The use of 3D computer graphics in the diagnosis and treatment of spinal vascular malformations

Clinical article

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Objective. Digital subtraction (DS) angiography is the gold standard for diagnosing spinal vascular malformations. Recently, multidetector-row spiral CT and contrast-enhanced MR angiography have been introduced as screening examinations before DS angiography. These methods, however, do not always determine the accurate location of an arteriovenous shunt because the resulting images lack information about the spinal cord or the dura mater.

Methods. Between April 2009 and December 2010, 13 patients underwent imaging evaluations for spinal vascular malformations at the authors’ university hospital. This group included 8 patients with spinal dural arteriovenous fistulas (AVFs), 3 with perimedullary AVFs, and 2 with intramedullary arteriovenous malformations. Using data from these patients, the authors attempted to develop 3D computer graphics (CG) based upon the fusion of 3D rotational angiography and postmyelographic CT. They subsequently verified the accuracy of this imaging method. Ten of these 13 patients underwent surgical treatment for their lesions (11 AVFs), and for these 11 lesions the authors compared the diagnoses obtained using 3D CG with those obtained using conventional DS angiography.

Results. In all 13 cases, 3D CG images of the spinal lesions were successfully developed using the patients’ actual data. Four (36%) of 11 AVFs were correctly identified using DS angiography, whereas 10 (91%) were correctly identified using 3D CG. Results from 3D CG of spinal AVFs corresponded well with operative findings, and 3D CG was significantly better than conventional DS angiography at predicting AVF location (p = 0.024, Fisher exact test).

Conclusions. To the authors’ knowledge, this is the first reported case series in which 3D CG of spinal vascular malformations was used to provide simultaneous, stereoscopic visualization of the spinal vascular system, spinal cord, dura mater, and bone. The 3D CG method provides precise visual images for the diagnosis and treatment of these lesions. (DOI: 10.3171/2011.8.SPINE111155)

Key Words • 3D computer graphics • spinal arteriovenous malformation • dural arteriovenous fistula • perimedullary arteriovenous fistula • intramedullary arteriovenous malformation • technique

Spinal vascular malformations are classified into types according to their location and vascular pathology and show wide morphological variation. To treat these lesions appropriately, it is essential to determine the relationship between an AV shunt and the spinal cord, dura mater, and bone in detail.1,2,7,11,14 The gold standard for diagnosing spinal vascular malformations is DS angiography.11,14 No other techniques provide results comparable to DS angiography with respect to sensitivity and specificity of diagnosis of these lesions. Recently, 3D rotational angiography has been tested, and this method appears to be superior to conventional 2D DS angiography in its ability to generate stereoscopic images.5,15 However, angiographic images lack information about the spinal cord or dura mater. Multidetector-row spiral CT and contrast-enhanced MR angiography have been used as screening examinations before DS angiography, but these methods also provide little information about the spinal cord or dura mater.9,10,12,15 Consequently, to enable
Use of 3D computer graphics in spinal vascular malformations

visualization of whole spinal vascular malformations, the authors of a number of reports have included medical illustrations and have discussed the results of conventional radiological examinations. To visualize the spinal vascular system, spinal cord, dura mater, and bone simultaneously, we developed 3D computer graphics (3D CG) using the fusion of 3D rotational angiography and post-myelographic CT. We then compared our findings from 3D CG and conventional 2D DS angiography against our intraoperative findings.

Methods

Between April 2009 and December 2010 at our institution, 13 patients (age range 32–88 years, Table 1) were evaluated for spinal vascular malformations. This group included 8 patients with spinal dural AVFs, 3 with perimedullary AVFs, and 2 with intramedullary AVMs. The mean duration of clinical follow-up was 10 months (range 2–22 months). In these 13 cases, we attempted to develop 3D CG as described below. Ten of the patients underwent surgery for the treatment of 11 AVFs (the patient in Case 4 had 2 lesions). The location of each of these 11 lesions was assessed preoperatively by means of 2D DS angiography (by 2 neuroendovascular surgeons blinded to the clinical data) and also by means of 3D CG (by 2 neurosurgeons, K.T. and T.K.). The conventional DS angiography and 3D CG findings were then compared.

Angiography

The associated arteries were identified for each AVF by means of conventional spinal angiography using an Allura Xper FD20/10 angiography unit (Philips). A contrast agent (Omnipaque, Amersham Health) was injected manually into the associated arteries at a rate of 1 ml/second (total volume 20 ml), and rotational angiographic

<table>
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<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Presentation</th>
<th>Type of Spinal AVM</th>
<th>Corresponding Artery of AV Shunt</th>
<th>Treatment</th>
<th>Predicted AVF Location</th>
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<tr>
<td>1</td>
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<td>hemiparesis</td>
<td>dural AVF</td>
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<td>op</td>
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<td>op</td>
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<td>dural AVF</td>
<td>rt T-7, T-8 intercostal artery‡</td>
<td>op</td>
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<td>op</td>
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<td>9</td>
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<td>op</td>
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<td>T-11 perimed portion</td>
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<td>bilat T-9, lt T-11 intercostal arteries‡</td>
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* The intraoperative findings corresponded with the location predicted by 2D DS angiography in 4 (36%) of 11 surgically treated lesions and with the location predicted by 3D CG in 10 (91%) of 11 surgically treated lesions (p = 0.024, Fisher exact test). Abbreviations: APA = ascending pharyngeal artery; CVJ = craniovertebral junction; DSA = DS angiography; intramed = intramedullary; perimed = perimedullary; VA = vertebral artery.
† The patient in Case 4 had 2 AVFs.
‡ Lesions with multiple feeding vessels.
data were acquired through a continuous 180° rotation of the C-arm for a total of 8 seconds. The imaging parameters for 3D rotational angiography were as follows: electrical voltage 80 kV, electrical current 10 mA/second, field of view 7 × 7 × 7 cm, matrix size 512 × 512 × 512.

Postmyelographic CT

Conventional myelography was performed using contrast medium (Omnipaque) injection via lumbar puncture. Lumbar puncture was performed below the level of the feeding vessels. After the procedure, a postmyelographic CT scan was performed on a helical CT scanner (Toshiba). The CT imaging parameters were as follows: electrical voltage 120 kV, electrical current 310 mA, field of view 15 × 15 cm, matrix size 512 × 512, slice thickness 0.5 mm.

Image Processing

The above data set was provided as image stacks coded in the DICOM format and processed using Avizo 6.1 software (Mercury Computer Systems Inc.) on a personal computer (Precision 470, Dell Inc.). The 3D images were visualized using a surface rendering method.8 The threshold was manually determined to optimize the contrast of axial images in each case. Arteries, veins, and abnormal vessels were identified based on anatomical location. The spinal cord and dura mater were visualized using postmyelographic CT. The 3D images obtained through 3D rotational angiography and postmyelographic CT were fused using a normalized mutual information method such that spinal bone in the angiograms and postmyelographic CT overlapped accurately.8 To help diagnose these AVFs and to produce an adequate surgical simulation, we manipulated these 3D images interactively by rotating them and enlarging and reducing their size.

Results

In all 13 cases, we successfully developed 3D CG of the spinal vascular lesions using the fusion of 3D rotational angiography and the postmyelographic CT scan. Arteriovenous shunts were identified correctly in 4 (36%) of the 11 surgically treated AVFs using 2D DS angiography and in 10 (91%) using 3D CG (Table 1). These rates were significantly different (p = 0.024, Fisher exact test). There were no complications associated with angiography or myelography. In all 10 surgical cases (involving 11 AVFs), postoperative DS angiography demonstrated an absence of residual AVF. After surgery, improvement was seen in 4 of 10 cases and the patients’ condition remained stable in the other 6. In the 2 cases treated by means of CyberKnife radiosurgery, the patients’ condition remained stable. CyberKnife treatment is being considered for the remaining patient in this series, who has an intramedullary AVM.

Illustrative Cases

Case 3

This 61-year-old man presented with numbness of both feet and paraparesis that had progressed over 7 months. An MR imaging study showed T2 signal-intensity changes at T-8 to the conus medullaris with surrounding flow voids. Two-dimensional DS angiography showed an AV shunt between the right T-6 intercostal artery and the intradural coronal venous plexus, as well as between the right T-7 intercostal arteries and the intradural coronal venous plexus. On the basis of 2D DS angiography, the location of the AVF was predicted to be in the dura at the right T-6 dorsal root (Fig. 1A). Angiography also showed a shunt between the T-7 intercostal artery and the intradural coronal venous plexus, but the details were not apparent. On the basis of 3D CG, the location was predicted to be in the more proximal portion (Fig. 1B, arrow). Additionally, collateral vessels between the T-6 and T-7 intercostal arteries were confirmed on the dura at the T-7 level (Fig. 1B, arrowhead). The operative findings corresponded exactly with the 3D CG findings (Fig. 1C and D).

Case 5

This 52-year-old man presented with bilateral disturbance of temperature sense on his feet and spasticity of the lower extremities that had progressed over an 8-month period. An MR imaging study showed T2 signal-intensity changes at T7–10 with surrounding flow voids. Two-dimensional DS angiography showed an AV shunt between the left T-8 intercostal artery and the intradural coronal venous plexus. On the basis of 2D DS angiography, the location of the AVF was predicted to be in the dura at the left T-8 dorsal root (Fig. 2A); however,
on the basis of 3D CG, the location was predicted to be in the dura between the T-8 and T-9 vertebrae, distant from the root sleeve (Fig. 2B). The operative findings corresponded exactly with the 3D CG findings (Fig. 2C and D).

Case 9

This 58-year-old woman presented with left hemiparesis due to subarachnoid and intramedullary hemorrhage. An MR imaging study showed intramedullary hemorrhage at the C-6 level. Two-dimensional DS angiography showed an AV shunt between the left C-8 radicular artery and the intradural coronal venous plexus, but obstruction by the shoulder and clavicle on the lateral view prevented accurate confirmation of the lower cervical lesion and identification of the precise location of the AVF (Fig. 3A). Three-dimensional CG showed that the left C-8 radicular artery arose from the vertebral artery at the level of the C-8 foramen and coursed along the center of the anterior aspect of the spinal cord. On 3D CG, the AVF was predicted to be at the perimedullary portion of the cord at the C7–8 level. The location of the dilated venous plexus was predicted to be along the ventrolateral side of the spinal cord (Fig. 3B). The operative findings corresponded exactly with the 3D CG findings (Fig. 3C and D). We divided this AVF, and postoperative DS angiography showed no abnormal dilated vessels.

Case 10

This 61-year-old man presented with numbness of the bilateral lower extremities that progressed over a 4-month period. An MR imaging study showed T2 signal-intensity changes from the level of T-9 to the conus medullaris with surrounding flow voids. Two-dimensional DS angiography showed an AV shunt between the left T-12 subcostal artery and the intradural coronal venous plexus. (We did not use 3D CG in this case until after the first operation.) On the basis of 2D DS angiography, this lesion was diagnosed as a dural AVF and the location of the AVF was predicted to be in the dura at the left T-12 root sleeve (Fig. 4A). The shunt was surgically divided at the right T-12 root sleeve, but postoperative DS angiography showed another AV shunt between the L-1 lumbar artery and the intradural coronal venous plexus. On the basis of 3D CG, the location of the AVF was predicted to be on the perimedullary portion of the cord at the T-11 level (Fig. 4B). A second operation was undertaken. The intraoperative findings confirmed the location of the perimedullary AVF and corresponded exactly with the 3D CG findings (Fig. 4C and D).

Case 12

This 38-year-old woman presented with mild gait disturbance. T2-weighted MR imaging showed intramedullary flow voids at the T10–11 level. Two-dimensional DS angiography showed a large nidus fed by the bilateral

![Fig. 2. Case 5. Dural AVF. A: A 2D DS angiogram showing the predicted location of the AVF in the dura at the left T-8 dorsal root (arrow). B: A 3D CG image showing the predicted location in the dura at T-8 and T-9 dorsal portion distant from the root sleeve (arrow). C and D: Intraoperative photographs showing exact correspondence with the 3D CG findings (arrows).](image1)

![Fig. 3. Case 9. Perimedullary AVF. A: A 2D DS angiogram showing that the location of the AVF could not be exactly predicted with this technique. B: A 3D CG image showing the left C-8 radicular artery arising from the vertebral artery at the level of the C-8 foramen and running along the center of the anterior aspect of the spinal cord; the AVF was predicted to be perimedullary at the C7–8 level. C and D: Intraoperative photographs showing exact correspondence with the 3D CG findings.](image2)
T-9 and left T-11 intercostal arteries (Fig. 5A–C). Three-dimensional CG allowed visualization of an intramedullary AVM being fed by these 3 arteries (Fig. 5D–F). In this case, CyberKnife treatment is under consideration because the feeding artery from the right T-9 artery was believed to be the Adamkiewicz artery, and the case therefore represents a potentially high operative risk.

Discussion

In this study, we successfully developed 3D CG of spinal vascular malformations using our patients’ actual data. To the best of our knowledge, this is the first case series of 3D CG of such lesions. We found that 3D CG corresponded more precisely with operative findings than conventional 2D DS angiography in predicting the locations of AVFs. The reason 3D CG is superior to 2D DS angiography in the diagnosis of spinal vascular malformations is because 3D CG allows simultaneous, stereoscopic visualization of the spinal vascular system, spinal cord, dura mater, and bone. Interactive manipulation of these 3D images allowed us to observe the lesions from multiple directions at higher magnification. Any tissue could be made transparent, and virtual-reality operations, including bone elimination, were available. Consequently, the images proved useful in correctly diagnosing AVFs as well as in preoperative simulations for deciding the optimal surgical approach and the range of spinal laminectomy.

Conventional angiography allows visualization of the
spinal level of an AVF based on information about the spinal body of the vertebra; the detailed relationship between the AVF and the spinal cord or dura, however, remains obscure. Because 2D DS angiograms lack information about the spinal cord or dura mater, the penetrating portion of the dural AVF or the position of the perimedullary AVF was not readily evident on these images in most cases. Conventional MR images allow visualization of the degree and range of spinal edema or flow void around the spinal cord, but the positional relationship between an AV shunt and the spinal cord or dura is ambiguous.

The 3D CG method does have some limitations. First, it requires lumbar puncture for myelography. To reduce the invasiveness, lumbar puncture was performed below the level of the feeding vessels. In our case series, there were no complications associated with myelography. Second, the accuracy of the fusion of 3D rotational angiography and postmyelographic CT data can be problematic in patients with multilevel lesions. The 3D images resulting from both examinations were fused using normalized mutual information methods such that spinal bone in both images overlapped accurately. Overlapping of one vertebral body can generally be achieved quite easily, but images of multiple vertebral bodies cannot be overlapped accurately if the spine bends or rotates, especially in cervical or lumbar regions. Therefore, to minimize spinal movement, a flat bed with a headrest and a lumbar pad should be used if the patient has multilevel AVFs. Third, there is no dynamic information on blood flow in the 3D CG method in contrast to conventional 2D DS angiography. Arteries, veins, and abnormal vessels were identified based on anatomical location. Therefore, pathological examination is required for differential diagnosis with respect to the identification of these vessels. Finally, the present study was limited to a small series of patients, and assessment of the accuracy of 3D CG diagnosis was based on the judgments of our own investigators. Therefore, further evidence-based studies comparing 3D CG with other imaging methods are needed in a larger series of patients. Despite the limitations described above, we believe that this new imaging technology offers an interesting and valuable step in the diagnosis and treatment of spinal AVM.

Conclusions

Three-dimensional CG provides precise visual images for the diagnosis and treatment of spinal vascular malformations.

Disclosure

The authors report no conflicts 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: Takai. Acquisition of data: Takai, Kin. Analysis and interpretation of data: Takai, Kin, Iijima, Shojima, Nishido. Drafting the article: Takai. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Takai. Statistical analysis: Takai. Study supervision: Saito.

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