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Time of Arrival Parametric Maps and Virtual Bolus Images derived from Contrast Enhanced Time-Resolved Radial MRA improve the display of Brain AVM Vascular Anatomy

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Abstract

Objectives—Time-of-arrival (TOA) maps can be derived from high-resolution 4D contrast-enhanced magnetic-resonance-angiography (MRA) datasets to provide a quantitative description of contrast material arrival time in each voxel. This information can further be processed in order to create a compressed time-evolution curve that virtually shortens the contrast bolus (Virtual Bolus [VB]). The purpose of this project is to determine whether TOA-enhanced 4D MRA and/or Virtual Bolus Imaging improve the display of contrast kinetics in patients with vascular disease.

Methods—High-resolution whole brain contrast enhanced 4D MRA exams with 1.2 second temporal reconstruction were acquired by using radial acquisition and highly constrained projection reconstruction (radial 4D CE HYPRFlow, is abbreviated to HFMRA in this manuscript) in 10 patients (8 patients with vascular malformations (AVM), one patient with an arteriovenous fistula (AVF) and one patient with a high-grade intracranial stenosis). The TOA for each voxel was defined as the time point when the signal intensity reached 20% of its maximum. In the first method, TOA maps were generated, color-encoded and then multiplied with the time-resolved contrast enhanced MRA images at each time frame to form new 4D MRA images (TOA-enhanced HFMRA) which contains the contrast arrival times with defined color encoding. In the second method, each time frame was weighted by a Gaussian distribution in the time domain to form a virtual 4D bolus map. This 4D bolus map was then color-coded and multiplied with the HFMRA images to form a digital subtraction angiography (DSA)-like virtual bolus, where at each time frame, only vessels with certain TOA values within the defined bolus length appear. HFMRA, TOA maps and virtual bolus images were scored qualitatively with regard to delineation of arteries, veins and nidus as well as artifacts. Furthermore, diagnostic confidence and arteriovenous overlap were evaluated and compared between techniques. A comparison with DSA was performed where DSA served as the reference standard in terms of number of arterial feeders, draining veins and Spetzler-Martin score of AVMs. In addition, TOA-maps were evaluated quantitatively.

Results—Overall diagnostic confidence score of TOA was significantly higher compared to HFMRA ($p=0.03$). Virtual Bolus (VB) showed significantly higher scores for overall diagnostic confidence ($p=0.02$) and reduced arteriovenous overlap (0.01) compared to HFMRA. Furthermore, Virtual Bolus reduced arteriovenous overlap significantly compared to TOA ($p=0.04$).

Agreement regarding AVM draining veins was lower between DSA and HFMRA ($k=0.3$) compared to TOA and VB ($k=0.56$).

Agreement regarding Spetzler-Martin score was lower between DSA and HFMRA ($k=0.56$) compared to TOA and VB ($k=0.74$).

Conclusion—TOA-enhanced HFMRA provides serial images and time of arrival maps in one inclusive display. In this study, TOA mapping combined with Virtual Bolus imaging improved diagnostic confidence in AVM patients and facilitated arteriovenous separation. The VB method further reduced overlap of arterial and venous structures.

Keywords

4D MRA; High-resolution; Time-of-arrival mapping; virtual contrast bolus shortening

Introduction

Contrast Enhanced Time-Resolved MRA techniques are able to depict arterial and venous components of complex vascular structures such as arteriovenous malformations (AVMs) (1-8). This is desirable in order to reduce the number of invasive procedures with their inherent radiation exposure for patients that otherwise may undergo repetitive angiograms during treatment planning or follow-up. Achieving sufficiently high temporal and spatial resolution with an appropriate FOV is challenging as the acquisition time per frame increases in proportion to the coverage of these 3D-techniques. However, high temporal and spatial resolution is essential to properly identify components, especially within lesions with rapid arteriovenous shunting. In this report, we use a recently introduced method termed HYPRFlow (HFMRA) which employs undersampled radial acquisition and constrained reconstruction to overcome these limitations (9). HFMRA depicts small vessel structures with a spatial resolution of 0.68 mm isotropic voxels and a temporal resolution as high as 0.75 seconds. The arterial delineation is comparable to widely used non dynamic time-of-flight MRA (10). Moreover, it has been shown to perform well in the evaluation of the complex vessel networks of intracranial AVMs and arteriovenous fistulas (11-13). In contrast to intra-arterial digital subtraction angiography (DSA), all time resolved imaging techniques using venous injection of contrast agent suffer from significant dispersion of the contrast bolus resulting from the circulation through the heart and lungs. This temporal bolus dispersion can reduce the confidence to differentiate arteries and veins in arteriovenous malformations and dural fistulas due to the rapid shunting of blood resulting in overlap of venous and arterial structures. Thus, Cartesian 4D CE MRA acquisition and radial acquisition/constrained reconstruction HFMRA have significant limitations compared to DSA (6, 14-16).

The visual distinction of arteries and veins in time resolved imaging can be facilitated with color encoding of time-of arrival maps (17). This technique can be applied to any type of

time resolved imaging technique and has been proven to enhance and improve visualization of arteries and veins (18, 19). A time-of-arrival (TOA) map can be estimated from the HFMRA data and provides a quantitative display of contrast material arrival time in each voxel.

In this study, we introduce a post-processing algorithm (termed Virtual Bolus) to address the limitation of contrast bolus dispersion in HFMRA. This investigation employs both TOA map and virtual bolus images to improve the visualization of contrast kinetics and provide images analogous to DSA. The purpose of this report is to assess the benefit of time of arrival and virtual bolus display for the display and characterization of brain arteriovenous malformations and dural arteriovenous fistulas.

Subjects and Methods

This prospective study was Health Insurance Portability and Accountability Act (HIPAA) compliant and approved by the local institutional review board (IRB). 10 patients were included in the study (mean age: 44.5y, 5 female). Vascular pathologies included: cerebral AVM (8), cerebral AVF (1), high-grade intracranial stenosis (1, basilar artery).

MR-acquisition

The imaging protocol uses a non-Cartesian 3-dimensional (3D) radial acquisition for dynamic and static imaging. The 3D radial sampling strategy allows for significant acceleration due to the incoherent nature of undersampling artifacts (vastly undersampled radial projection reconstruction [VIPR]). The radial imaging methods used in this report have been previously described (20, 21). HYPRFlow images are derived from data acquired during 3 radial acquisitions. The first is a 60-second non-contrast mask, the second a high temporal resolution 60-second dynamic series obtained during the first pass of a contrast bolus through the cerebrovascular system. The third scan is a 3D phase contrast acquisition with high spatial resolution (PC-VIPR) that is used as the spatial constraint for HYPR-LR reconstruction with a scan time of 4:35min (22). For the dynamic and static scans, the background tissue signal is subtracted to sparsify the data sets resulting in only the vascular structures being present within the imaging volumes.

Dynamic Scan

The dynamic contrast-enhanced 3D radial scan (CE-VIPR) was obtained using the following imaging parameters: field of view (FOV), 22×22×22 cm³; repetition time (TR)/echo time (TE), 3.0/0.4 milliseconds; bandwidth, ±125 kHz; temporal reconstruction window, 1.2 seconds; spatial resolution, 1.7 × 1.7 × 1.7 mm³. Ten thousand radial projections were acquired per dynamic scan. Gadobenate dimeglumine (MultiHance; Bracco Diagnostics, Princeton, NJ) was administered at a dose of 0.1 mmol/kg. Injections were performed using a power injector (Spectris Solaris, MedRad Inc., Warrendale, PA) at 3ml/s followed by 20 ml saline flush injected at the same rate.

Static Scan

The constraining static scan is obtained using a 5-point phase contrast MRA using a radial acquisition (PC-VIPR) (23). The five point encoding method is described by Johnson and Markl (23) and be considered to be in the family of dual-Venc methods. Briefly, this encoding scheme uses 4 non-zero flow encodings and 1 additional flow compensated flow encoding. The 4 flow encodings are identical to that of 4 point balanced/hadamard encoding. The fifth point can be considered a reference point for phase unwrapping of aliased signal. This leads to 60% increase in dynamic range with only a 25% increase in scan time.

The imaging parameters for the postcontrast PC-VIPR were the following: FOV, 22×22×22 cm³; TR/TE, 7/2.5 milliseconds; velocity encoding, 80 cm/s; bandwidth, ±62.5 kHz. The spatial resolution for the phase contrast study was 0.68 mm isotropic. PC-VIPR data are used as the constraint for the HYPR LR reconstruction (22). The result of this approach is a series of time resolved whole brain contrast enhanced images of the cerebrovascular system with 0.67mm isotropic spatial resolution and temporal reconstruction window of 1.2s.

Time-of arrival maps from HFMRA serial images

The TOA map is estimated based on signal intensity changes over time for each voxel. For this implementation, the TOA of a voxel was defined as the time point when the signal intensity of this voxel first reaches 20% of its maximum intensity. Linear interpolation was used for more accurate estimation. A 3D TOA map was generated, colored encoded and then multiplied with the time-resolved contrast enhanced MRA images at each time frame to form a new 4D MRA image (TOA-enhanced 4D HFMRA) which not only represent the contrast enhancement of vessels at different time frames, but also contain the contrast arrival times with defined color encoding (Figure 1a). TOA values in this study consist of the interval from the beginning of the injection to contrast arrival in the given vessel. TOA maps were generated for all 10 subjects.

Virtual Bolus maps

The time of arrival and HYPRflow images contain high temporal resolution depiction of vascular filling; however, the simultaneous depiction of arteries and veins obscures the interpretation of the images. As suggested by Cashen et al (24), a compact bolus can be created utilizing the subtraction of time frames with a fixed time between them. While this technique can be effective, the optimal time between time frames is highly dependent on the dispersion of the contrast agent through the vascular system, which is dependent on the disease, subject, and injection protocol. In this work, we investigated an alternative visualization technique, which utilizes the time of arrival map and a simple Gaussian dispersion assumption. For each voxel in the volume, the time intensity of the signal is assumed to be a Gaussian function of the form:

$$VB(l)=HF_{low}(l)\exp\left(\frac{-(L-TOA)^2}{2\sigma^2}\right)$$

where σ determined the a fixed width (Full width at half maximum, FWHM) of the bolus (set to 6 seconds in this work). The effect of this processing is to cut the tail of the bolus to form a DSA-like display, where at each time frame, only vessels with current TOA values within the defined virtual bolus length appear (Figure 1b). The color of the virtual bolus is set to the time of arrival. 4D VB images were generated for all 10 subjects.

Digital subtraction angiography

Except one external examination, all digital subtraction angiography examinations were obtained using an Artis Zee biplane system (Siemens Healthcare, Erlangen, Germany). The biplane DSA acquisitions were obtained with temporal resolution ranged from a minimum of 2 frames per second to 6 frames per second in standard projections with injections in both ICAs and at least 1 vertebral artery. Hand injections were used for 2D projections and a power injector was applied for 3D rotational DSA.

Image Analysis

Qualitative evaluation—The HFMRA 4D images, TOA 4D images and Virtual Bolus 4D images were evaluated independently in random order by two neuroradiologists (with 35 and 7 years experience, respectively), blinded to patient history and identity. The evaluation criteria included: 1) delineation of vessels (arteries, veins, nidus); 2) homogeneity of vascular signal intensity; 3) streak or motion artifacts; 4) overlap of arterial and venous structures and 5) diagnostic confidence. The grading system is described in Table 1 (25, 26), intermediate grades (i.e. 3.5) were allowed. Arteries, veins and nidus were assessed separately regarding delineation, homogeneity and artifacts. The Spetzler-Martin grade was recorded for each display method and compared with the DSA grade (27).

DSA comparison—In a second step, reader 1 evaluated MRA-examinations (HF, TOA and VB) and reader 2 (5 years of experience in DSA) evaluated DSA-examinations with regard to number of arterial feeders, draining veins and sequential filling of draining veins in all AVM cases (n=8). Spetzler-Martin grades for all DSA-examinations were extracted from the DSA-report. For MRA examinations, Spetzler-Martin grade was used from the initial analysis of reader 1. The analysis was carried out 8 weeks after the qualitative scoring of MRA techniques in order to avoid bias.

Quantitative evaluation—TOA maps were evaluated quantitatively in all AVM cases. Time-of-arrival values were recorded for the following vessels: Upstream territorial cerebral artery supplying the AVM and the contralateral equivalent artery and sigmoid sinus bilaterally (venous drainage).

Arteriovenous transit times were calculated for the passage from upstream territorial artery to venous outflow (SS) bilaterally (TOA_Art – TOA_SS).

Statistical analysis

Qualitative analysis—Wilcoxon-rank tests were performed in order to evaluate for statistical significant differences of scores for arteriovenous overlap and diagnostic performance between HFMRA, TOA maps and VB maps. Data from reader 1 (most

experienced reader) were used for the qualitative analysis. Inter-reader agreement for each of the visualization methods and for agreement between DSA and MRAs was assessed using Cohens-Kappa statistics. A κ -value of 0.10 – 0.20 indicated slight agreement; 0.21 – 0.40 fair agreement; 0.41 – 0.60 moderate agreement; 0.61 – 0.80 good agreement and 0.81 – 1.00 excellent agreement (28).

Quantitative analysis—Differences between upstream artery to sigmoid sinus passage times on both sides were evaluated with 2-sided, paired t-tests.

The level of significance for was set at $p < 0.05$.

Results

Qualitative image analysis scores

Mean scores and k-values for interreader agreement of the different visualization methods are summarized in table 2. TOA showed a significantly higher scores for overall diagnostic confidence ($p=0.03$) compared to HFMRA. Virtual Bolus scores were significantly higher compared to HFMRA arteriovenous overlap ($p=0.01$) and overall diagnostic confidence ($p=0.02$). Virtual Bolus showed significantly higher scores compared to TOA for arteriovenous overlap ($p=0.04$). Cohens-Kappa-values ranged from 0.36 (VB delineation of veins) to 1 (TOA/VB Spetzler-Martin grade).

Cohens-Kappa-values ranged from 0.36 (VB delineation of veins) to 1 (TOA/VB Spetzler-Martin grade).

DSA comparison

Arterial feeders—In 2 patients, the full number of feeders was missed by one feeder each on HFMRA, TOA and VB ($k=0.68$ for agreement between DSA and HFMRA, TOA and VB).

Draining veins—The full number of draining veins was missed in 5 cases with HFMRA ($k=0.3$) and in 3 cases with TOA and VB ($k=0.56$). In total, 6 draining veins were missed with HFMRA and 4 with TOA and VB.

Sequential filling of draining veins was missed in 5 cases with HFMRA ($k=0.05$) and in 4 cases with TOA and VB ($k=0.06$).

Spetzler-Martin score—Mean Spetzler-Martin score of all DSA-examinations was 3. Full Spetzler-Martin score was missed in 2 cases with HFMRA ($k=0.56$) and in one case with TOA and VB ($k=0.74$).

Figure 2 shows an example of a large, right temporal high-flow AVM highlighting the benefit of VB maps in separating arterial and venous structures in the later venous frames. Figure 3 shows an example of a patient with a left hemispheric high-flow AVM where arterial feeders and draining veins cannot be separated based on sequential filling due to limited temporal resolution in HFMRA. TOA- and VB maps are able to show a

hypertrophied MCA-branch and a dilated cortical vein in close proximity but clearly different color. Figure 4 shows an example of an occipital AVM where different nidus flow patterns are highlighted in the TOA map and a sequential drainage can be separated with VB in a late venous frame.

Quantitative analysis of TOA-maps

Ipsilateral to the AVM, the TOA values for the upstream territorial artery (middle cerebral artery (M1) in 7 cases, superior cerebellar artery in one case) ranged from 15.05 to 17.95 seconds (mean: 16.29s, Standard deviation: 1.1s) and from 15.25 to 18.9 s (mean: 16.65s, StDev 1.2s) on the contralateral side. The paired t-test revealed a statistical significant difference between sides ($p=0.02$).

For the sigmoid sinus on the side of the AVM, mean TOA ranged from 17.1 to 20.1 s (mean: 18.6, StDev 1.4s), on the contralateral side values ranged from 19.4 to 23.4 s (mean: 20.7, StDev 1.4s). The paired t-test revealed a statistical significant difference between both sides ($p=0.004$).

Average arteriovenous transit time from MCA to SS ranged from 1s to 4.8s (mean: 2.3, StDev 1.1s) on the AVM side and from 2.4 to 5.7s (mean: 4, StDev 1.1s) on the contralateral side. Arteriovenous transit time was significantly shorter on the AVM-side ($p=0.007$).

Discussion

When compared to digital subtraction angiography (DSA), the length of the intravenously administered contrast bolus in dynamic MRA is considerably greater after circulation through heart and lungs, leading to partially simultaneous opacified arterial and venous structures. This may complicate differentiation of arteries and veins as well as an AVM-nidus. Our hypothesis was therefore that a virtual bolus shortening might be helpful to facilitate differentiation of closely related vessel structures with little difference in contrast arrival time. This is especially helpful in regions with multiple pathologic vessels such as AVMs and AVFs, where it is oftentimes impossible to distinguish arterial feeders from draining veins on static images.

In the present study, we showed that the application of time of arrival maps to a high-resolution dynamic MRA increases diagnostic confidence and that the introduction of a virtual temporal bolus shortening algorithm furthermore reduces the arteriovenous overlap and may facilitate the identification of feeders and draining veins of cerebral AVMs. Moreover, we were able to show that TOA maps and Virtual Bolus show a slightly better performance in determining the Spetzler-Martin score in patients with AVMs compared to HFMRA. However, these results are a first report of VB and are based on a small collective. HFMRA has been shown to be well suited to study AVMs and the addition of TOA and VB further improves the performance of the technique (11, 13). This is underlined by the theoretical consideration that HYPRFlow produces images which depict subtle changes in signal intensity; however, temporal signal variations are only one factor that influences brightness and thus it may be challenging to interpret the images. The addition of time of arrival allows an intensity-normalized depiction of the temporal dynamics.

While TOA allows the depiction of the subtle temporal differences, the overlay of all structures may cloud their visualization. Virtual bolus is able to narrow the focus.

Our results are in accordance with the literature, where TOA maps are reported to have the potential to facilitate the interpretation of time-resolved imaging, proven in DSA and MRA studies (17, 19). Furthermore, a recent study has reported that color-coding of time of arrival maps is beneficial for the evaluation of AVMs with 4D MRA (18).

In our study, TOA maps were found to be especially helpful in high arteriovenous shunt conditions (i.e. early draining vein) where the temporal resolution of 4D MRA is too low to capture small differences in contrast arrival in a single frame (Figure 3). This finding is in accordance with the study of Illies et al (18) that could show different intranidal flow patterns, an observation that we could reproduce in our study (Figure 4).

In contrast to TOA maps, VB was found to be especially helpful in the evaluation of later time frames where slower flow components dominate, reflected by the fact that arteriovenous separation in the later frames was significantly improved in VB maps (Figure 2).

It should be noted that the definition of TOA (to a certain percentage of the maximum signal intensity) does not affect the temporal display of TOA and VB maps. Lower threshold (smaller percentage of the maximum signal intensity) detects the leading edge of the bolus, whereas the higher threshold represents the central/main bolus. In this study, 20% was selected as the threshold to track the edge of the bolus without noise contamination. However, width of the Gaussian function affects the VB display. Short bolus improves arterial venous separation, yet too short a bolus makes vessel identification difficult. In this paper, the FWHM of the Gaussian function was set to 6s. This was based on optimization of FWHM in a limited number of cases and therefore may further be optimized in future analyses.

Alternate methods have been proposed to achieve an apparent shorter bolus passage with less overlap of arteries and veins. In the first publication regarding TOA based on MRA, Riederer et al. used only voxels whose TOA fall within a prescribed range in order to narrow the display without further postprocessing (17). Cashen et al. (24) used a sliding window mask subtraction to improve isolation of arterial feeders and reduce arteriovenous overlap in the region of the AVM. This technique is able to achieve a high frame rate together with an appropriate spatial resolution due to repeated acquisition of N segments of a whole volume such that frames can be formed by any contiguous set of N segments (29). However, sliding window mask subtraction requires an optimized lag time (temporal interval between frames) that may vary with temporal bolus passage and therefore may be altered by other physiological events such as the cardiac output of the patient. Furthermore, the temporal window of one reconstructed image frame remains unchanged. An advantage of the sliding window technique is the smooth signal vs. time curves due to the high reconstructed temporal resolution of overlapping frames.

In contrast, our proposed Virtual Bolus technique depends on a voxel wise time of arrival map and therefore works independently of the contrast dynamics. Moreover, it can be

applied to any time resolved imaging sequence, including CT and DSA methods. In this study, we show that this technique can be successfully applied together with color encoded TOA maps to HFMRA in a cohort of patients with cerebral AVMs.

Potential applications of TOA maps are not only of qualitative but also of quantitative nature. I.e. for treatment planning when targeting high flow feeders as well as providing information about flow changes in the post-treatment course. The quantitative information of TOA maps may also be exploited to serve as a reference for methods that rely on appropriate imaging delay such as arterial spin labeling (30). The contrast arrival times in our study showed little intersubject variation and are in accordance with the existing literature (17, 18, 31). With HFMRA, quantitative flow measurements can additionally be derived from the phase-contrast (PC VIPR) velocity data.

Conclusion

TOA enhanced HFMRA provides serial images and time of arrival maps in one inclusive display. Our results suggest that TOA mapping combined with Virtual Bolus imaging are beneficial for the characterization of AVMs. The VB method improves delineation of the venous structures.

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Figure 1a.

Workflow example of extraction of time-of-arrival enhanced 4D HFMRA (F-H) from time resolved images (A-C). Contrast arrival can be calculated voxelwise (in this case, contrast arrival curves are extracted from ROIs in the internal carotid artery (red) and sigmoid sinus (blue), D). Predefined TOA-values (20% of max. signal intensity in this report) can then be calculated from contrast arrival curves (E).

Figure 1b.

Workflow example of the processing steps of Virtual Bolus maps (C-E). Based on the TOA-map (A), a virtual time evolution curve can be generated for each voxel using a Gaussian filter (B, 6s full width at half maximum) to further separate arterial and venous signal intensity (SI) curves compared to the actual SI curves measured with HFMRA (Fig 1a, D)).

Figure 2.

Axial MIPs of a large, right temporal high flow AVM. Time-of-arrival maps (TOA, upper row) and virtual bolus maps (VB, lower row) show no detectable differences in the early arterial phase (2nd reconstructed frame, left column). In the 5th reconstructed frame (middle column), arteriovenous overlap is diminished in VB maps (note the decreasing signal intensity of arterial structures). In the 14th reconstructed frame (last frame, right column), arterial structures are still well visible in TOA maps but do not show in VB maps.

Figure 3.

Axial MIPs of an early arterial frame (3rd reconstructed frame) of HYPRFlow MRA (HF, left), Time-of-arrival maps (TOA, middle) and virtual bolus maps (VB, right) of a left-hemispheric high-flow AVM show dilated arterial feeders (arrows) and a large caliber cortical draining vein (arrowheads) in close proximity. These vessels cannot be well separated in time resolved MRA due to rapid shunting, however, TOA and VB maps clearly show the different contrast arrival times with differences in color-coding. No difference can be detected between TOA and VB maps in this early arterial frame.

Figure 4.

Axial MIPs of an early arterial frame (3rd reconstructed frame, upper row) and a late venous frame (10th reconstructed frame) of HYPRFlow MRA (HF, left), Time-of-arrival maps (TOA, middle) and virtual bolus maps (VB, right) of a right occipital AVM with early drainage via the right sigmoid sinus. In frame 4, subtle differences in color of a draining vein (arrows) and the nidus (arrowheads) can be detected equally in TOA and VB maps. In the last frame (lower row), VB maps clearly show diminished signal intensity of the nidus compared to TOA-maps.

Table 1
Criteria and scores for qualitative evaluation

Delineation of arteries/veins	
Score 1	Poor, barely visible rendering the study non-diagnostic
Score 2	Fair, ill-defined vessels with suboptimal image quality for diagnosis
Score 3	Good, sufficient delineation with adequate image quality for diagnosis
Score 4	Excellent, sharply defined vessel borders with excellent image quality for highly confident diagnosis
Homogeneity of intravascular signal	
Score 1	Poor, completely inhomogeneous vascular signal with no continuous signal throughout the vessel
Score 2	Fair, moderate inhomogeneities with ill-defined arterial borders
Score 3	Good with some minor inhomogeneities not influencing vessel delineation
Score 4	Homogeneous signal throughout the entire vessel
Image Quality (undersampling artifacts, blurring due to misregistration)	
Score 1	No or minimal artifacts
Score 2	Moderate artifacts, not significantly affecting image interpretation
Score 3	Major artifacts, affecting image interpretation
Score 4	Not interpretable
Overall diagnostic confidence	
Score 1	Poor with no definite diagnosis possible
Score 2	Fair with only major pathological vessels identified
Score 3	Good with definite diagnosis possible
Score 4	Excellent with high confidence of vascular components
Arteriovenous Overlap – arterial/venous separation	
Score 1	severe overlap, not diagnostic
Score 2	Slight overlap, still diagnostic
Score 3	At least one arterial/venous frame without overlap
Score 4	More than one arterial/venous frame without overlap

Table 2

Mean scores and their standard deviations (brackets) of the qualitative evaluation criteria and k-values for interreader agreement of the different visualization methods. Statistically significant differences of arteriovenous overlap scores were found between HFMRA and VB ($p=0.01$, indicated by *) and between TOA and VB ($p=0.04$, indicated by ^). Statistically significant differences of diagnostic confidence scores were found between HFMRA and TOA ($p=0.03$, indicated by *) and between HFMRA and VB ($p=0.02$, indicated by ^).

	Scores	HFMRA	TOA	VB	kappa HFMRA	kappa TOA	kappa VB
Arteries	Delineation	3 (0.4)	3.2 (0.46)	3.37 (0.59)	0.83	0.82	0.75
	Homogeneity	2.9 (0.49)	2.95 (0.52)	2.92 (0.57)	0.7	0.71	0.75
	Artifacts	1.35 (0.55)	1.35 (0.55)	1.45 (0.57)	0.6	0.61	0.46
Veins	Delineation	3.05 (0.38)	3.2 (0.51)	3.37 (0.63)	0.7	0.54	0.36
	Homogeneity	3 (0.55)	3.05 (0.41)	3.02 (0.48)	0.66	0.7	0.42
	Artifacts	1.35 (0.49)	1.45 (0.55)	1.45 (0.56)	0.54	0.58	0.54
Nidus	Delineation	2.94 (0.44)	3.06 (0.44)	3.36 (0.42)	0.8	0.7	0.42
	Homogeneity	2.93 (0.39)	3 (0.43)	3.07 (0.53)	0.61	0.66	0.51
	Artifacts	1.19 (0.63)	1.3 (0.7)	1.37 (0.71)	0.47	0.45	0.66
	Spetzler-Martin score	2.75 (0.7)	2.88 (0.64)	2.88 (0.64)	0.78	0.78	1
	Arteriovenous overlap	2.85 (0.45)*	2.9 (0.64)^	3.47 (0.65)*^	0.79	0.71	0.74
	Diagnostic Confidence	2.9 (0.49)*^	3.2 (0.49)*	3.4 (0.48)^	0.83	0.7	0.68