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Non-contrast, Pseudo-Continuous Arterial Spin Labeling and Accelerated 3D Radial Acquisition Intracranial 3D MR Angiography for the detection and classification of intracranial arteriovenous shunts

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Abstract

Objectives—To assess the sensitivity and specificity of Pseudo-Continuous Arterial Spin Labeling (PCASL) magnetic resonance angiography (MRA) with 3D radial acquisition for the detection of intracranial arteriovenous (AV)-shunts.

Materials and Methods—32 patients that underwent PCASL-MRA, clinical MRI/MRA-exam and digital subtraction angiography were included in this retrospective analysis. 12 patients presented with arteriovenous malformations (AVM, n=8) and arteriovenous fistulas (AVF, n=4). The clinical MRI/MRA included 3D time-of-flight MRA in all cases and time-resolved, contrast-enhanced MRA in 9 cases (6 cases with AV-shunting). Research MR-imaging and clinical MR-imaging were independently evaluated by two neuroradiologists blinded to patient history. DSA-imaging was evaluated by a third radiologist. A diagnostic confidence score was used for the presence of abnormalities associated with AV-shunting (1–5). AVMs were characterized using the Spetzler-Martin-scale, AVFs were characterized using the Borden classification. K-statistics were applied to assess intermodality agreement.

Results—Compared to clinical MRA, non-contrast PCASL-MRA with 3D radial acquisition yielded excellent sensitivity and specificity for the detection of intracranial AV-shunts (reviewer 1: 100%/100%, clinical MRA: 91.7%, 94.4%; reviewer 2: 91.7%/100%, clinical MRA: 91.7%/100%). Diagnostic confidence was 4.8/4.66 with PCASL-MRA and 4.25/4.66 with clinical MRA. For AVM-characterization with PCASL-MRA, intermodality agreement with DSA showed κ -values of 0.43 and 0.6 for readers 1 and 2. For AVF-characterization, intermodality agreement showed κ -values of 0.56 for both readers.

Conclusion—Non-contrast PCASL-MRA with 3D radial acquisition is a potential tool for the detection and characterization of intracranial arteriovenous shunts with a sensitivity and specificity equivalent or higher than routine clinical MRA.

Keywords

Magnetic resonance angiography; non-contrast; arterio-venous shunting

Introduction

Cerebral arteriovenous malformations (AVMs) and arteriovenous fistulas (AVFs) are congenital or acquired direct communications between the arterial and venous circulations bypassing the capillary bed. Small AVMs and AVFs can be challenging to diagnose with noninvasive imaging. Therefore, digital subtraction angiography (DSA) remains the gold standard in the diagnosis and grading of such lesions due to its high spatial and temporal resolution. A number of studies have evaluated different MR-angiography techniques for the diagnosis and evaluation of AVMs and AVFs. Among these, 3D time-of flight (TOF) has shown to be a sensitive, non-contrast technique (1, 2). However, a subset of AVFs and small AVMs may not be visualized due to in-plane saturation and the lack of temporal dynamics (3). A higher sensitivity, specificity and better characterization has been achieved with dynamic contrast enhanced MRA (CE-MRA) (3–7). However, dynamic contrast enhanced MRA fails to match the temporal resolution provided by DSA and there are potential safety concerns associated with Gadolinium deposition in the deep brain nuclei. Highly sensitive and specific non-contrast MRA techniques would be beneficial for diagnosis and assessment of suspected AVMs and AVFs.

Arterial spin labeling (ASL) is a non-contrast MR-imaging technique that can be applied for perfusion as well as angiographic imaging (8, 9). ASL allows for reduced inflow effects compared to TOF and higher effective temporal resolution compared to CE-MRA. ASL sequence designed for perfusion have been found useful in detecting and grading AVMs and AVFs (10–12). In these studies, ASL images collected with inherently low spatial resolution were shown to increase the sensitivity and specificity in the detection of AV-shunting when applied as an adjunct to a clinical MR examination. However, ASL perfusion sequences do not provide angiographic information and thus could not serve as a stand-alone sequence for the detection and grading of pathologies with AV-shunting. ASL sequences designed for MRA have been refined since their introduction by Dixon et al (13), with substantial improvements in image quality and spatial resolution (14, 15). In particular, 3D-volumetric pseudo-continuous ASL (PCASL)-MRA sequences with a high spatial resolution and comparable image quality to ToF-MRA have been developed (16, 17). This technique has further been shown feasible to image AVMs (18–20) as static, but also time resolved non-contrast MRA (21).

The purpose of this work is to evaluate the sensitivity and specificity of an accelerated PCASL-based 3D MRA technique that utilizes a 3D radial acquisition technique in the detection and grading of cerebrovascular pathologies with AV-shunting. The diagnostic efficacy of PCASL-MRA was compared to standard clinical MRI including MRA-examination. In all cases, DSA served as a reference standard.

Materials and Methods

Study population

This study was Health Insurance Portability and Accountability Act (HIPAA) compliant and approved by the local institutional review board (IRB). Written informed consent was obtained from all subjects.

32 subjects that were prospectively enrolled to undergo a research PCASL-MRA and had existing clinical MRA and DSA exams were included in this analysis. This cohort included 8 AVM and 4 AVF cases that did not receive treatment between DSA and both MRI exams. Of the remaining 20 patients, 10 presented with untreated aneurysms, 7 with treated aneurysms, 1 with high-grade MCA stenosis, 1 with ischemic infarction and one with microhemorrhages. The patients without AV-shunting were included as a negative control group. Mean age of the patient group with AV-shunting was 58.5y (range 41–75y) with a female/male ratio of 5/7. Mean age of the negative control group was 59.7y (range 37–80y) with a female/male ratio of 15/5. Patient characteristics are summarized in table 1.

Imaging methods

PCASL—All PCASL-MRA scans were performed at 3T (Discovery MR 750w, GE Healthcare, Waukesha, WI). To avoid off-resonance artifacts that are a particular issue in intracranial applications of PCASL due to susceptibility at the skull base and nasal fossa, the acquisition module consists of a low flip angle SPGR readout combined with an undersampled 3D radial sampling strategy. The PCASL acquisition has been described in detail (blinded for review).

PCASL—vastly undersampled isotropic-voxel radial **projection** imaging (VIPR) parameters include: labeling duration 3 s; image acquisition window 1 s; FOV 22×22×16 cm³; 3D isotropic resolution 0.68 mm; readout bandwidth +/-62.50 kHz; TR/TE=5.06/1.07ms; fractional echo 0.75; flip angle 10°; no flow compensation. A total of 12,000 projections were collected in a scan time of 8:27 minutes. Compared to Nyquist this represents a 13× undersampling. Data acquired for the label image and control image are first subtracted in k-space then reconstructed utilizing an optimized gridding routine (22) zero-filled to 0.46mm isotropic resolution. Individual coil images were combined utilizing coil sensitivities estimated from low resolution unsubtracted images (23).

Clinical MRA

Of the 32 subjects, 14 (44%) were scanned at a field-strength of 1.5T (Signa HDxt / Optima MR 450w, GE Healthcare, Waukesha, WI) and 18 (56%) at 3T (Discovery MR 750 / Discovery MR 750w, GE Healthcare, Waukesha, WI). All examinations included the following sequences: 3D-Time-of-Flight-MRA (Spatial resolution: 3T: 0.7mm ×0.6mm ×0.7mm, 1.5T 0.7mm ×0.8mm ×1.4mm, axial/3D gradient-echo T1w, axial T2w FSE, 3D-FLAIR and axial diffusion weighted imaging. In addition, 17 (55%) underwent contrast-enhanced 3D-MRA (spatial resolution: 3T: 0.7mm ×0.8mm ×1.6mm, 1.5T: 0.7×0.8×1.6mm) and 9 underwent time-resolved, contrast-enhanced MRA (spatial resolution: 3T: 0.8mm ×0.9mm ×2mm, 1.5T: 0.8mm ×1mm ×3mm). Among the 12 patients with AVMs and AVFs,

6 were scanned at 1.5T and 6 at 3T. Among the 12 patients with AVMs and AVFs, 11 received contrast-enhanced gradient echo T1w and 10 underwent contrast-enhanced 3D-MRA, among those, 6 patients had a time-resolved contrast enhanced MRA.

DSA 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 ranging 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

The PCASL-MRA images and clinical MRAs were evaluated independently in random order by two neuroradiologists (with over 25 and 9 years experience, respectively), blinded to patient history and identity. Research and clinical images were evaluated in 2 separate session 4 weeks apart in order to avoid bias due to case recognition. A PACS workstation was used for image analysis (McKesson, San Francisco, CA, USA). A separate reader with 4 years of experience in DSA imaging evaluated all DSA exams. The DSA reader had access to all clinical and imaging information. He utilized the DSA imaging data as well as the DSA report composed by a staff neurointerventionist to report the Spetzler-Martin score or the Borden score.

An electronic evaluation form was applied by using a “drilldown” methodology in which specific aspects of the imaging modality and vascular pathology (if any) were answered on the basis of the evaluator’s previous selections. For example, for the vascular malformation cases, the form took the evaluator through the pertinent questions starting with the presence or absence of an abnormality and, if present, which type of abnormality and then a series of morphologic and measurement questions to determine the clinical grade. Study data were collected and managed by using Research Electronic Data Capture (REDCap) electronic data capture tools (<https://catalyst.harvard.edu/services/redcap/>) with grant support (Clinical and Translational Science Award program, through the National Institutes of Health National Center for Advancing Translational Sciences, grant UL1TR000427) (24).

During the assessment of the clinical MRA exam, readers were allowed to review all available imaging additional to the MRA sequence(s) they found useful for the evaluation of the case.

The evaluation criteria included: 1) Venous signal in PCASL/ToF-MRA or early venous signal if time-resolved CE-MRA available (yes/no) 2), diagnostic confidence of AV-shunting present (1=definitely not/2=probably not/3=unsure/4=probably yes/5=definitely yes); 3) Type of abnormality (AVM/AVF); 4) Image quality PCASL/ToF-MRA (5–point-scale: 1=not interpretable – 5 excellent).

AVM grading: Evaluation criteria included: Location, size (x/y/z), number of arterial feeders (main branches), number of draining veins, location of draining veins (superficial/deep), Spetzler-Martin score (25).

AVF grading: Evaluation criteria included: Presence of cortical venous reflux (y/n), number of arterial feeders (main branches), Borden-classification (26).

Statistical analysis

In order to assess the validity of using the PCASL-MRA or clinical MRA result in diagnosing either AVM or AVF, the specificity, sensitivity, positive predictive value (PPV), and negative predictive values (NPV) were calculated. These probabilities are listed for each reader, separated by their use of either PCASL-MRA or clinical MRA. The DSA results are considered the truth when assessing the subject's diagnosis.

Upon identifying cases of AVM and AVF, the level of agreement between each reader and DSA for Spetzler-Martin score (AVMs) and Borden-classification (AVFs) was calculated using the κ -statistics.

Number of arterial feeders and draining veins were analyzed using the median and interquartile range (IQR).

K-statistics can range from -1 to 1 , with 0 indicating random guessing and $+1$ indicating 100% agreement. Statistical significance of κ -statistics is widely debated and is generally not presented in papers.

Results

Figure 1 shows a representative case without AV-shunting. No venous signal can be identified. The image exclusively shows the intracranial arteries as well as the branches of the external carotid arteries.

Figure 2 shows a small, residual cerebellar AVM that was treated microsurgically 10 years earlier. The nidus is better delineated with PCASL-MRA compared to ToF-MRA due to the lack of inplane saturation effects. The nidus size and venous drainage is confirmed by DSA.

Figure 3 illustrates a left sigmoid sinus AVF without symptoms at the time of MR imaging. ToF-MRA visualized the feeding artery, but AV-shunting was suspected to be absent or diminutive. PCASL-MRA shows some residual AV-shunting in the sigmoid sinus. A DSA exam prior to the MRAs shows the left sigmoid sinus AVF.

Figure 4 shows an anterior cranial fossa AVF fed by branches originating from the ophthalmic artery. PCASL-MRA, time-resolved, contrast enhanced MRA and DSA agree on the location and feeder of the fistula. This AVF could not be visualized with ToF-MRA.

Figure 5 illustrates a case of a left transverse/sigmoid sinus fistula with multiple feeders. Feeders originating from the contralateral external carotid artery are well delineated in PCASL-MRA as well as in TOF-MRA. Feeders from the middle meningeal artery are

slightly better delineated in PCASL-MRA. Furthermore the high shunt volume results in a very bright left transverse and sigmoid sinus in PCASL-MRA compared to TOF-MRA. Findings are confirmed by DSA.

Sensitivity, specificity, PPV and NPV for the diagnosis of AVMs and AVFs

Two PCASL-MRA cases were rated non-diagnostic by both reviewers accordingly. Both consisted of untreated aneurysms, the clinical MRA was diagnostic in both of the cases. These two cases were excluded from further analysis for both PCASL and clinical MRA.

PCASL-MRA

12 out of 12 cases with AV-shunting were correctly identified by reader 1 (8 AVMs, 4 AVFs). 11 out of 12 cases with AV-shunting were correctly identified by reader 2 (7 AVMs, 4 AVFs). 1 AVM-case was rated false-negative by reader 2. 18 out of 18 cases without AV-shunting were correctly identified as negative for AV shunting by both readers. This leads to a sensitivity of 100% and a specificity of 100% for reader 1 and a sensitivity of 91.7% and a specificity of 100% for reader 2 for the diagnosis of AV-shunts. PPV/NPV were 100%/100% for reader 1 and 100%/94.7% for reader 2.

Venous signal was reported in 12 out of 30 cases (reader 1) respectively 11 out of 30 cases (reader 2). All of these patients were confirmed with AVMs or AVFs. Both readers reported no venous signal in 18 control-cases. Average score of diagnostic confidence of AV-shunting present was 4.8 (reader 1) resp. 4.66 (reader 2) in all confirmed cases with AVMs and AVFs. Average diagnostic confidence scores were and 1.15 for both readers in the control group. Average score for image quality was rated 4.0 by reader 1 and 4.4 by reader 2.

Clinical MRA

11 out of 12 cases with AV-shunting were correctly identified by both readers (7 AVMs, 4 AVFs). 1 AVM-case was rated false negative by both readers. 1 case was rated false positive with a carotid-cavernous AV-fistula by reader 1. 17 out of 18 cases were correctly identified as negative for AV shunting by reader 1 and 18 out of 18 by reader 2. This leads to a sensitivity of 91.7% and a specificity of 94.4% for reader 1 and a sensitivity of 91.7% and a specificity of 100% for reader 2 for the diagnosis of AV-shunts. PPV/NPV were 91.7%/94.7% for reader 1 and 100%/94.7% for reader 2 respectively.

Venous signal in ToF-MRA was reported in 13 out of 30 cases for reader 1 and in 14 out of 30 cases for reader 2. Of these cases, 10 for reader 1 and 11 for reader 2 were confirmed AVMs or AVFs. Venous signal in ToF-MRA was reported in 3 out of 18 control-cases by reader 1 and in 3 out of 18 control cases by reader 2. Average score of diagnostic confidence of AV-shunting present was 4.25 (reader 1) resp. 4.66 (reader 2) in all confirmed patients with AVMs and AVFs. Average diagnostic confidence scores were 1.15 (reader 1) resp. 1.2 (reader 2) in the control group. Average score for image quality of the ToF-MRA was rated 4 by reader 1 and 4.1 by reader 2. None of the ToF-MRAs were rated non-diagnostic.

Sensitivity and specificity of both imaging modalities are summarized in Table 2.

AVM-Grading

DSA—Of the 12 cases with intracranial AV-shunts, 7 were identified as AVMs and 5 as AVFs. One posterior-fossa pathology initially reported as tentorial AVF was resected and found to be a small AVM. The ratings for this study were consistent across the DSA reader and the initial DSA report.

Comparison between PCASL-MRA and DSA

Cohen's unweighted κ revealed a value of 0.43 for the agreement of Spetzler-Martin score between reader 1 and DSA and a value of 0.6 between reader 2 and DSA. Median of arterial feeders reported was 1 (IQR: 1) by reader 1 and 2 (IQR: 1.5) by reader 2 respectively. Median of arterial feeders reported on DSA was 2 (IQR: 0.5). Median of draining veins was reported 2.5 (IQR: 2.25) by reader 1 and 3 (IQR: 1.5) by reader 2 respectively. Average number of draining veins reported on DSA was 2 (IQR: 4.5).

Comparison between clinical MRA-DSA

Cohen's unweighted κ revealed a value of 0.45 for the agreement of Spetzler-Martin score between reader 1 and DSA and a value of 0.61 between reader 2 and DSA. Median of arterial feeders reported was 2 (IQR: 1) by reader 1 and 1 (IQR: 1.5) by reader 2 respectively (DSA: 2, IQR: 0.5). Median of draining veins was reported 4 (IQR: 2) by reader 1 and 3 (IQR: 1.5) by reader 2 respectively (DSA: 2, IQR: 4.5).

AVF-classification

Comparison between PCASL-MRA and DSA—Cohen's unweighted κ revealed a value of 0.56 for the agreement of the Borden-classification between reader 1 and DSA and a value of 0.56 between reader 2 and DSA. Average number of arterial feeders reported was 2.75 by reader 1 and 3.75 by reader 2 respectively (DSA: 3.4).

Comparison between clinical MRA and DSA—Cohen's unweighted κ revealed a value of 0.2 for the agreement of the Borden-classification between reader 1 and DSA and a value of 0.56 between reader 2 and DSA. Average number of arterial feeders reported was 2.5 by reader 1 and 3.75 by reader 2 respectively (DSA: 3.4).

AVM and AVF scores and κ -values are summarized in Table 3.

Discussion

In this study, we showed that high-resolution, non-contrast PCASL-MRA is an effective tool to detect and classify intracranial arterio-venous shunts. PCASL-MRA proved to be as sensitive and specific as a full clinical MRA-exam with multiple sequences including a ToF-MRI in all cases and a time resolved, contrast enhanced MRA in 50% of cases with AV-shunting.

Several reports have shown the benefit of ASL and PCASL-MRA in the diagnosis of intracranial AV-fistulas and AV-malformations (2, 6, 10, 12). However, the role of ASL was limited to an adjunct to a clinical MRI-scan due to the lack of angiographic information and

the low spatial resolution in these studies. Further studies have shown the ability of non-contrast ASL MRA to properly visualize AVMs, but did not evaluate the sensitivity and specificity (18–20, 27). To our knowledge, this is the first report evaluating the sensitivity and specificity of high-resolution non-contrast PCASL-MRA alone to detect intracranial AV-shunting.

PCASL is used for brain perfusion imaging and increasingly as a non-contrast MRA technique (28, 29). In this technique, arterial spins are labeled and therefore can be imaged when travelling through the arterial tree. However, as soon as excited protons enter the capillary system, they undergo an exchange with water protons contained in the extracellular space. This leads to a rapid signal loss within the capillary bed and consecutively a highly specific display of the arterial system without venous contamination. However, if a direct communication between the arterial and the venous system exists, the labeled arterial spins are able to carry over signal into the venous vasculature. Therefore, venous signal in a PCASL angiogram is likely to reflect arterio-venous shunting with high specificity. TOF-MRA and contrast enhanced MRA can perform with similarly high sensitivity. However, there are more potential sources of venous contamination possible in TOF-MRA (veins entering the imaging slab in the same direction as arteries (i.e. skull base), suboptimal placement of saturation bands) and contrast enhanced MRA (primarily suboptimal bolus timing).

The excellent sensitivity and specificity in diagnosing intracranial AV-shunts is reflected by the results of both readers, with reader 1 achieving a higher sensitivity and specificity than with a full clinical MRI exam.

For AVM characterization, agreement with DSA on Spetzler-Martin score was equivalent utilizing PCASL-MRA or the clinical MRA for both readers. However, we could not reproduce the very high agreement on Spetzler-Martin classification reported for time-resolved PCASL-MRA (20). For AVF characterization, agreement with DSA on Borden classification was higher utilizing PCASL-MRA than the clinical MRA exam for both readers. The lower numbers of agreement in our study compared to the referenced study on AVMs may be due to the low case numbers when ungrouping AVMs and AVFs for characterization.

Additional advantages of PCASL-MRA are the lack of contrast agent, which allows high spatial resolution imaging compared to dynamic contrast enhanced MRA, where rapid imaging is necessary to capture the passing contrast bolus. Furthermore, the growing evidence of Gadolinium deposition in the brain likely leads to a greater interest in contrast-free alternatives to contrast-enhanced MRI. The utilized PCASL-MRA sequence provides consistent results, as shown by a low number of non-diagnostic scans in our study. This might be related to the 3D radial trajectory, which makes acquisitions less sensitive to patient motion and mitigates blurring from magnetization evolution through the readout. Additionally, while the spoiled gradient readout provides lower overall SNR compared to alternative readouts, it is insensitive to off-resonance. This is especially important for AVFs and AVMs of the posterior fossa, where alternative readout strategies (i.e. bSSFP) can suffer from macroscopic gradients in regions of large susceptibility changes (18, 20). Especially

for AVFs, that are frequently found in the posterior fossa close to the skull and fed by external carotid artery branches, this is an essential characteristic. Compared to PCASL MRA, no non-diagnostic TOF-MRAs were observed in this study. This is most likely related to the shorter scan time but also smaller spatial coverage of the TOF MRA.

Our study has several shortcomings. First, this was a retrospective study with potential unknown biases. Specifically, intracranial pathologies other than AVFs or AVMs might lead to negative bias in the sense of a satisfaction of search error. Second, most of the very subtle, small AV-shunts in this study were located in the posterior, middle and anterior cranial fossa. Location of small AVMs and AVFs in the apical cranial convexity might affect the sensitivity of PCASL-MRA as the labeled blood loses signal travelling the greater distance from the labeling plane. Further tailoring of the applied labeling delay could be used to optimize the sequence respective to small convexity AVMs.

Finally, the clinical MRA exams were performed at different magnetic field strength with different MRA protocols. Consistent scanning at 3T might improve sensitivity given the higher SNR.

In conclusion, PCASL-MRA yields excellent results in the detection and moderate results in grading of cerebrovascular diseases with AV-shunting without the need for exogenous contrast agents in the present study. Due to the lack of special hardware, the utilized MR-sequence could be applied on different MR-scanner platforms.

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Figure 1.
PCASL-MRA of a representative case without AV-shunting. No venous signal can be identified. The image exclusively shows the intracranial arteries as well as the branches of the external carotid arteries.

Figure 2.

Case of a small, residual cerebellar AVM that underwent microsurgical treatment 10 years earlier. The nidus (arrows in A1, B1, asterisk in A2, B2) can be better delineated with PCASL-MRA (A1, A2) compared to ToF-MRA (B1, B2) due to the lack of inplane saturation effects. The venous drainage via the superior petrosal sinus / sigmoid sinus are visualized in PCASL- and ToF-MRA. The nidus size and venous drainage are confirmed by DSA. The clinical MRA was performed at 3T.

Figure 3.

Illustration of an AVF that showed symptom regression without treatment. PCASL-MRA (A) shows residual AV-shunting (arrow in A) in the sigmoid sinus. ToF-MRA (B) visualized the feeding artery, but AV-shunting was suspected to be absent or diminutive (arrow in B). The DSA-exam with left external carotid injection (C) 18 months prior to the MRAs shows concordant findings of a left transverse sinus fistula (arrow). The clinical MRA was performed at 3T.

Figure 4.

Fig. 4 shows an ethmoidal AVF fed by the anterior/posterior ethmoidal artery (arrows). PCASL-MRA (A), time-resolved, contrast enhanced MRA (B) and DSA (C) agree on the location and feeder of the fistula. Note the hyperintensity in the superior sagittal sinus in PCASL-MRA (short arrow in A). Time-resolved CE MRA and DSA confirm AV-shunting (short arrows in C, D). This AVF could not be visualized with ToF-MRA. The clinical MRA was performed at 3T.

Figure 5.

Representative case of a left transverse/sigmoid sinus fistula with multiple feeders originating from bilateral ECAs. PCASL-MRA is displayed in the first column (A, B), ToF-MRA in the second (C, D) and the corresponding DSA in the third column (E, F). Feeders originating from the contralateral external carotid artery are well delineated in both PCASL-MRA (arrow in A) and ToF-MRA (arrow in C) and confirmed by DSA (arrow in E). Feeders from the ipsilateral middle meningeal artery (MMA) are better delineated in PCASL-MRA (arrow in B) compared to TOF-MRA (arrow in C). Feeders originating from the contralateral ECA and ipsilateral MMA are confirmed by DSA (arrow in F). For comparison reasons, we showed to TOF-MRA derived during the research exam as the clinical TOF-MRA was performed at 1.5T and covered a smaller volume.

Table 1

Summary of patient characteristics and distribution of clinical MRA exams at 1.5T and 3T

	AV-shunting	No AV-shunt
Number of patients	12	20
Mean age (years)	58.5	59.7
Female/male	5/7	15/5
<i>Diagnosis</i>		
AVMs	8	0
AVFs	4	0
Aneurysms untreated	0	10
Aneurysms treated	0	7
Stenosis	0	1
Ischemia	0	1
Microhemorrhage	0	1
<i>MRI field strength</i>		
Clinical MRA 3T	6	12
Clinical MRA 1.5T	6	8

Test results of the different imaging modalities (PCASL-MRA and clinical MRA) and their sensitivity and specificity per modality per reader.

Table 2

	Shunting	No shunting	Sensitivity	Specificity
Reader 1	PCASL-MRA positive	14	0	100%
	PCASL-MRA negative	0	16	100%
	Clinical MRA positive	13	1	91.7%
	Clinical MRA negative	1	15	94.4%
Reader 2	PCASL-MRA positive	13	0	91.7%
	PCASL-MRA negative	1	16	100%
	Clinical MRA positive	13	0	91.7%
	Clinical MRA negative	1	16	100%

Summary of median values of Spetzler-Martin-scores for AVMs and Borden-scores for AVFs as well as each readers' agreement with DSA (κ -value).

Table 3

		Spetzler-Martin-Score	Agreement with DSA (κ -value)	Borden-Score	Agreement with DSA (κ -value)
PCASL-MRA	Reader 1	1.5	0.43	1	0.56
	Reader 2	2	0.6	1	0.56
Clinical-MR	Reader 1	3	0.45	1.5	0.2
	Reader 2	3	0.61	1	0.56
DSA		2		2.5	