysms.\textsuperscript{10,11} The utility of this technique in the diagnosis and treatment planning of SVMs is not nearly as well established.\textsuperscript{14,19,24}

We report a heterogeneous collection of cases of SVMs involving patients who underwent 3D RA with detailed post-processing of the rotational dataset, including standard and optimized tomographic maximum intensity projections (MIPs) and 3D volume rendering prior to operative obliteration or radiosurgery. Postprocessed images from the 3D RA provided superior diagnostic information compared with traditional DSA in operative planning for SVMs by precise localization of the lesion in relation to the surrounding bony anatomy and should be considered part of the standard angiographic work-up for these lesions.

Methods

The study population consisted of all patients who underwent diagnostic spinal angiography at the Brigham and Women’s Hospital between 2007 and 2010. Angiograms performed for the purpose of targeted intervention (for example, preoperative tumor embolization) or postoperative evaluations were excluded from the study. All medical records were reviewed to extract demographic information, clinical symptoms, imaging findings, angiography parameters, and information about hospital courses. The study was approved by the Brigham and Women’s Hospital and Partners Healthcare Institutional Review Board.

All angiographic procedures were performed on the General Electric Innova 3131 biplane fluoroscopy system (GE Healthcare). Patients received intravenous conscious sedation and local anesthesia prior to the procedure. All angiograms were performed via 5-Fr transfemoral sheath access. A 4-Fr Berenstein II catheter was used to access the internal iliac, vertebral, and carotid arteries as well as the thyro- and costocervical trunks, and a 5-Fr Mickelson catheter was used to access the thoracolumbar segmental and middle sacral arteries. The rotational angiogram was configured to carry out a 200° spin from the AP x-ray projector with one of 3 preset rotation speeds (40°/second, 20°/second, or 10°/second), depending on the amount of soft tissue and bony information desired for the reconstructed images. Contrast medium (Ultravist 240) was injected at a rate of 1–2 ml/second for a total of 10–20 ml during each rotational angiogram depending on the duration of the rotation. Postprocessing analyses were completed on an AW workstation (Innova 3D software, GE Healthcare) to reconstruct 3D vascular models and produce adjustable maximum intensity projection (MIP) images of various thicknesses. Images for postprocessing were available in near real-time (with a delay of only 60–90 seconds) following acquisition, and postprocessing could therefore be carried out with the catheter remaining in the selected vessel to ensure that the quality of the acquired dataset was adequate or if further manipulation was required.

Radiation exposure was evaluated with cumulative air kerma (in Gy) and dose-area product (DAP, in Gy·cm\textsuperscript{2}), both of which were obtained directly from the angiography station. The cumulative air kerma (or cumulative dose) was measured 15 cm below the isocenter of the fluoroscopy tubing, and the DAP was calculated as the integral of air kerma across the x-ray beam emission. These radiation exposure parameters were routinely recorded for all neuroangiography procedures.

Differences in demographic and clinical characteristics for patients who received 3D RA and traditional spinal angiography were examined using chi-square and 2-tailed t-tests for categorical and continuous variables, respectively. Statistical significance was defined as a probability of Type I error less than 0.05. All statistical analyses were performed using SAS version 9.2 (SAS Institute, Inc.) and Excel 2007 (Microsoft Corporation).

Results

Between 2007 and 2010, 37 patients underwent diagnostic spinal angiography at the Brigham and Women’s Hospital; of these, 3D RA was performed in 8 patients. Demographic and clinical characteristics are summarized in Table 1. The average age of patients who underwent 3D RA was 46.5 years, and 5 of these 8 patients

<table>
<thead>
<tr>
<th>Variable</th>
<th>2D DSA (29 patients)</th>
<th>3D RA (8 patients)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>age at procedure (yrs)</td>
<td>mean 52.5 ± 15.6</td>
<td>46.5 ± 17.4</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>range 25–79</td>
<td>20–65</td>
<td></td>
</tr>
<tr>
<td>sex</td>
<td>0.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>male</td>
<td>16</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>female</td>
<td>13</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>diagnosis</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>negative for SVM</td>
<td>23</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>SDAVF</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>spinal AVM</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>aneurysm</td>
<td>0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>radiation dosage (Gy)</td>
<td>mean 2.96 ± 1.94</td>
<td>3.44 ± 2.45</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>range 0.72–6.43</td>
<td>0.55–6.75</td>
<td></td>
</tr>
<tr>
<td>DAP (Gy·cm\textsuperscript{2})</td>
<td>mean 372.7 ± 267.8</td>
<td>409.5 ± 318.6</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>range 65.9–808.0</td>
<td>60.9–932.0</td>
<td></td>
</tr>
</tbody>
</table>

* Values represent numbers of patients unless otherwise indicated. Mean values are presented with SDs.
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were male. Although the mean cumulative dose and DAP were higher for patients who were examined with 3D RA than those examined with 2D traditional DSA, the difference was not statistically significant (p = 0.61).

Table 2 summarizes the clinical and specific imaging findings in the 8 patients who underwent 3D RA. Cases 1 and 3, who had intradural aneurysms (one of which was associated with an SDAVF), and Case 8, who had a cervical intramedullary AVM, presented with spontaneous intradural hemorrhage and acute onset of neurological deficits, whereas the patients with Type I SDAVFs and a pial AVM presented with progressive neurological deficits. Case 6 presented with radiographic recanalization of an intramedullary AVM that was previously embolized. Initial MRI and/or CTA demonstrated stigmata of vascular pathology, and all patients underwent spinal angiography prior to operative or radiosurgical management. No intra- or periprocedural complications were encountered in those undergoing 3D RA.

**Illustrative Cases**

**Case 1**

This 52-year-old woman presented with sudden onset of severe headache, right-sided neck spasm, upper-extremity paresthesias, and episodic vertigo after chiropractic manipulation of her neck. Physical examination revealed minimal left biceps weakness, and a noncontrast head CT scan demonstrated evidence of hydrocephalus with dilated temporal horns and SAH in the basal cisterns (Fig. 1A). Magnetic resonance imaging revealed SAH in the anterior cervical canal, extending down to the level of C-7 (Fig. 1B). Standard cerebral and cervical spinal angiograms demonstrated an arteriovenous fistula supplied by the ASA and musculoskeletal branches of the left vertebral artery, draining superiorly into the anterior median spinal vein (Fig. 1C). The fistula was associated with a small aneurysm. Incidentally, the ASA had an aberrant supply from the costocervical trunk. Three-dimensional RA was performed from the right costocervical trunk, which showed the dural AVF to be located on the left anterior surface of the cervical spinal cord associated with a 3-mm ASA aneurysm located between the levels of C-4 and C-5 (Fig. 1D–F; rotational angiogram slow spin of 20°/second). The ability to freely tumble the 3D model allowed analysis of the anatomy in any projection (Fig. 1G, rotational angiogram fast spin of 40°/second). The patient underwent C3–6 laminectomies for resection of the fistula and clipping of the aneurysm. The patient recovered well from surgery, and her initial mild proximal left upper extremity weakness had resolved at 6-month follow-up.

**Case 2**

This 58-year-old man presented with progressively worsening paresthesias and weakness in his legs over 6 weeks. He also reported occasional urinary retention and constipation. Neurological examination demonstrated bilateral ankle clonus but no strength or sensory deficits. An MRI study of the spine revealed T2 prolongation and gadolinium enhancement from T-9 to the conus medullaris, consistent with chronic venous congestion, and multiple flow voids in thoracic and lumbar spine (Fig. 2A and B). Spinal DSA demonstrated an SDAVF fed by the radiculomedullary branches of the left T-12, bilateral L-1, and left L-2 segmental arteries and draining superiorly into a perimedullary vein as well as a paraspinal vein (Fig. 2C and D). Three-dimensional RA was performed from the left L-1 and left T-12 segmental arteries and showed that the fistula was directly behind the L-1 vertebral body, anterior to the spinal cord, and just medial to the left L-1 pedicle (Fig. 2E–G, slow spin of 20°/second; Fig. 2H, fast spin of 40°/second). The arteriovenous transition could be

**TABLE 2: Demographic and clinical summary for patients who underwent 3D rotational spinal angiography**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Symptoms</th>
<th>Noninvasive Imaging</th>
<th>Diagnosis (levels)</th>
<th>Arterial Supply</th>
<th>Management</th>
<th>FU (mos)</th>
<th>mRS at FU</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52, F</td>
<td>headache, neck pain, paresthesias, left arm weakness</td>
<td>MRI, CTA</td>
<td>SDAVF (C4–5), ASA aneurysm</td>
<td>ASA, left VA</td>
<td>3D RA, surgical obliteration</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>58, M</td>
<td>paresthesias</td>
<td>MRI</td>
<td>SDAVF (T12–L2)</td>
<td>It T-12, bilateral L-1, bilateral L-2 segmental artery</td>
<td>3D RA, surgiccal obliteration</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>42, M</td>
<td>back pain, left leg weakness &amp; numbness</td>
<td>MRI</td>
<td>PSA aneurysm (T-11)</td>
<td>L-1 segmental artery</td>
<td>3D RA, surgical obliteration</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>61, M</td>
<td>urinary retention, myelopathy</td>
<td>MRI</td>
<td>pial AVM (T-6)</td>
<td>rt T-6 segmental artery</td>
<td>3D RA, surgical obliteration</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>65, F</td>
<td>myelopathy, urinary retention</td>
<td>MRI</td>
<td>SDAVF (T-10)</td>
<td>right T-10 segmental artery</td>
<td>3D RA, surgical obliteration</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>20, M</td>
<td>paraplegia, radiographic residual spinal AVM after embolization</td>
<td>MRI</td>
<td>residual intramedullary AVM (T-8)</td>
<td>It T-9 segmental artery</td>
<td>3D RA, radiosurgery</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>53, F</td>
<td>paresthesias</td>
<td>MRI</td>
<td>SDAVF (L-1)</td>
<td>L-1 segmental artery</td>
<td>3D RA, surgical obliteration</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>21, M</td>
<td>hemiplegia, paresthesias</td>
<td>MRI</td>
<td>intramedullary AVM (C2–3)</td>
<td>ASA</td>
<td>3D RA, radiosurgery</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

* FU = follow-up; mRS = modified Rankin Scale score; VA = vertebral artery.

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traced through the thin-slice (2-mm) tomographic MIP images from coronal reconstructions of the 3D RA (Fig. 3A–H, slow spin of 20°/second). The reconstructed images enhanced the view of the fistulous point in multiple projections. The patient underwent T12–L2 laminectomies and resection of the SDA VF with clipping of the feeding artery (Fig. 2I). He recovered well from the operation with no neurological deficits and resolution of the preoperative paresthesias.

**Case 3**

This 42-year-old man developed acute onset of low back pain and left leg numbness and weakness, which persisted for 1 day. His left leg weakness rapidly worsened and he was unable to ambulate. Physical examination revealed a plegic left leg, distal right leg weakness, a left T-11 sensory level, and absent rectal tone. Magnetic resonance imaging showed an acute intradural hemorrhage in the thoracic and lumbar spine without clear evidence of a vascular abnormality (Fig. 4A). Spinal angiogram with 3D RA demonstrated a fusiform aneurysm of the left posterior spinal artery at level of T-11, fed by the left L-1 segmental artery (Fig. 4B). Tomographic MIP reconstructions from the 3D RA allowed tracing of the feeding artery from the anterior canal to the posterior canal, demonstrating that the aneurysm was fed by the posterior spinal artery (Fig. 4C–F, slow spin of 20°/second). He underwent urgent T10–L1 decompressive laminectomies and obliteration of the left posterior spinal artery aneurysm. The patient made a complete recovery after surgery, was able to ambulate without difficulty, and had normal bowel and bladder functions.

**Case 4**

This 61-year-old man presented to another institution with urinary retention and increased tone in both legs that limited his gait. He underwent L3–5 laminectomies for presumed lumbar stenosis, but his symptoms did not improve following surgery. At presentation to our institution, 10 days after his laminectomies, he had preserved strength in his lower extremities but bilateral ankle clonus and increased tone in both legs (to a greater extent on the right). There was numbness over the dorsal and ventral aspects of both feet, but it was more pronounced on the right. An MRI study showed increased T2 signal in the lower thoracic cord suggestive of venous congestion, and a formal angiogram was performed. The right T-6 segmental artery injection demonstrated arteriove-
nous shunting with early opacification of a large, caudally draining perimedullary vein (Fig. 5A). Analysis of the 3D RA suggested that this lesion represented an AVM with a plexiform nidus located on the right posterior surface of the spinal cord, displacing the cord anteriorly (Fig. 5B–E, fast spin of 40°/second). He underwent T5–6 laminectomies and ligation-resection of the AVM. Postoperatively, the patient’s sensory symptoms improved.

Discussion

Spinal vascular malformations are rare in the general population, and the majority (60%–80%) are in the form of SDAVs. They are usually supplied by dural branches of radicular arteries and drain into medullary veins at the dural sleeve of a nerve root and ultimately into the coronal venous plexus of the spinal cord. Symptoms are thought to arise secondary to vascular steal or venous congestion and may include myelopathy, weakness, sensory disturbance, gait disturbance, and bowel or urinary problems. These lesions are classically difficult to diagnose and may be confused with radiculopathy from degenerative disc disease, neuromuscular disease, or demyelinating neuropathy. The median time from onset of
Fig. 3. Case 2. A–H: Sequential (anterior to posterior) thin-cut coronal reconstructions of the 3D angiogram (the asterisk indicates the fistula point). This technique allows for detailed anatomical views of the SDAVF in relation to the surrounding pedicles, laminae, and disc spaces, essential for preoperative planning.

Fig. 4. Case 3. A 42-year-old man with acute left leg numbness and weakness. Imaging demonstrated a PSA aneurysm that was subsequently clipped. A: Sagittal T2-weighted MR image showing evidence of subarachnoid blood (arrowheads) surrounding the thoracolumbar spinal cord. B: An AP-view DS angiogram obtained with selective left L-1 segmental artery injection demonstrating an aneurysm (asterisk) rostral to the injected level. C–E: Tomographic MIP axial (C), coronal (D), and sagittal (E) reconstructions of a 3D rotational angiogram showing the presence of a PSA aneurysm (asterisk) inferior to the left pedicle of T-11. These images helped to demonstrate that the aneurysm was in the posterior portion of the spinal canal and its precise level relative to the vertebrae. F: Magnified 3D reconstruction of the PSA aneurysm at the T-11 level, fed by the left L-1 segmental artery inferiorly.
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Symptoms to diagnosis of an SDAVF is between 12 and 44 months.13 Spinal artery aneurysms are even less common than fistulas and may occur either in association with an SDAVF22 or in isolation. A recent review reported only 26 cases of ruptured isolated spinal artery aneurysms in the literature.15 Seven of those 26 aneurysms were located on the ASA, 5 on the artery of Adamkiewicz, 4 on the PSA, and the remaining aneurysms were fed by segmental or radiculomedullary branches.

Despite the improvements in technology discussed below, neither cross-sectional imaging modality—MRI or CT—currently approaches the necessary degree of sensitivity and spatial resolution of standard DSA to rule out spinal vascular lesions. Therefore, DSA remains the “gold standard” in the diagnosis of these often-elusive spinal vascular lesions. Magnetic resonance imaging has emerged as the standard initial diagnostic screening tool for the workup of SVMs. Characteristic MRI findings of SDAVF include centrally located T2 hyperintensity with peripheral sparing12 and tortuous “flow voids” on both T1- and T2-weighted images.7 Contrast enhanced MRA has been used to visualize SVMs in multiple studies with promising results. Binkert and colleagues6 reviewed MRA and DSA studies performed in 12 consecutive patients with suspected SVMs and found that MRA correctly identified the categories of 9 vascular lesions (6 AVMs, 3 SDAFVs). Mull et al.20 studied how accurately MRA could localize SVMs compared with DSA and reported that MRA-derived spinal levels agreed with DSA in 14 of 19 SDAFV cases. Ali et al.1 used the newer technology of dynamic multiphase time-resolved MRA in 11 patients with suspected SVMs. The authors correctly diagnosed 6 vascular lesions and were able to localize within 1 vertebral level in 5 of the 6 cases. In general, however, the imaging quality of MR-based modalities is easily affected by motion degradation secondary to respirations, especially in the thoracolumbar region, and the spatial resolution does not yet approach the sensitivity or anatomical detail provided by standard DSA.19

Three-dimensional CTA has also been used to diagnose spinal vascular lesions and has the advantage of excellent visualization of bony anatomy. Lai et al.18 evaluated 8 patients with suspected SDAVF via multidetector CTA and DSA and reported good correlation between the 2 modalities in all 8 cases. Differentiation of arterial from venous phases on “dynamic” multidetector CTA has proven to be quite challenging and tends to degrade imaging quality.19

The utility of 3D RA has been described before, specifically by those evaluating its role in the endovascular treatment of spinal vascular lesions. Prestigiacomo et al.24 reviewed their experience with 17 3D spinal angiograms in 14 patients, who had undergone angiography for the diagnosis and treatment of a variety of SVMs. Surgical planning for hemangioblastoma resection after embolization has also benefitted from the use of 3D rotational angiograms, as described by Kern et al.16 One significant technical difference in our approach is the ability

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**Fig. 5.** Case 4. A 61-year-old man with a history of myelopathy and urinary retention. Previous lumbar decompression for radiographic stenosis did not relieve his symptoms. MR imaging of the spine was nondiagnostic, but an angiogram revealed a pial AVM. Surgery confirmed this diagnosis and he underwent thoracic laminectomies and surgical obliteration of the AVM. **A:** Preoperative DS angiogram, AP view of the right T-6 segmental artery injection showing the malformation. **B–D:** Tomographic MIP axial (B), coronal (C), and sagittal (D) reconstructions of a 3D rotational angiogram demonstrating the nidus of the pial AVM and its relation to the vertebral canal. The asterisk indicates the plexiform nidus; the arrow, a perimedullary draining vein. **E:** A 3D reconstruction of the pial AVM (asterisk) with a T-6 segmental artery feeder (arrowhead) and draining perimedullary vein (arrow).
to choose varying rotational speeds depending on the amount of soft tissue and bony details desired from the angiogram. Fast spin (40°/second, used for all 3D rendering models) allows crisp vascular imaging with relatively less soft tissue information. Slow spin (20°/second, used for Case 2 as described above) maximizes bony detail in addition to providing good delineation of angioarchitecture. The quality of rotational spinal angiography can be influenced by the stability of the catheter position and the degree of cooperation from the patient if he or she is not in a state of general anesthesia. High-flow AVMs may not allow a sufficient volume of contrast agent to be injected during the rotation flow." In addition, image quality can be limited due to respiratory artifacts. Rotational spinal angiography does require marginally more contrast medium (10–20 ml) than standard 2D DSA, but does not expose the patient to significantly more radiation (Table 1). Radiation exposure in our series was comparable to that reported in the spinal angiography literature. Furthermore, the mean dose area product (DAP) (409.5 Gy·cm²) delivered to patients receiving 3D RA was comparable to the mean DAP (413 Gy·cm²) delivered to patients during cranial aneurysm embolization procedures.

The cases presented in this series demonstrate the specific benefits of 3D RA as an adjunct to traditional DSA—in particular the utility and superior anatomical detail provided by the adjustable tomographic MIP images, as well as the volume-rendered 3D reconstructions. Rapid, near real-time postprocessing of the image dataset allowed us to create a 3D model of the lesion and tumble it in any desired projection. Features of the malformation can be easily correlated with bony and even soft tissue anatomy. The anatomical detail obtained from these reconstructions in conjunction with the standard DSA findings can be used to better differentiate an SDAVF from an AVM, as in Case 4 in the current report. Differentiation of an aneurysm associated with the anterior versus posterior spinal artery, as in Case 3, is absolutely critical when considering treatment options such as sacrifice of an artery. Ligation of the PSA is usually well tolerated, whereas sacrifice of a major ASA contribution can have devastating effects. Tracing a vascular malformation on 3D reconstructions and the corresponding tomographic MIP reconstructions provides precise localization of the fistulous connection as demonstrated in the case of Case 2. Placed in the context of the soft tissue and bony anatomy, this high-resolution vascular dataset supplies unprecedented detail while being visually intuitive and therefore easily applicable clinically. Information provided by this advanced imaging tool is likely to improve the planning of endovascular as well as surgical approaches required for lesion obliteration.

Conclusions

In summary, 3D RA is an advanced imaging tool producing extraordinary anatomical detail in the characterization and delineation of spinal vascular pathology and should become a standard part of the invasive workup of these lesions. Routine use of this tool may improve our understanding and management of AVMs, both for open surgical and endovascular approaches.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Frerichs, Ropper, Lin, Thiex. Acquisition of data: Frerichs, Ropper, Lin, Zarzour, Du. Analysis and interpretation of data: Frerichs, Ropper, Lin, Gross, Zarzour. Drafting the article: Frerichs, Ropper, Lin, Gross. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Statistical analysis: Lin. Study supervision: Frerichs.

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Manuscript submitted September 17, 2011.
Accepted January 27, 2012.
Please include this information when citing this paper: DOI: 10.3171/2012.1.FOCUS11254.
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