INTEGRATION OF THREE-DIMENSIONAL ROTATIONAL ANGIOGRAPHY IN RADIOSURGICAL TREATMENT PLANNING OF CEREBRAL ARTERIOVENOUS MALFORMATIONS

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Purpose: Accuracy in delineating the target volume is a major issue for successful stereotactic radiosurgery for arteriovenous malformations. The aim of the present study was to describe a method to integrate three-dimensional (3D) rotational angiography (3DRA) into CyberKnife treatment planning and to investigate its potential advantages compared with computed tomography angiography (CTA) and magnetic resonance angiography.

Methods and Materials: A total of 20 patients with a diagnosis of cerebral arteriovenous malformation were included in the present study. All patients underwent multislice computed tomography and 3D-volumetric CTA, 3DRA, and 3D magnetic resonance angiography. The contouring of the target and critical volumes was done separately using CTA and thereafter directly using 3DRA. The composite, conjoint, and disjoint volumes were measured.

Results: The use of CTA or 3DRA resulted in significant differences in the target and critical volumes. The target volume averaged 3.49 ± 3.01 mL measured using CTA and 3.26 ± 2.93 mL measured using 3DRA, for a difference of 8% (p < .05). The conjoint and disjoint volume analysis showed an 88% volume overlap. The qualitative evaluation showed that the excess volume obtained using CTA was mostly tissue surrounding the nidus and venous structures. The mean contoured venous volume was 0.67 mL measured using CTA and 0.88 mL (range, 0.1–2.7) measured using 3DRA (p < .05).

Conclusions: 3DRA is a volumetric angiographic study that can be integrated into computer-based treatment planning. Although whether 3DRA provides superior accuracy has not yet been proved, its high spatial resolution is attractive and offers a superior 3D view. This allows a better 3D understanding of the target volume and distribution of the radiation doses within the volume. Additional technical efforts to improve the temporal resolution and the development of software tools aimed at improving the performance of 3D contouring are warranted.

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INTRODUCTION

Stereotactic radiosurgery (SRS) is an effective treatment modality for properly selected cerebral arteriovenous malformations (AVMs). This procedure can result in the obliteration of the AVM, after a latency of 24–36 months, in 60–90% of cases (1–3). Several factors will influence the outcome of SRS for AVMs, including the nidus volume, prescription dose, patient age, lesion location, angioarchitecture, and previous embolization (1–6). Accuracy in delineating the target volume has been a major issue (2, 7, 8). The entire nidus should be included in the target volume to achieve obliteration of the AVM; at the same time, highly conformal treatment should be delivered to reduce the risk of radiation-induced brain complications.

Biplanar digitally subtracted angiography (DSA) remains the benchmark imaging modality to delineate cerebral AVMs in SRS treatment planning. At present, DSA is the only imaging study that can provide sufficient temporal resolution to study the AVM hemodynamics (9). It also provides the greatest spatial resolution. Nevertheless, when using DSA, the target volume is reconstructed from the contours drawn independently on two or more perpendicular or...
oblique two-dimensional (2D) views, using stereo-viewing conditions. Because of the bidimensional nature of DSA, the three-dimensional (3D) target volume cannot be reconstructed with complete accuracy (10). This limitation of DSA has long been acknowledged, especially in the case of complexly shaped AVMs (11).

The CyberKnife (Accuray, Sunnyvale, CA) is a frameless system for SRS. It uses noninvasive image-guided localization, a lightweight high-energy radiation source, and a robotic delivery system to deliver SRS in single or multiple sessions (12–14). With the CyberKnife, the reference coordinates for the intracranial space are not provided by a stereotactic frame but are obtained directly from the skull. A skull-tracking system compares the pretreatment computed tomography (CT) images with images of the skull obtained during treatment delivery. Accordingly, the use of biplanar stereotactic DSA is not available for this frameless SRS system. Instead, volumetric imaging, such as 3D-CT angiography (CTA) and 3D magnetic resonance (MR) angiography (MRA), are used. Both CTA and MRA improve the 3D target volume definition, but they can lack sufficient spatial and temporal resolution to discriminate among the nidus, normal vessels, such as the feeding arteries or draining veins, and the immediately surrounding normal brain. Therefore, an improvement in CyberKnife treatment planning demands an imaging modality that is both angiographic and truly three-dimensionally navigable.

Three-dimensional rotational angiography (3DRA) is a volumetric angiographic study generated from a rotational sequence of biplanar DSA images. Because of its planar reconstruction in Digital Imaging and Communications in Medicine (DICOM) format, it can be included in CyberKnife treatment planning. The aim of the present report is to describe a simple method to integrate the 3DRA volume images into CyberKnife treatment planning and to investigate its potential advantages compared with conventional CTA in the treatment of cerebral AVMs using the CyberKnife SRS system.

METHODS AND MATERIALS

Patients

A total of 20 patients (12 men and 8 women, mean age, 52 years; range, 13–72) with a diagnosis of cerebral AVM underwent SRS at the CyberKnife Center of the University of Messina (Messina, Italy) between July 2007 and March 2010. A prospective review of these cases was undertaken. A multidisciplinary team of neurosurgeons, radiation oncologists, and neuroradiologists evaluated each patient for treatment eligibility and treatment parameters. All patients provided informed consent before enrollment in the present institutional review board-approved clinical study.

Image acquisition

CT angiography. Three-dimensional volumetric CTA was performed using a multislice CT scanner (Siemens Sensation 16, Siemens, Erlangen, Germany). A nonionic contrast medium (Ultravist, 300 mg/mL, Bayer-Schering, Berlin-Wedding, Germany) was injected, in amounts ranging from 1.7 to 2.5 mL/kg, depending on the patient body weight. The injection was performed at a rate of 1.5 mL/s. Image acquisition was performed after a patient-specific delay, using internal carotid artery bolus tracking. The CT protocol was elaborated according to the CyberKnife-specific requirements (acquisition, 16 × 0.75 mm; 120 kV; 320 mA; rotation time, 1 s; and pitch, 0.45; and reconstruction, 1-mm slice thickness, 1-mm reconstruction increment; filter reconstruction B30, smooth; and 512 × 512 matrix).

MR angiography. Magnetic resonance imaging and MRA were performed using a Magnetom Vision 1.5 T scanner (Siemens). A multiplanar reformatting, gradient echo, contrast-enhanced volumetric study was performed with the following parameters: repetition time, 9.7 ms; echo time, 4 ms; 200 × 256 matrix; 12° flip angle; 0.88-mm slice thickness; number of excitations (NEX): 1; and sagittal orientation. For the angiographic portion of the study, a 3D time of flight MRA acquisition sequence was performed with the following parameters: repetition time, 39 ms; echo time, 6.5 ms; 192 × 512 matrix; 20° flip angle; 1.25-mm slice thickness; nes: 1.

3D rotational angiography. Two-dimensional angiographic examinations were performed using a commercially available biplanar angiographic unit (Axiom Artis, Siemens). Selective four- or six-vessel angiography, using a standard projection format, was performed initially, and additional views were obtained if required to identify the parent vessel and aneurysm neck more clearly.

Rotational angiography was performed using the frontal plane of a biplanar C-arm. The C-arm rotates in a continuous 180° (+90° to −90°) arc with the path of the x-ray tube. The isocenter for the rotational field was the area of interest in the patient’s head.

A total of 133 digital angiograms with a 512 × 512 matrix were obtained during the 180° rotation of the C-arm. The total rotation and angiogram acquisition was accomplished within 8 s.

Rotation of the C-arm was first performed without injection to acquire the masks, then the C-arm was rotated back to the initial position, and, finally, the C-arm was rotated again during contrast material injection. The acquisition can be made in any of the fields of view available for DSA (i.e., 33, 22, or 16 cm). With an automatic injector, 14 mL of 300 mg/mL of iopamidol contrast material was injected at a rate of 2 mL/s in either the internal carotid or vertebral artery; this provided continuous filling of the intracranial arteries during rotational angiography.

Both the mask data and the contrast data were electronically transferred to the workstation (Leonardo, Siemens). A 3D reconstruction algorithm using an algebraic reconstruction technique was used to digitally produce 3D DSA images on the workstation within 8 minutes. The reconstructed images, including the maximal intensity projection, surface shaded display, and virtual endoscopic view, were made available from the data.

Image processing

The rotational sequence was used as input to a tomographic reconstruction algorithm that produced as output a 3DRA volume on a cube of 256 × 256 × 256 voxels. The resulting volume was a relatively high-resolution 3D reconstruction of the vasculature, the 3D rotational angiogram.

A volumetric data set, the 3D (multiplanar reformating) full-native image set, was sent from the Leonardo angiographic workstation to the CT Siemens Sensation 16 workstation (Siemens). The volume was segmented using a maximal intensity projection algorithm with a 1-mm slice thickness and 1-mm reconstruction increments and then sent to the CyberKnife workstation. The 2D cut planes, obtained from the 3DRA image, were used as the secondary images to be coregistered with the CTA images. Subsequently,
conventional 2D contouring in the three planes (sagittal, coronal, and axial) was performed (Fig. 1). In all cases, thin-slice contrast-enhanced, volumetric MR images were also obtained (Siemens Magnetom 1.5 T, Siemens). The treating surgeons manually outlined critical structures (i.e., brainstem, optic chiasm, optic nerves, eyes) on the MR images using the MultiPlan software (Accuray, Sunnyvale, CA).

The contouring of the target volume was performed separately using the CTA and thereafter directly using 3DRA. To achieve real 3D contouring, an iterative delineation on the 2D angiographic cut planes and directly on the 3DRA using the 3D visualization tool of the treatment planning system was performed (Fig. 2). A qualitative and quantitative comparison of the target volumes obtained using CTA and 3DRA was performed (Fig. 3). The analysis of conjoint (overlapping) and disjoint (mutually exclusive) volumes was also performed (15, 16). The analysis was performed using the MultiPlan system tools according to the following steps: (1) a first volume was obtained from the CTA; (2) a second volume was obtained, without knowledge of the first volume, using 3DRA; (3), the two volumes were recalled and superimposed; and (4) the conjoint volume was measured and two new volumes were defined: the CTA outside the 3DRA volume and the 3DRA outside the CTA volume.

**SRS treatment planning**

After completing the contouring procedure, the treatment was planned using the MultiPlan software. The treatment plans were developed to have a prescription dose to the target of 20 Gy. The dose limits to the critical structures were subsequently determined according to established radiosurgical experience. The optimal collimator dimension was selected according to the volume and shape of the target, depending primarily on the minimal target cross-sectional dimension. An inverse planning optimization procedure could then be initiated. To ensure that the treatment plans from CTA and 3DRA were comparable, we sought to achieve the same prescription dose and target coverage for each plan.

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Fig. 1. (Upper Left) Two-dimensional cut planes of skull in three views (sagittal, axial, and coronal) derived from three-dimensional rotational angiography volumetric data set. (Upper Right) Corresponding images obtained from using conventional computed tomography angiography. Three-dimensional rotational angiography showed better spatial resolution. (Lower) Three-dimensional rotational angiography (Left) and computed tomography angiography (Right) were coregistered using image fusion procedure based on mutual information algorithm with bony edges as landmarks.
Finally, we used plans optimized for the first imaging modality (CTA) to calculate the dosimetric indexes for critical structures and target derived from the second imaging modality (3DRA).

Statistical analysis

Statistical analysis was accomplished using the Wilcoxon matched pairs test. The data analysis was performed using Instat, version 3.0, and Prism, version 4.0 (GraphPad, San Diego, CA). The values are expressed as the mean ± standard deviation.

RESULTS

The treatment parameters and statistics are summarized in Table 1. A detailed comparison of the target volumes obtained using CTA and 3DRA is reported in Table 2. The mean target volume was larger for the CTA-based plans (3.49 ± 3.01 mL) than for those constructed using 3DRA (3.26 ± 2.93 mL; \( p < .05 \)). The CTA-based target volumes were larger than those constructed using 3DRA by 0.23 ± 0.23 mL, resulting in an average difference of 8%. To assess whether the volumes were coincident, we measured the conjoint and disjoint volumes according to the method of Buis et al. (19) and Hamm et al. (20). The overlap of the two volumes was 88.4% ± 5.8% (Fig. 4). The volume included in the target using CTA that was not contoured using the 3DRA was 0.31 ± 0.25 mL, and the volume included using 3DRA that was not present in the CTA-based contour was 0.08 ± 0.09 mL.

In all cases, the draining veins were contoured as a critical volume. The mean contoured venous volume was significantly smaller using the CTA-based plans (0.67 mL; range, 0.07–2.3) than using the 3DRA-based plans (0.88 mL; range, 0.1–2.7; \( p < .05 \)). Also, a qualitative evaluation showed that the excess volume obtained using CTA, not ascribable to venous structures, was mostly peripheral (Fig. 3), namely at the interface between the AVM and the brain.

In both treatment plans, the average prescription isodose line was 79% (range, 75–84%), and the maximal dose to the target averaged 2,466 cGy (range, 2,380–2,663). The coverage of the target was >91%. The size of the collimators, average number of beams, conformity index, and homogeneity index did not differ between the two treatment plans (Table 1).

We also calculated the radiation dose received by the venous structures, including the maximal dose, dose to 1% of the volume, dose to 90% of the volume, volume irradiated to 50% of the maximal dose, and volume irradiated to the target using CTA that was not contoured using the 3DRA was 0.31 ± 0.25 mL, and the volume included using 3DRA that was not present in the CTA-based contour was 0.08 ± 0.09 mL.

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**Fig. 2.** Contouring of target volume performed in two dimensions with contextual and iterative visualization of target volume in three dimensions. Three-dimensional view allowed full three-dimensional navigation of target volume (Right). Artificial landmarks (blue, green, and yellow circles) were created to maintain orientation in three-dimensional view.

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**Fig. 3.** (A) Large arteriovenous malformation of left sylvian fissure directly visualized in three dimensions and two biplanar views (sagittal and coronal). (B) First target volume (blue) obtained using computed tomography angiography. (C) Second target volume (red) obtained using three-dimensional rotational angiography. (D) Analysis of conjoint (overlapping) volumes performed by superimposing both volumes. (E) Quantitative and qualitative analysis of disjoint (mutually exclusive) volume was also possible. The volume obtained using computer tomography angiography exceeded that contour using the 3D rotational angiography. This exceeding volume, here shown in yellow, turned out to be a shell of normal brain tissue surrounding the nidus and portions of the draining veins.
20% of the maximal dose (Table 1). No substantial differences were found between the CTA-based and 3DRA-based plans (Table 1). When the plans optimized for CTA-based contours were used to calculate the dosimetric indexes for the critical structures and target derived using 3DRA, the conformality index increased to 1.45 (p < .01). The maximal dose and dose to 1% of the critical venous volumes increased to 2,237 cGy and 2,189 cGy, respectively (p < .01). The volume irradiated to 50% of the maximal dose of the critical venous volumes increased to 1.3 mL (p < .01; Table 1).

### DISCUSSION

The integration of 3DRA into our SRS treatment planning enabled full 3D contouring. It was possible to outline the target volume in the primary planes (i.e., axial, coronal, and sagittal) with contextual 3D visualization and full navigation of the AVM (Fig. 2), an opportunity not possible with CTA or DSA. The use of 3D imaging led us to eliminate substantial volumes of apparently normal tissue from the final target (Fig. 3) and, in some instances, to add abnormal vascular

### Table 1. Summary of treatment parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CTA contouring</th>
<th>3DRA contouring</th>
<th>CTA-based plans applied to 3DRA-based contours</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose to target (cGy)</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
<td>NS</td>
</tr>
<tr>
<td>Dmax to target (cGy)</td>
<td>2,466 (2,380–2,663)</td>
<td>2,466 (2,380–2,663)</td>
<td>2,466 (2,380–2,663)</td>
<td>NS</td>
</tr>
<tr>
<td>Prescription isodose (%)</td>
<td>79.3 (75–84)</td>
<td>79.3 (75–84)</td>
<td>79.3 (75–84)</td>
<td>NS</td>
</tr>
<tr>
<td>Target volume (mL)</td>
<td>3.49 (0.26–11.9)</td>
<td>3.26 (0.22–10.7)</td>
<td>3.26 (0.22–10.7)</td>
<td>&lt;.05*</td>
</tr>
<tr>
<td>Target coverage (%)</td>
<td>94.5 (91.2–97.1)</td>
<td>95.1 (91.2–97.3)</td>
<td>98.3 (93.2–99.1)</td>
<td>&lt;.05†</td>
</tr>
<tr>
<td>Beams (n)</td>
<td>183 (138–231)</td>
<td>183 (138–231)</td>
<td>183 (138–231)</td>
<td>NS</td>
</tr>
<tr>
<td>Conformality index</td>
<td>1.3 (1.1–1.59)</td>
<td>1.3 (1.1–1.59)</td>
<td>1.45 (1.23–1.67)</td>
<td>&lt;.05†</td>
</tr>
<tr>
<td>Homogeneity index</td>
<td>1.3 (1.1–1.33)</td>
<td>1.3 (1.1–1.33)</td>
<td>1.3 (1.1–1.33)</td>
<td>NS</td>
</tr>
<tr>
<td>Critical venous volumes (mL)</td>
<td>0.67 (0.07–2.3)</td>
<td>0.88 (0.1–2.7)</td>
<td>0.88 (0.1–2.7)</td>
<td>&lt;.05*</td>
</tr>
<tr>
<td>Dmax to critical venous volumes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1% to critical venous volumes</td>
<td>2,166</td>
<td>2,131</td>
<td>2,237</td>
<td>&lt;.05†</td>
</tr>
<tr>
<td>D90% to critical venous volumes (cGy)</td>
<td>&lt;300</td>
<td>3.26 (0.1–2.7)</td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>V50% of critical venous volumes (mL)</td>
<td>0.27</td>
<td>0.32</td>
<td>1.3</td>
<td>&lt;.05†</td>
</tr>
<tr>
<td>V20% of critical venous volumes (mL)</td>
<td>0.59</td>
<td>0.65</td>
<td>0.72</td>
<td>NS</td>
</tr>
</tbody>
</table>

**Abbreviations:** CTA = computed tomography angiography; 3DRA = three-dimensional rotational angiography; NS = not significant; Dmax = maximal dose; D1% = dose to 1% of volume; V50% = volume irradiated to 50% of maximal dose; V20% = volume irradiated to 20% of maximal dose.

Data in parentheses are ranges.

* Statistically significant difference between CTA-based and 3DRA-based plans.

† Statistically significant difference between CTA-based plans and same plans applied to 3DRA-based contours.

### Table 2. Comparison of target volumes obtained using CTA and 3DRA

<table>
<thead>
<tr>
<th>Pt. No.</th>
<th>CTA (mL)</th>
<th>3DRA (mL)</th>
<th>Δ CTA vs. 3DRA (mL)</th>
<th>Overlap (mL)</th>
<th>CTA outside 3DRA (mL)</th>
<th>3DRA outside CTA (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.68</td>
<td>0.57</td>
<td>0.11 (16.4)</td>
<td>0.50 (73.6)</td>
<td>0.18</td>
<td>0.07</td>
</tr>
<tr>
<td>2</td>
<td>1.36</td>
<td>1.50</td>
<td>0.07 (4.3)</td>
<td>1.46 (93.4)</td>
<td>0.10</td>
<td>0.04</td>
</tr>
<tr>
<td>3</td>
<td>3.43</td>
<td>3.22</td>
<td>0.21 (6.1)</td>
<td>3.12 (91)</td>
<td>0.31</td>
<td>0.10</td>
</tr>
<tr>
<td>4</td>
<td>3.77</td>
<td>3.65</td>
<td>0.12 (3.1)</td>
<td>3.49 (92.6)</td>
<td>0.28</td>
<td>0.16</td>
</tr>
<tr>
<td>5</td>
<td>1.10</td>
<td>1.02</td>
<td>0.08 (7.4)</td>
<td>0.99 (89.6)</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>6</td>
<td>9.68</td>
<td>9.55</td>
<td>0.13 (1.3)</td>
<td>9.23 (95.4)</td>
<td>0.44</td>
<td>0.32</td>
</tr>
<tr>
<td>7</td>
<td>1.46</td>
<td>1.32</td>
<td>0.14 (9.8)</td>
<td>1.30 (89.2)</td>
<td>0.16</td>
<td>0.01</td>
</tr>
<tr>
<td>8</td>
<td>0.26</td>
<td>0.22</td>
<td>0.03 (13.3)</td>
<td>0.19 (74.2)</td>
<td>0.07</td>
<td>0.03</td>
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<td>9</td>
<td>1.43</td>
<td>1.27</td>
<td>0.16 (11.3)</td>
<td>1.23 (86)</td>
<td>0.20</td>
<td>0.04</td>
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<tr>
<td>10</td>
<td>11.89</td>
<td>10.77</td>
<td>1.12 (9.4)</td>
<td>10.64 (89.5)</td>
<td>1.25</td>
<td>0.13</td>
</tr>
<tr>
<td>11</td>
<td>3.46</td>
<td>3.27</td>
<td>0.19 (5.5)</td>
<td>3.24 (93.8)</td>
<td>0.21</td>
<td>0.02</td>
</tr>
<tr>
<td>12</td>
<td>3.65</td>
<td>3.50</td>
<td>0.16 (4.3)</td>
<td>3.21 (88)</td>
<td>0.44</td>
<td>0.28</td>
</tr>
<tr>
<td>13</td>
<td>1.52</td>
<td>1.32</td>
<td>0.21 (13.7)</td>
<td>1.29 (84.5)</td>
<td>0.24</td>
<td>0.03</td>
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<tr>
<td>14</td>
<td>8.01</td>
<td>7.57</td>
<td>0.45 (5.6)</td>
<td>7.54 (94.1)</td>
<td>0.47</td>
<td>0.03</td>
</tr>
<tr>
<td>15</td>
<td>1.43</td>
<td>1.29</td>
<td>0.15 (10.1)</td>
<td>1.23 (85.5)</td>
<td>0.21</td>
<td>0.06</td>
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<tr>
<td>16</td>
<td>3.22</td>
<td>3.00</td>
<td>0.22 (6.7)</td>
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<td>0.22</td>
<td>0.00</td>
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<tr>
<td>17</td>
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<td>1.53</td>
<td>0.16 (9.3)</td>
<td>1.47 (87.2)</td>
<td>0.22</td>
<td>0.06</td>
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<td>18</td>
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<td>3.01 (90.1)</td>
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<td>0.11</td>
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<td>19</td>
<td>5.63</td>
<td>5.23</td>
<td>0.40 (7.1)</td>
<td>5.11 (90.8)</td>
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<tr>
<td>20</td>
<td>2.54</td>
<td>2.24</td>
<td>0.30 (11.7)</td>
<td>2.21 (87.1)</td>
<td>0.33</td>
<td>0.03</td>
</tr>
<tr>
<td>Mean</td>
<td>3.49</td>
<td>3.26</td>
<td>0.23 (8.1)</td>
<td>3.17 (88.4)</td>
<td>0.31</td>
<td>0.08</td>
</tr>
<tr>
<td>SD</td>
<td>3.01</td>
<td>2.93</td>
<td>0.23 (3.9)</td>
<td>2.88 (5.8)</td>
<td>0.25</td>
<td>0.09</td>
</tr>
</tbody>
</table>

**Abbreviations:** Pt. No. = patient number; SD = standard deviation; other abbreviations as in Table 1.

The values outside of brackets are expressed in mL, those in brackets are in percentage.

* Statistically significant.
structures to the final target. In particular, because of the high spatial resolution of 3DRA, we had a better understanding of the interface between the AVM and the surrounding brain tissue, which was more blurred using CTA (Fig. 3). Moreover, the 3D view allowed the identification of vascular structures adjacent to the nidus, in particular the venous structures, that could be excluded from the final target volume (Fig. 5).

Current SRS treatment planning systems can use the 3D information obtained from CT and MR imaging scans to contour the target volume. Nonetheless, the use of stereotactic 2D DSA for AVM radiosurgery is still considered by many to be the standard of care. DSA offers the best temporal resolution because a series of images can be obtained at different phases after contrast medium injection, allowing a clearer differentiation between the AVMs’ arteriolar nidus (the target volume) and the normal vessels, such as the feeding arteries or draining veins (critical volumes). DSA also offers superior spatial resolution, which is essential for SRS of dural arteriovenous fistulas and for better definition of partially embolized AVMs.

However, the use of stereotactic DSA alone has been recognized as a source of inaccuracy (11, 17, 18). A 3D definition of the target is required for radiosurgery, but DSA presents a 2D view of the nidus. This can lead to error in estimating the actual nidus size, both because the 3D structure of the AVM is usually not fully interpretable from the 2D reconstructions and because the feeding arteries and draining veins can be superimposed on the 2D DSA view (19). This limitation can be particularly relevant in the case of complexly shaped AVMs (19, 20).

The coregistration of stereotactic 2D DSA with stereotactic 3D CTA or MRA has been advocated as a possible strategy to overcome those shortcomings. Kondziolka et al. (21) compared 3D MRA and stereotactic angiography in 28 patients with AVMs. They reported that in 16 cases (57%), MRA revealed 3D features that were not apparent from the 2D angiograms alone. However, in 1 case, conventional angiography showed a vascular anomaly not visualized on MRA. Bednarz et al. (22) evaluated the advantages of using 3D time-of-flight MRA as an adjunct to conventional

Fig. 5. Comparison between target volume obtained using (Left) computed tomography angiography and (Right) three-dimensional rotational angiography in three-dimensional rendering of small arteriovenous malformation. Three-dimensional rotational angiography-based contouring resulted in definition of final volume harmonic with anatomic structure of those vascular malformations. Three-dimensional view allowed qualitative characterization of target, with clear identification of nidus, draining veins, feeders, and neoangiogenesis.
stereotactic angiography to obtain 3D information. In 12 (55%) of 22 cases, including MRA, the information led to modification of the SRS plan, with a mean coverage of the MRA nidus by the angiography-based plan of 93%. However, in 10 (45%) of 22 cases, both MRA and MR imaging failed owing to clip artifacts and embolization material. The investigators concluded that MRA increased conformity but could only be used alone for patients who had not previously undergone embolization or surgery and who had medium-size, compact nidi. Zhang et al. (23) compared the estimated nidus volume using conventional DSA, 3D rendering of the target volume reconstructed from bidimensional DSA, and combined CT-DSA plans. They described a significant mean nidus volume reduction of 32% using 3D-rendered DSA plans and an additional significant reduction of 10% using CT-DSA plans. The mean overlapping volume between the CT plans and CT-DSA plans was 64%. Hamm et al. (20) analyzed the data from 34 patients for whom MR imaging and MRA 3D time-of-flight data sets were used to define the target volumes. The target volumes compared with those obtained using stereotactically localized CT and DSA. The median volume was 2.14 cm³ for the DSA volume and 3.07 cm³ for the final volume. This difference was statistically significant. Nevertheless, in 3 cases, outlining the AVM was not possible without DSA because of a fistulous nidus. All these studies have demonstrated that 3D stereotactic imaging is essential for conformal treatment of an AVM nidus and to preserve the surrounding normal tissue and vascular critical volumes. Also, angiographic imaging is essential for a correct understanding of the angioarchitecture, especially in cases of partially embolized AVMs or complex AVMs with a fistulous nidus or neoangiogenesis.

Treatment planning for CyberKnife radiosurgery uses CT data for target definition and a skull tracking system to define the intracranial space instead of a stereotactic frame (12–14). The use of conventional stereotactic DSA is, therefore, not available for this frameless SRS device. Nevertheless, CyberKnife treatment planning system enables the integration of several data sets, including 3DRA. 3DRA is a volumetric data set built from a rotational sequence of DSA images. This volumetric reconstruction can be segmented to obtain 2D cut planes, exactly corresponding to that of the volumetric CT scans used by CyberKnife for

Fig. 6. (Upper Left) Three-dimensional reconstruction of final target volume obtained from combined three-dimensional rotational angiography and computed tomography (red) and distribution of prescribed dose (superimposed in orange). Target volume surrounded by large and dilated veins (blue and purple). (Lower Left) Isodose distribution around nidus. Vessels surrounding nidus kept outside higher isodose lines. (Upper Right) Three-dimensional rotational angiography-based contouring of AVM. Both target volume (red) and critical venous volumes (blue) could be contoured in three dimensions. (Lower Right) Three-dimensional view of complete vascular tree reconstructed viewing combined three-dimensional rotational angiography and computed tomography angiography in volume-rendered presentation. Three-dimensional distribution of prescription isodose around arteriovenous malformation nidus shown in orange.
localization (Fig. 1). After performing 3DRA, both native nonsubtracted and digitally subtracted images will be available, and the bony landmarks can be used for easy and automatic coregistration of 3DRA and the CT scans used for localization. In the case of enbomized AVMs, the integration of a third data set, the subtracted 3DRA, will be needed for precise target definition. 3DRA has substantial advantages compared with 3D MRA, including greater spatial resolution and, owing to the opportunity to use bony landmarks, the potential for more precise coregistration with the localizing CT scan.

The role of 3DRA in the evaluation of the structure of an AVM has previously been emphasized. Kakizawa et al. (24) demonstrated that the information obtained from 3DRA could improve the strategies for treating large and complex AVMs, enabling visualization of the compartmentalization of the AVMs and safe, staged resection, embolization, and reduction of the AVM size for radiosurgery. Colombo et al. (25) described a technique for iterative and manual 3DRA/stereotactic CT image coregistration and demonstrated that this procedure both improved the ability to discriminate between different vascular components of an AVM nidus and reduced the target volume for linear accelerator radiosurgery. Recently, Colombo et al. (26) reported the technical data and early clinical results for a cohort of 279 patients. In this first series reporting the results of CyberKnife radiosurgery of AVMs, they described a technique in which 3DRA was integrated into the CyberKnife treatment plan and used as a reference imaging modality. Also, the investigators used 3DRA to perform automatic contouring. Thus, that study, not only demonstrated the importance of this imaging modality in AVM radiosurgery, but also suggested the possibility of developing totally automated SRS treatment.

With respect to the work by Colombo et al. (25, 26), we sought to quantify the advantage of using 3DRA compared with other imaging modalities. We emphasize that, using the 3D tools of the treatment planning system to visualize the volumetric reconstruction of the AVM, it was possible to fully navigate in three dimensions (Fig. 2). The contouring was performed using the segmented data set, in one of the three planes of the space; however, for each 1-mm slice, we could verify the results three dimensionally. Similarly, it was possible to reconstruct any selected isodose surface in three dimensions (Fig. 6). This isodose reconstruction gave an immediate indication of the adequacy of the treatment plan.

Although the use of 3DRA allowed us to define smaller target volumes, no evidence is yet available that the use of this imaging modality will result in superior accuracy compared with CTA or MRA. 3DRA also has potential pitfalls, including the potential for distortion. Bridcut et al. (27) evaluated the accuracy of 3D reconstruction in a 3DRA system. They found a maximal error of 1.4 mm in target location and concluded that this level of accuracy would be acceptable for SRS target definition. This error level was not dissimilar from the typical distortion using uncorrected DSA (28). Furthermore, we measured and corrected distortion using the manufacturer’s calibration procedure (29). Nevertheless, we suggest coregistration with CTA to avoid any spatial distortion. More relevant is the limited temporal resolution of 3DRA compared with conventional DSA. In 3DRA, all the anatomic components of the AVM (i.e., feeders, nidus, and draining veins) can be visualized at the same time. Thus, a part of the dynamic AVM flow information provided by serial examinations will be lost (e.g., it was more difficult to identify the fistulous components of the nidus). Thus, to exploit the full potential of 3DRA, a contextual analysis of dynamic DSA images is recommended.

CONCLUSIONS

Three-dimensional rotational angiography is a volumetric angiographic study. As such, it can be integrated into computer-based treatment planning systems. This will allow a better 3D understanding of the target volume and distribution of the radiation doses in the space. In the present study, the iterative delineation of the target volumes using CTA and 3DRA resulted in significant modifications from the initial target volumes defined using only a bidimensional study. Additional technical efforts to improve the quality of this imaging method, in particular, the temporal resolution, and the development of software tools intended to achieve real 3D contouring are warranted.

REFERENCES