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Planning Evaluation of C-Arm Cone Beam CT Angiography for Target Delineation in Stereotactic Radiation Surgery of Brain Arteriovenous Malformations

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Abstract

Purpose—Stereotactic radiation surgery (SRS) is one of the therapeutic modalities currently available to treat cerebral arteriovenous malformations (AVM). Conventionally, magnetic resonance imaging (MRI) and MR angiography (MRA) and digital subtraction angiography (DSA) are used in combination to identify the target volume for SRS treatment. The purpose of this study was to evaluate the use of C-arm cone beam computed tomography (CBCT) in the treatment planning of SRS for cerebral AVMs.

Methods and Materials—Sixteen consecutive patients treated for brain AVMs at our institution were included in this retrospective study. Prior to treatment, all patients underwent MRA, DSA, and C-arm CBCT. All images were coregistered using the GammaPlan planning system. AVM regions were delineated independently by 2 physicians using either C-arm CBCT or MRA, resulting in 2 volumes: a CBCT volume (VCBCT) and an MRA volume (V_{MRA}). SRS plans were generated based on the delineated regions.

Results—The average volume of treatment targets delineated using C-arm CBCT and MRA were similar, 6.40 cm^3 and 6.98 cm^3 , respectively ($P = .82$). However, significant regions of nonoverlap existed. On average, the overlap of the MRA with the C-arm CBCT was only 52.8% of the total volume. In most cases, radiation plans based on V_{MRA} did not provide adequate dose to the region identified on C-arm CBCT; the mean minimum dose to V_{CBCT} was 29.5%, whereas the intended goal was 45% ($P < .001$). The mean volume of normal brain receiving 12 Gy or more in C-arm CBCT-based plans was not greater than in the MRA-based plans.

Conclusions—Use of C-arm CBCT images significantly alters the delineated regions of AVMs for SRS planning, compared to that of MRA/MRI images. CT-based planning can be accomplished without increasing the dose to normal brain and may represent a more accurate definition of the nidus, increasing the chances for successful obliteration.

Introduction

An arteriovenous malformation (AVM) is a tangle of dilated blood vessels associated with abnormal blood flow within its dense center or nidus. AVMs may cause headache, seizures, or hemorrhage in the brain. In appropriately selected patients, treatment techniques such as embolization, microsurgery, and radiation surgery can reduce or eliminate the risk of bleeding and improve the long-term outcomes for patients.

Stereotactic radiation surgery (SRS) is often chosen as the treatment for brain AVM because of its low initial morbidity and relatively low cost and proven efficacy, corroborated by outcome data from the past 20 years. Recently, SRS using the Gamma Knife (Leksell; Elekta Inc, Stockholm, Sweden) has played a role as the sole treatment or as an adjunct treatment to surgery. A guideline by the International Radiation Surgery Association, originally issued in 2003 and recently modified in 2009, supports the use of Gamma Knife SRS (GK SRS) treatment.

Precise target delineation is important for SRS because of the highly conformal nature of the treatment. Contemporary methods of AVM targeting have resulted in variable obliteration rates, reportedly between 50% and 90%, and are highly dependent on lesion volume and radiation dose. Techniques such as those described here to optimize accurate anatomical identification of the AVM are important not only to maximize treatment efficacy but also to minimize morbidity of SRS (1).

Conventionally, the imaging studies combined to identify the target for GK SRS treatment are magnetic resonance angiography (MRA) and digital subtraction angiography (DSA) using orthogonal x-rays. The purpose of this study was to evaluate the use of C-arm (DynaCT; Siemens, Munich, Germany) cone beam computed tomography (CBCT) angiography in the treatment planning of GK SRS for AVMs. The C-arm CBCT system has been used to delineate the targets, with the goal of improving the image quality in both contrast and spatial resolution. We assessed the extent of agreement between target definitions of C-arm CBCT/DSA images and MRA/DSA images. We explored the dosimetric impact of these differences, with the caveat that validation of target identification at the tissue level was not possible and that a different choice of MR imaging sequence or imaging modality could provide further enhanced imaging capabilities.

Methods and Materials

For this retrospective radiation planning study, we analyzed 16 consecutive brain AVM patients treated at Johns Hopkins Hospital (Baltimore, MD) between June 2009 and December of 2009. This study was conducted with the approval of the institutional review board. Prior to imaging, a head frame (Leksell G-frame; Siemens) was affixed to each patient's head with pins, and images were acquired with a stereotactic localization box in

place. All patients received an MRA with a 1.5-T Magnetom Espree system (Siemens). The MRA protocol is a flow-dependent technique that relies on spin labeling and is not dependent on contrast injection. The MRA study was performed in a transmit-receive head coil using the following parameters: bandwidth = 100 Hz; Time to echo (TE) = 6.0 ms; Time of repetition (TR) = 28 ms; and flip angle = 25°. The matrix size for the MRA protocol was 320 × 320 pixels, and the field of view was 230 × 230 mm², resulting in a spatial resolution of 0.7 × 0.7 mm² with 1.5-mm slice thickness.

Following MRA, DSA was performed using a biplanar neuroangiography suite (Artis zee; Siemens Medical). Standard femoral arterial access was used in all cases (4-F systems in children, 5-F systems in adults). To complement the 2-dimensional biplanar angiographic projections, a CBCT dataset (rotational data set of CT projections) was acquired with commercially available imaging software (DynaCT; Siemens), and multiplanar reconstructions were generated with a dedicated workstation (Leonardo model; Siemens). This 3-dimensional protocol used the following parameters: 20-second rotational acquisition generating 600 projections with an angular step of 0.4°, for a total coverage of 240°, with a dose/frame of 1.2 µGy; reconstructions with a 512-matrix algorithm (0.46-mm³ voxel size). The arterial distribution of interest was opacified using a mixture of 25% iodinated contrast agent (300 mgI/mL) and 75% normal saline; the injection rate was 2 mL/sec with a 5-sec acquisition delay, resulting in a total injected volume of 50 mL (ie, 12.5 mL of iodinated contrast agent). No complications were noted during the angiographic investigations. With this protocol, CBCT does not acquire phase information in the same way that biplanar angiography does, which is why CBCT remains the gold standard because of this advantage. It does, however, allow for clearer visualization of the vessels of the nidus due to the transarterial administration of contrast, which cannot be achieved with the MRI/MRA modality.

MRA, DSA, and C-arm CBCT images were digitally transferred to the radiation surgery planning system version 8.3.1 (Leksell GammaPlan; Elekta Inc, Stockholm, Sweden) and registered via stereotactic fiducial markers built into the localizer boxes. The accuracy of this registration was validated prior to treating patients by means of tests with a phantom that included an embedded target for visualization. Submillimeter registration accuracy was achieved.

For this study, two neurosurgeons (J.H. and D.R.) delineated the AVM region on MRA/DSAs (according to standard practice) without reference to the C-arm CBCT. Projection images of the AVM from the orthogonal DSA images were overlaid on the MRA volume to aid in visualization. On a different day, the neurosurgeons contoured the AVMs on C-arm CBCT/DSAs, blinded to the MRA-based contours. The orthogonal DSA images were also overlaid on the C-arm CBCT images to identify the region of interest. The result was 2 target structures: an MRA volume (V_{MRA}) and a C-arm CBCT volume ($V_{\text{C-arm CBCT}}$). The target definitions in both sets of images are reviewed by the neuroradiologist (PG).

Target structures were compared in terms of both overall volume and regions of mismatch between the 2 modalities. Mismatch was quantified by 3 parameters: the volume of overlap

between MRA and C-arm CBCT, the volume of MRA that lay outside the C-arm CBCT, and the volume of C-arm CBCT that lay outside the MRA.

To assess the dosimetric consequences of differences in target delineation on MRA versus those on C-arm CBCT, 2 radiation surgery plans were created: one plan targeted the V_{MRA} and the other plan targeted the VC-arm CBCT. Each plan was optimized for best conformity by using the Leksell GammaPlan system according to standard clinical practice. In order to reduce variation, a single planner (J.K.) performed all radiation surgery planning. Plans were set to deliver the prescribed radiation dose to the 50% isodose line according to standard practice. The plan conformity index and the minimal dose to the target (D_{min}) were used as the metrics for treatment planning quality control (2). The goal in planning is to deliver the most conformal plan possible while maintaining a coverage of the AVM with at least the 45% isodose line (D_{min} of $>45\%$). The conformity index is defined as the volume encompassed by the 50% prescription isodose surface divided by the target volume (3, 4). With this definition of conformity index, the ideal value is 1.0 (ie, perfect conformity of the isodose volume with the target volume). As an indicator of possible late toxicity to brain tissue, we calculated the volume of brain receiving at least 12 Gy ($V_{12\text{Gy}}$). $V_{12\text{Gy}}$ serves as the endpoint for plan comparison (5, 6). In testing statistical significance, we used a 2-tailed paired Student t test. We note that, although the AVM volumes span a wide range, the paired t test provides a legitimate means for comparing the 2 volumes for each patient.

Results

Representative cases are shown in Figures 1 to 4 for various scenarios (Figs. 1–4[A], red line signifies the contour line based on CBCT image sets; Figs. 1–4[B], green line signifies the contour line based on MRA image sets; overlaid thin red lines are projections from the orthogonal DSA images).

Figure 1 shows a case in which C-arm CBCT-based and MRA volumes are very similar (24.0 cm^3 vs 24.5 cm^3 , respectively). The observed differences between the contoured areas for the same structure in the CBCT and MRA datasets can be attributed to the differences of slice thickness on the 2 image sets. Figure 2 shows a case in which the VC-arm CBCT is much larger than the V_{MRA} (16.0 cm^3 vs 10.7 cm^3 , respectively). The nidus of this AVM is diffuse. C-arm CBCT allowed clearer distinction of the arterial feeders leading to the compact portion of the nidus from the surrounding brain tissue than is possible with MRA. This results in the inclusion of a greater target volume (Fig. 2, red line) when planned using C-arm CBCT. Figure 3 shows a case in which the V_{MRA} is larger than the VC-arm CBCT (13.4 cm^3 vs 8.7 cm^3 , respectively). The C-arm CBCT enables distinction among the arterial vessels of the nidus from the draining veins because vessel calibers are more readily discernable. This permits exclusion of the draining veins from the target volume, which is particularly helpful in instances of larger AVMs when minimizing dosage is desired. Finally, Figure 4 shows the case of a small AVM (volume, 0.054 cm^3) in which the nidus was visualized only on C-arm CBCT and not on MRA.

Table 1 lists the volume statistics for all patients. Although the total target VC-arm CBCT and V_{MRA} are within a similar range (average volume of 6.40 cm^3 vs 6.98 cm^3 , respectively,

$P = .83$ paired t test), there are significant mismatches between the regions covered by the 2 target volumes. This is quantified in Table 1 in terms of the volumes of the 3 regions: the overlap between the VC-arm CBCT and V_{MRA} , the region of the VC-arm CBCT that lies outside the V_{MRA} , and the region of the V_{MRA} that lies outside the VC-arm CBCT. These values are reported as percentages of the total volume encompassed by both CT and MRA target volumes. On average, the overlap is 52.8%, whereas the volume of CT not in MRA is 25.0% and volume of MRA not in CT is 22.2%.

To further quantify the consequences of contouring differences between C-arm CBCT and MRA, we analyzed radiation surgery plans generated from the 2 different data sets. In order to address the impact of current MRA-based planning on the new CBCT modality under investigation, we use the MRA volume as a baseline. We generated an MRA-based plan and then calculated the minimum dose (D_{min}) delivered to the VC-arm CBCT.

Figure 5 shows a sample plan for patient 4. The target VC-arm CBCT (Fig. 5, red) extends well beyond the MRA target volume (Fig. 5, green). Therefore an MRA-based plan (Fig. 5, yellow isodose lines [A and B]) clearly provides inadequate coverage of the target VC-arm CBCT. The MRA-based plan delivers D_{min} of 25.9% to the target VC-arm CBCT. The minimum intended dose to the target identified on C-arm CBCT is 45%. When a plan was generated based on the C-arm CBCT (Fig. 5, yellow isodose line [C]), the delivered dose, D_{min} , was 45.0% to the target VC-arm CBCT. Figure 5(D, E, F) shows a counter-example (patient 14) in which the MRA-based plan (Fig. 5, yellow isodose line [A and B]) provides overly generous coverage to the target VC-arm CBCT (Fig. 5, red). The conformity index for the MRA-based plan on the target VC-arm CBCT was 2.95 (ie, an overly generous coverage). By design, an MRA-based plan is conformal to the MRA-based volume, with a conformity index of 1.82 (Table 1). As expected, a C-arm CBCT-based plan did not produce more irradiation of normal brain tissue (Fig. 5F).

Table 1 summarizes the dosimetric parameters from the 2 plans for all patients. For most of the cases, use of an MRA-based plan resulted in an underdose of the VC-arm CBCT; the average D_{min} to the VC-arm CBCT was 29.5%, which is significantly lower than the goal of 45% ($P < .0001$). The C-arm CBCT-based plans had a mean brain V_{12Gy} of $9.8 \pm 8.5 \text{ cm}^3$ compared to MRA-based plans, which had a V_{12Gy} of $13.2 \pm 11.2 \text{ cm}^3$, a difference that favors the C-arm CBCT-based plan but only at a marginally significant level ($P = .04$). This indicates that C-arm CBCT-based plans do not result in more irradiation of normal brain.

We noted that critical to this side-by-side planning study is the fact that the quality of the 2 plans is similar and unbiased. Data in Table 1 demonstrate that this was the case. Averaging over the first 15 patients, for whom there are both CBCT and MRA data, the minimum target coverage, D_{min} , was $44.9\% \pm 0.6\%$ in CT-based plans versus $45.7\% \pm 1.2\%$ in MRA-based plans ($P = .11$). As shown in Table 1, the average conformity indexes for the first 15 patients were also similar: 1.96 ± 0.26 in CT-based plans versus 1.85 ± 0.22 in MRA-based plans ($P = 1.00$).

Discussion

This study of 16 patients demonstrated that it is feasible to acquire and use C-arm CBCT for radiation surgery of AVMs. In all cases, the nidus was clearly visualized on C-arm CBCT. The resulting target regions are different than those derived from the standard MRA/DSA imaging routinely used in our clinic. On average, the overlap of the MRA with the C-arm CBCT is only 52.8% of the total volume. As expected, this has a direct dosimetric impact. If the MRA is used for delineation, then the C-arm CBCT volume will not receive full dose. In MRA-based plans, the CT-derived volume received an average minimum dose of only 29.5% compared to an intended minimum dose of 45%.

Accurate delineation of the AVM target is crucial for the success of radiation surgery. Underestimation of target volume can lead to underdosage and treatment failure. This is supported by numerous previous studies that concluded that a main cause of failure after radiation surgery is underdosing of the nidus (7–11). Underdosing may be a particular challenge for very small AVMs (12). An example in the present study is patient 16 (Fig. 4), who had a small AVM (0.054 cm^3), which is undetectable in the contrast-enhanced MRA.

Delineation accuracy is also important because draining veins should be kept outside the volume irradiated during radiation surgery, as the irradiation may damage these vessels before the obliteration of the nidus, which could potentially lead to venous stenosis and result in the risk of intracerebral hemorrhage (13, 14). More generally, overestimation of the AVM size results in higher dose to normal brain, which could lead to increased acute and late toxicity (15).

The limitations of MR for the visualization of AVMs have been noted previously in a number of studies. Yu et al (16) found that volumes based solely on MRI overestimated the actual treatment volume, which is delineated on angiography-guided MRI by a mean of 57% for AVMs larger than 2 cm^3 and by a mean of 25% for AVMs smaller than 2 cm^3 . Groups from Japan also found that the target defined on MRA might have included an unnecessary area of the AVM (the feeding artery or draining vein) but missed an important portion (the nidus) (17). Kenieda et al (18) investigated the use of intra-arterial CT angiography using a helical CT scan protocol (18). They found that intra-arterial CT angiography imaging was effective at distinguishing draining veins from the nidus in 18 of 20 cases (90%). Tanaka et al (19) also found that CT angiography provided better visualization of veins than MRA, although fewer arteries were detected than in MRA. These studies indicate a possible advantage of CT-based target identification. Another advantage of CT is that it allows clear visualization of the vessels of the nidus due to the trans-arterial administration of contrast, which can not be achieved with the MRI/MRA modalities. Because C-arm CBCT is performed as an integrated part of the angiography procedure, a selective injection for the interested region is possible. A final practical advantage is that C-arm CBCT systems may be more accessible than MRI units in some centers.

There are several limitations to this study. First, the potential advantages of CBCT and the limitations of MRI must be balanced with the fact that a different choice of MR imaging sequence or another modality could provide imaging enhancements that would be beneficial.

This is an important caveat to the present study. In this study we can only compare target visualization between 2 modalities and have no way to validate the target identification at the tissue level. As can be noted in several of the figures presented here, contouring could have been quite different depending on the expert interpretation. As such, the role for CBCT in the near future may be to serve as a complementary imaging modality. A second limitation is the possible impact of interobserver variability. It was not possible to quantify this effect in this study with only 2 neurosurgeons. Inter-observer variability is an important issue in addition to the mode-specific considerations treated here.

Image resolution certainly plays a key role in the potential advantage of various modalities. To compare the available image resolutions, we note that the C-arm CBCT protocol used here results in a 0.46 mm^3 voxel (ie, voxel dimension of $770 \text{ }\mu\text{m}$). For comparison, the 64-slice helical CT scanner can present an isotropic voxel size of 0.22 mm^3 , and our MRI protocol is 0.735 mm^3 voxels. For the selected field of view and matrix, MRI units usually present a voxel size of $400 \times 400 \times 1500 \text{ }\mu\text{m}^3$ for MRA protocol; so the C-arm CBCT system has a spatial resolution that falls between these other systems, at least in terms of voxel sizes.

To our knowledge no previous studies have investigated the dosimetric impact of these volumetric mismatches. Results obtained in this study demonstrate that the use of C-arm CBCT imaging for GK SRS treatment planning can be beneficial. Referring to Figure 4, the nidus is visualized only on C-arm CBCT and not on MRA. Also, the image in Figure 2 shows that physicians can distinguish the vessels of the nidus from the surrounding brain tissue with C-arm CBCT image more readily than with MRI/MRA. In the example shown in Figure 3, C-arm CBCT enables arterial vessels of the nidus to be distinguished from the draining veins. Although CBCT does not acquire phase information in the same way that biplanar angiography does, it does play an important role to be used in complementary form with the angiography image modality.

While keeping the plan quality similar, our study shows that C-arm CBCT-based planning does not introduce more radiation to normal brain, as indicated by the volume of normal brain tissue receiving 12 Gy or less (Table 1). This is important because early and late normal tissue toxicity is a major factor that affects the quality of patient life after receiving radiation therapy.

One possible limitation of the C-arm CBCT is the artifacts in the CT reconstructions (20). These can be caused by the presence of the head frame, especially the metallic pins. We did note such artifacts in most cases, but these were not severe enough to interfere with AVM delineation.

Conclusions

These data demonstrate that inclusion of C-arm CBCT imaging into treatment planning is feasible and significantly alters the delineated regions of AVMs for GK SRS planning. This study comes with the important caveat that the actual target structure is not known at the tissue level and that other MRI sequences or other modalities may also provide good

visualization. However, to the extent that C-arm CBCT accurately represents the actual nidus, large underdosing of AVMs may occur if this modality is not used and thus negatively impact the obliteration rate. Incorporating C-arm CBCT imaging is a promising new and safe approach to target definition and plan evaluation in radiation surgery for brain AVMs. It represents an adjunct to biplanar DSA, which provides further information for the dynamics of AVM filling and draining. Future examination of obliteration rates after radiation surgery will be necessary in order to determine the widespread applicability of this novel technique.

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Summary

Cone beam computed tomography (CBCT) in the angiography suite represents a new technology for visualizing cerebral arteriovenous malformations, beyond magnetic resonance angiography (MRA) and digital subtraction angiography. Here we show that stereotactic radiation surgery plans based on MRA result in substantial underdoses to the region identified on CBCT. CBCT-based plans do not increase the dose to normal brain. CBCT may represent a more accurate definition of the nidus, increasing the chances of successful obliteration.

Fig. 1.

AVM target definition for patient 3. Red line represents the C-arm CBCT-based target contour, and the green line represents the MRA-based target contour, overlaid on the C-arm CBCT image (A) and the MRA (B). Overlaid lines are the projections from the orthogonal DSA images. AVM = arteriovenous malformation; CBCT = cone beam computed tomography; DSA = digital subtraction angiography; MRA = magnetic resonance angiography. A color version of this figure is available at www.redjournal.org.

Fig. 2.

Target definition for patient 4. Red line represents the C-arm CBCT-based target contour and green line represents the MRA-based target contour, overlaid on the C-arm CBCT image (A) and the MRA (B). Overlaid lines are the projections from the orthogonal DSA images.

CBCT = cone beam computed tomography; DSA = digital subtraction angiography; MRA = magnetic resonance angiography. A color version of this figure is available at www.redjournal.org.

Fig. 3.

Target definition for patient 14. Red line represents the C-arm CBCT-based target contour, and green line represents the MRA-based target contour, overlaid on the C-arm CBCT image (A) and the MRA (B). Overlaid lines are the projections from the orthogonal DSA images. CBCT = cone beam computed tomography; DSA = digital subtraction angiography; MRA = magnetic resonance angiography. A color version of this figure is available at www.redjournal.org.

Fig. 4.

C-arm CBCT-based target definition for patient 16. Red line represents the C-arm CBCT-based target contour (A) and the MRA (B). Overlaid lines are the projections from the orthogonal DSA images. CBCT = cone beam computed tomography; DSA = digital subtraction angiography; MRA = magnetic resonance angiography. A color version of this figure is available at www.redjournal.org.

Fig. 5.

The impact of target delineation on radiation dose distributions for patients 4 and 14. A plan for patient 4 based on MRA (green [A]) provides inadequate dosimetric coverage of the C-arm CBCT-based structure (red [B]). The yellow line represents the prescription isodose line. (C) Plan based on the C-arm CBCT target. A plan for patient 14 based on MRA (green [D]) provides overly generous coverage of the C-arm CBCT-based structure (red [E]). The yellow line represents the prescription isodose line. (F) Plan based on the C-arm CBCT target. CBCT = cone beam computed tomography; MRA = magnetic resonance angiography. A color version of this figure is available at www.redjournal.org.

Table 1

AVM volumes and overlap of each imaging modality

Patient	CT and MRA overlap (%)				V _{C-ARM CBCT} -based plan				V _{MRA} -based plan			
	V _{C-ARM CBCT} (cm ³)	V _{MRA} (cm ³)	CT not in MRA (%)	MRA not in CT (%)	D _{min} of V _{C-ARM CBCT} (%)	CI	D _{min} of V _{MRA} (%)	V _{12Gy} (cm ³)	D _{min} of V _{MRA} (%)	CI	D _{min} of V _{C-ARM CBCT} (%)	V _{12Gy} (cm ³)
1	0.32	0.24	56.5	32.9	44.2	2.24	36.8	0.9	44.5	2.16	19.2	0.7
2	4.50	2.50	55.6	44.4	44.8	1.54	42	6.8	45.7	1.19	19.5	4.2
3	24.00	24.50	58.0	20.2	45.1	2.15	37.8	4.1	44.6	1.89	20.6	10.4
4	16.00	10.70	59.9	35.9	45.0	1.71	46.1	18.2	45.7	1.98	25.9	13.8
5	0.14	0.12	39.7	36.5	45.6	2.21	31.4	0.5	49.0	1.83	12.0	0.5
6	2.00	1.80	69.8	19.6	45.9	2.06	46.9	5.4	44.2	1.94	46.9	5.4
7	9.30	16.00	47.1	7.0	45.4	2.21	27.5	26.8	44.2	1.75	30.0	36.2
8	2.10	1.10	45.5	50.0	44.0	2.14	45.2	0.1	47.6	2.36	25.4	0.2
9	12.40	18.40	54.0	8.0	44.0	2.05	23.0	32.0	45.9	1.54	29.7	46.2
10	0.94	0.67	52.4	36.6	45.4	2.45	54.3	2.9	47.5	2.38	20.5	2.1
11	3.90	4.00	83.5	7.1	45.5	1.53	33.2	9.2	45.8	1.6	45.4	10.1
12	1.20	1.50	54.9	13.9	45.9	1.75	16.5	2.7	44.0	1.87	43.9	3.8
13	2.20	4.00	52.5	1.6	44.8	1.59	20.0	7.2	44.4	1.55	43.8	11.5
14	8.70	13.40	14.5	30.6	43.9	2.38	12.9	26.4	47.3	1.82	32.1	40.5
15	14.60	12.80	48.9	30.4	44.2	1.39	15.8	12.5	45.2	1.82	28.1	13.0
16	0.054	na	n/a	n/a	45.5	4.15	n/a	0.5	n/a	n/a	n/a	n/a
Avg(1–15)	6.82	7.45	52.8	25.0	44.9	1.96	32.63	10.38	45.7	1.85	29.5	13.2
Avg (1–16)	6.40				44.9	2.10	32.6	9.8				

Abbreviations: AVM = arteriovenous malformation; CBCT = cone beam CT; CI = conformity index; CT = computed tomography; D_{min} = minimum dose to the target volume; MRA = magnetic resonance angiography; V_{12 Gy} = volume of the organ receiving 12 Gy; V_{C-ARM CBCT} = volume of the C-arm CBCT; V_{MRA} = volume of MRA.

The overlap value is reported as the percentage of total volume encompassed by both CT and MRA. Shown are D_{min}, CI, V_{12 Gy} with the VC-ARM CBCT and VMRA-based plans, respectively.