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Original Article

Validity of PETRA-MRA for Stent-Assisted Coil Embolization of Intracranial Aneurysms

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Objective: Pointwise encoding time reduction with radial acquisition (PETRA) using magnetic resonance angiography (MRA) is a non-enhanced MRA technique employing an ultrashort echo time, and is known to significantly reduce the magnetic susceptibility of coils and stents during post-embolization imaging. We evaluated the quality of PETRA-MRA images for use at the follow-up assessment of stent-assisted coil embolization procedures performed to treat aneurysms.
Methods: A total of six aneurysm patients who were treated by stent-assisted coil embolization were included. All patients underwent PETRA-MRA, time-of-flight (TOF)-MRA performed with MAGNETOM Skyra (Siemens), and digital subtraction angiography (DSA) performed with Infinix Celeve-i INFX-8000V (Canon Medical Systems) and Allura Clarity FD20/15 (Philips). The PETRA-MRA images were compared with those from DSA and TOF-MRA to validate the aneurysm occlusion status and visually assess the blood flow within the stent. Four independent specialists graded occlusion status and flow visualization through the stent using a four-point scale, where 4 points represented excellent visualization of flow within the stent.
Results: The aneurysm was located in the internal carotid artery in two patients, the middle cerebral artery in two patients, the top of the basilar artery in one patient, and the vertebral artery-posterior inferior cerebellar artery (VA-PICA) in one patient. Three patients were treated using a Neuroform Atlas Stent system, one using an Enterprise2 VRD, one using two Neuroform Atlas stents for Y-stenting, and the remaining patient using a Neuroform Atlas and an Enterprise2 VRD for Y-stenting. With DSA, the postoperative aneurysm occlusion status was neck remnant (NR) in five cases and complete obliteration (CO) in one case. DSA and PETRA-MRA evaluations demonstrated an equal occlusion status in five of six cases, whereas DSA and TOF-MRA were equal in two of six cases. The mean visualization score for PETRA-MRA was 3.33 ± 0.82, whereas that for TOF-MRA was 2.17 ± 1.33. On the PETRA-MRA images, blood flow through the stent was well-visualized and produced an aneurysm occlusion status score comparable to DSA, especially in the three cases using the Neuroform Atlas Stent System where the visualization was scored 4 points. In the case of the VA-PICA aneurysm, for which an Enterprise2 VRD was used, PETRA-MRA images were insufficient for postoperative assessment.
Conclusion: PETRA-MRA can provide good visualization of the blood flow within a stent and displays a clear blood signal near the coils, barring small magnetic susceptibility artifacts. Therefore, PETRA-MRA may be an effective option for follow-up imaging after stent-assisted coil embolization.

Keywords ▶ pointwise encoding time reduction with radial acquisition-MRA, stent assisted coil embolization, cerebral aneurysm, ultrashort echo time MRA, postoperative evaluation

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Introduction

Stent-assisted coil embolization of intracranial aneurysms has recently been performed more widely in patients who are difficult to treat using coils alone.[1] Intracranial blood vessels can be non-invasively evaluated using time-of-flight (TOF)-magnetic resonance angiography (MRA)[2–5] and neck remnants (NRs) are relatively favorably visualized after embolization with coils alone. However, following stent placement, digital subtraction angiography (DSA) is considered useful to evaluate the state after embolization and the blood flow through the stent lumen because of marked metal artifacts. Although DSA enables detailed evaluation, there are test-induced embolic complications, radiation exposure, and contrast media reactions.[6] Contrast-enhanced MRA was used in several reports, but adverse reactions to contrast media are of concern.[5,7,8]

MRA with a very short echo time (ultrashort echo time MRA), such as Silent Scan MRA (GE Healthcare, Milwaukee, Wisconsin, USA), was recently developed and acquisition of images with reduced magnetic susceptibility artifacts has been reported, attracting attention.[1,9–12] Its use has been reported for evaluating occlusion status post-coil embolization and post-stent-assisted coil embolization.[10,11,13] In this study, we used ultrashort echo time MRA acquired via the Pointwise Encoding Time reduction with Radial Acquisition (PETRA) method, or PETRA-MRA, to evaluate occlusion status after coil embolization and visualization of the blood flow lumen (of the stented parent artery) in patients after stent-assisted coil embolization of intracranial aneurysms to assess the efficacy of PETRA-MRA.

Materials and Methods

The subjects were six patients (six lesions) with unruptured intracranial aneurysms treated by stent-assisted coil embolization at our hospital between April 2017 and February 2020 who could be followed by PETRA-MRA, and these patients were studied retrospectively (**Table 1**). PETRA and TOF-MRA images were acquired simultaneously using a 3-T MRI from device of Siemens Healthcare, MAGNETOM Skyra, and DSA images were acquired using Infinix Celeve-i INFX-8000V from Canon Medical Systems or Allura Clarity FD20/15 from Philips. Occlusion status after coil embolization and visualization of the blood flow lumen of the stented parent artery were evaluated and compared between PETRA/TOF-MRA and DSA images. The PETRA-MRA acquisition conditions employed at our facility were: repetition

Table 1 Characteristics of all patients

Case No.	Age (y.o.)	Sex	Aneurysms location/ size (mm)	ID of PA (mm)	Stent/length (mm)	Visualization score of the flow in stent		Aneurysm occlusion status				Interval between from EVT	
						PETRA	TOF	Right after	DSA	PETRA	TOF	to DSA	to MRA
No. 1	93	F	IC/6 × 6 × 6	3.8	Neuroform Atlas/4.5 × 30	4	3	NR	NR	NR	NR	0 day	3 months
No. 2	69	M	MCA/5 × 4 × 4	2.4	Neuroform Atlas/3.0 × 21	4	4	NR	NR	NR	NR	2 years	2 years
No. 3	71	F	IC/8 × 5.5 × 5	3.9	Neuroform Atlas/4.5 × 21	4	3	BF	NR	NR	CO	6 months	1 year
No. 4	49	F	MCA/4 × 2.5 × 2.5	1.2	Neuroform Atlas/3.0 × 15 & 3.0 × 21	3	1	CO	CO	CO	UE	7 days	2 days
No. 5	53	F	VA-PICA/12 × 11 × 11	1.3	Enterprise2 VRD/4.0 × 16	2	1	NR	NR	UE	UE	6 months	9 months
No. 6	77	M	Basilar tip/10 × 9 × 9	2.7	Neuroform Atlas/4.0 × 21 Enterprise2 VRD/4.0 × 23	3	1	NR	NR	NR	UE	0 day	2 days

Visualization score of the flow in stent: 1; not visible (almost no signal in the stent); 2: poor (structures are slightly visible but with significant blurring or artifacts, not diagnostic); 3: good (good quality diagnostic information with minimal blurring or artifacts); 4: excellent (excellent-quality diagnostic information; the shape of depiction is nearly equal to that of DSA). BF: body filling, CO: compete obliteration, EVT: endovascular treatment, IC: internal carotid artery, ID: internal diameter, MCA: middle cerebral artery, NR: neck remnant, PA: parent artery, PICA: posterior inferior cerebellar artery, UE: unevaluable, VA: vertebral artery time, 3.45 msec; echo time, 0.07 msec; flip angle, 6°; field of view, 240 mm; voxel size, 0.75 (isovoxel); reconstruction matrix, 320; radial spokes, 63000; phase partial Fourier, off; and the acquisition time was 10 minutes and 11 seconds. TOF-MRA acquisition time was 4 minutes and 24 seconds.

Maximum intensity projection (MIP) images and volume rendering (VR) images of DSA, TOF-MRA, and PETRA-MRA were prepared using a work station of Fuji Film, SYNAPSE VINCENT. For the standard evaluation, MIP images were used, and highly visual stereoscopic VR images were referred to when necessary (**Fig. 1D–1F**).

Evaluations were made by three neurosurgeons and one specialist in neuroendovascular therapy. The state after embolization was classified into three categories and then evaluated: complete obliteration (CO), NR, and body filling (BF). For evaluation blood flow visualization within the stent lumen, visualization was rated using the scoring system reported by Irie et al.[10]: 1, not visible (almost no signal in the stent); 2, poor (structures are slightly visible but with significant blurring or artifacts; not diagnostic); 3, good (good quality diagnostic information with minimal blurring or artifacts); and 4, excellent (excellent-quality diagnostic information; the shape of depiction is nearly equal to that of DSA). A score of 2 or lower after embolization was judged to be insufficient for assessing occlusion status after stent-assisted coil embolization of intracranial aneurysms and regarded as unevaluable (UE).

Results

The intracranial aneurysm was located in the internal carotid artery in two patients, middle cerebral artery in two, basilar tip in one, and vertebral artery-posterior inferior cerebellar artery (VA-PICA) bifurcation in one patient. The mean interval of time between performing TOF/PETRA-MRA and DSA was 65.1 days (2–192 days). The stent used was the Neuroform Atlas Stent System (Stryker, Kalamazoo, MI, USA) in three patients, the Enterprise2 VRD (Johnson & Johnson, Raynham, Miami, Florida, USA) in one, the Y-stent using 2 Neuroform Atlas stents in one, and the Y-stent using the Neuroform Atlas and Enterprise2 VRD in one patient.

The evaluation after embolization using DSA images was NR in five patients and CO in one patient. The evaluation was consistent with these DSA image findings for five (83.3%) patients when PETRA-MRA images were used and two (33.3%) patients when TOF-MRA images were used (**Table 1**). Coil protrusion into the parent artery and NR was evaluated in detail on PETRA-MRA compared with on TOF-MRA (**Fig. 1D–1F**).

The mean visualization score for PETRA-MRA was 3.33 ± 0.82 (scored 2 in one patient, 3 in two, and 4 in three patients) and the mean score on TOF-MRA was 2.1 7 ± 1.33 (scored 1 in 3 patients, 3 in two, and 4 in one patient) (**Table 1**). No difference was noted in the evaluation after coil embolization or visualization of the blood flow in the stent in MIP or VR image between TOF-MRA and PETRA-MRA.

In Case Nos. 1–3 using 1 Neuroform Atlas alone, the score for PETRA-MRA was rated 4 in all cases, demonstrating favorable visualization of the blood flow within the stent and the evaluation after embolization on DSA images was also consistent in all cases. In Case 4, using 2 Neuroform Atlas stents for Y-stenting, the score for TOF-MRA was rated as 1, with poor visualization of the blood flow within the stent. However, the score for PETRA-MRA from the same case was rated as 3 (i.e., superior to TOF-MRA).

In Case No. 5 with VA-PICA aneurysm (VA-PICA An) using Enterprise2 VRD, visualization of the blood flow within the stented parent artery on PETRA/TOF-MRA was insufficient.

Case Presentation

1. Case No. 2

Patient: A 69-year-old male. For an unruptured right middle cerebral artery aneurysm (5 × 4 × 4 mm) (**Fig. 1A**), a Neuroform Atlas 3.0 × 21 mm stent was deployed from the right M2 inferior trunk over M1 (**Fig. 1B**) and embolization was completed with mild NR (**Fig. 1C**). On comparison between the findings of follow-up DSA images 2 years after treatment and PETRA/TOF-MRA images performed 24 days after DSA, the evaluation was NR in both images (**Fig. 1D–1F**). When the details were investigated, the artery was visualized up to the vicinity of the coil from PETRA-MRA images and DSA compared with TOF-MRA images (**Fig. 1D–1F**).

2. Case No. 4

Patient: A 49-year-old female. For an unruptured left middle cerebral artery aneurysm (4 × 2.5 × 2.5 mm) (**Fig. 2A**), a Neuroform Atlas 3.0 × 15 mm stent was placed in the left anterior temporal artery over M1 and a Neuroform Atlas 3.0 × 21 mm stent was deployed from the distal to proximal M1 to set Y-stent, and embolization was completed with CO (**Fig. 2C**). On comparison between the findings of follow-up DSA images 7 days after treatment and PETRA/TOF-MRA images 2 days after treatment, the

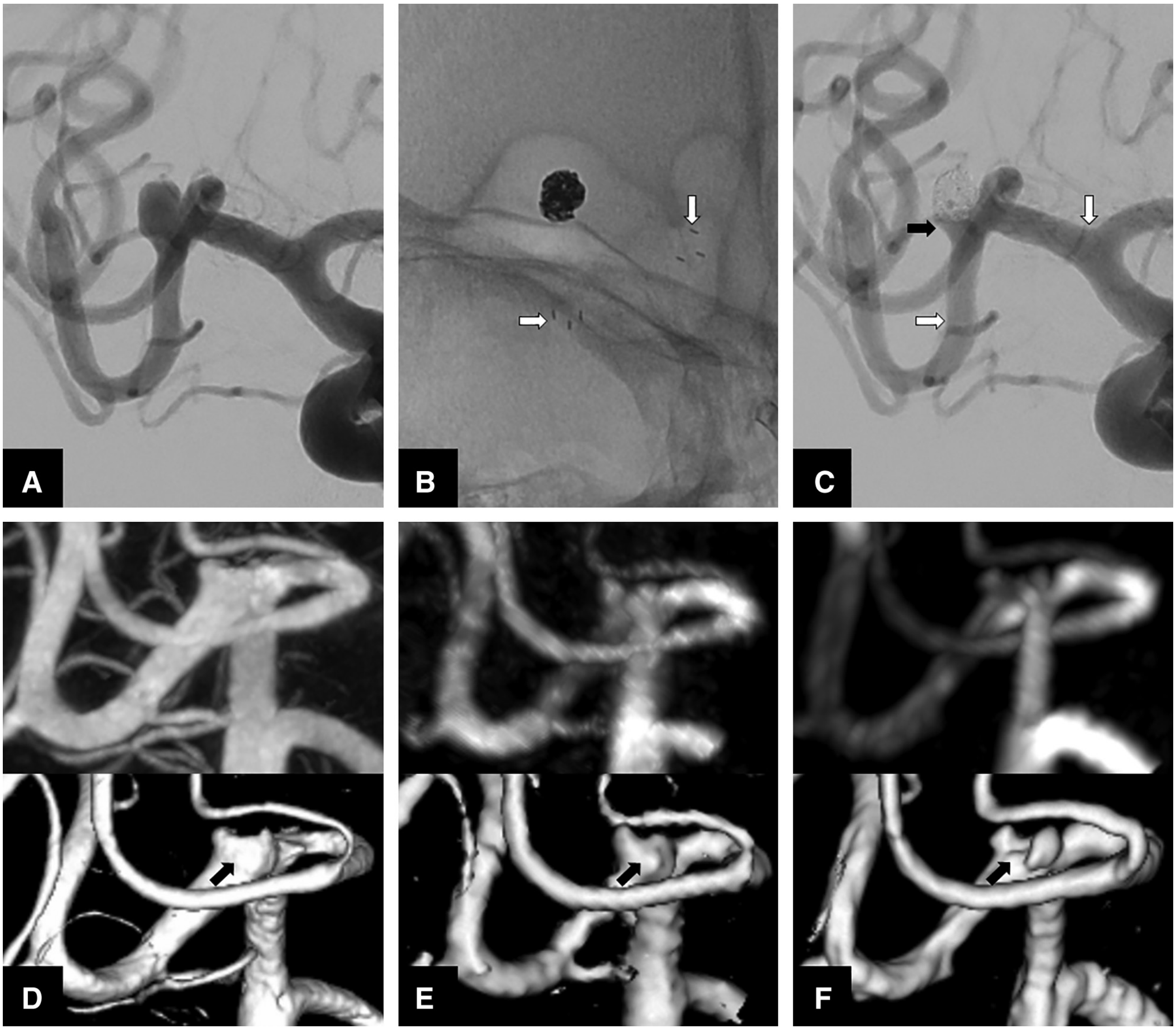

Fig. 1 (**A**) Working view on right internal carotid angiography showing the wide neck M1M2 aneurysm. (**B**) Neuroform Atlas was deployed from M2 inferior trunk to M1 (between the white arrows). (**C**) Right internal carotid angiography right after the procedure showing the slight NR (black arrow) of the aneurysm. The white arrows show the distal and proximal ends of the stent. (**D**) MIP and VR images of 2-year follow-up DSA show the remnant of the aneurysm (black arrow) and the blood flow in the stent. (**E**) MIP and VR images of 2-year follow-up PETRA-MRA show the remnant of the aneurysm (black arrow) and the blood flow in the stent as well as DSA. (**F**) MIP and VR images of 2-year follow-up TOF-MRA show the remnant, but there is a defect in the remnant area (black arrow). DSA: digital subtraction angiography; MIP: maximum intensity projection; NR: neck remnant; TOF-MRA: time-of-flight-magnetic resonance angiography; VR: vertebral artery

anterior temporal artery was not visualized on TOF-MRA and the evaluation was UE. Conversely, the same area was successfully evaluated using DSA and PETRA-MRA images, and the evaluation was CO (**Fig. 2D–2F**). In this case, the evaluation of the blood flow visualization within the stent on PETRA-MRA was similar to that on DSA despite Y-stenting using 2 Neuroform Atlas stents.

3. Case No. 5

Patient: A 53-year-old female. For a right VA-PICA aneurysm (12 × 11 × 11 mm), which re-enlarged after coil embolization, an Enterprise2 VRD 4.0 × 16 mm stent was deployed from the right PICA over the right distal VA and embolization was completed with NR (**Fig. 3A** and **3B**).

The evaluation was NR on follow-up DSA images 6 months after treatment (**Fig. 3C**). On PETRA/TOF-MRA at 9 months after treatment, the visualization score of the blood flow within the stent was rated as 1 for TOF-MRA images and 2 for PETRA-MRA images. Visualization was insufficient for these modalities, and the evaluation after embolization was judged as UE on both (**Fig. 3D–3F**). However, NR and the stent placement region in the right

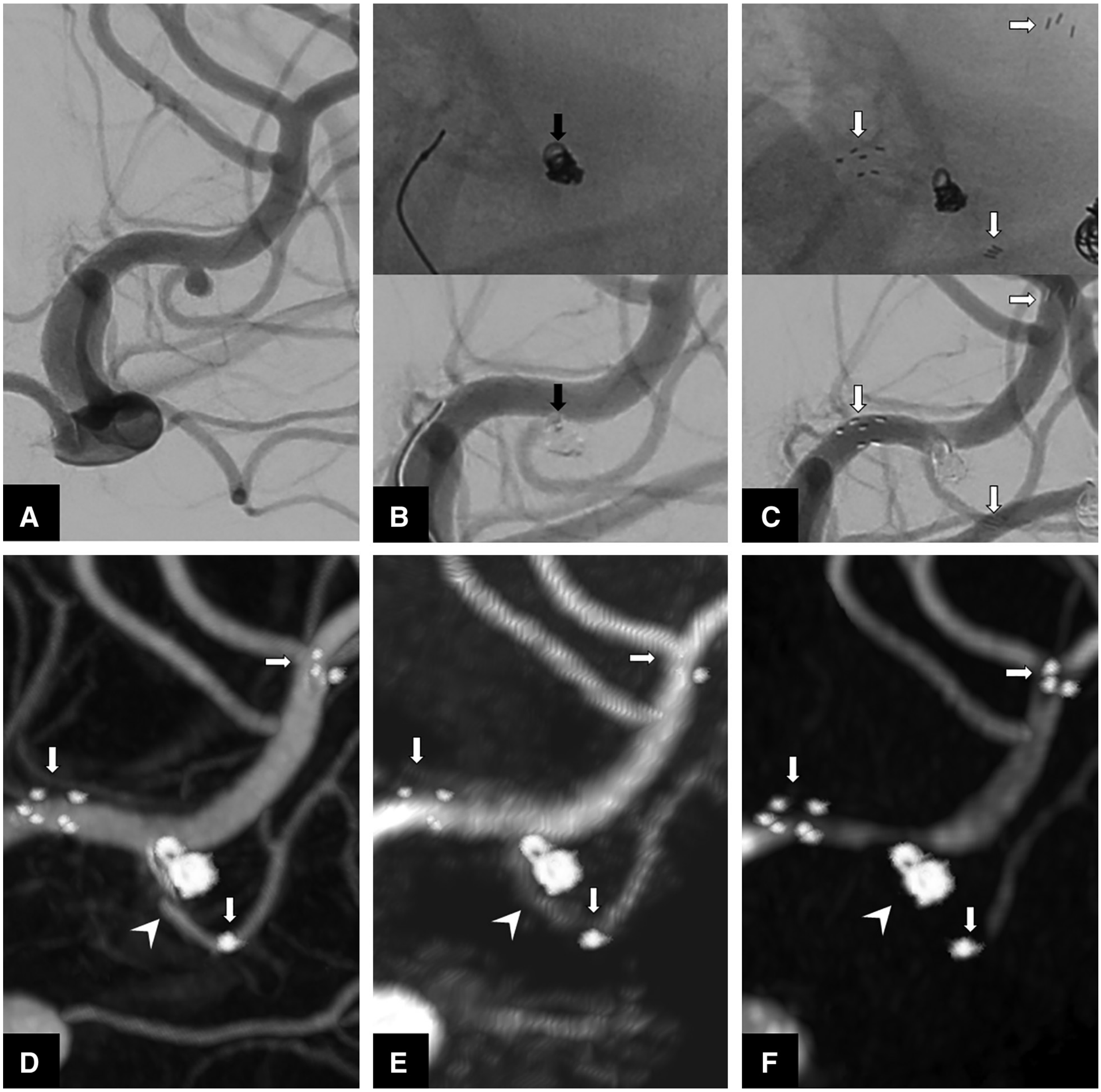

Fig. 2 (**A**) Working view on left internal carotid angiography showing the M1-anterior temporal artery aneurysm. (**B**) Two loops of the 1st coil were at the orifice of the anterior temporal artery and M1 (black arrow). (**C**) Two Neuroform Atlas stents were deployed from the distal anterior temporal artery to M1 and from the distal M1 to proximal M1. The white arrows show the distal and proximal ends of the stents. (**D**) Fusion MIP image of DSA at 7 days after the procedure showing the blood flow in the stent clearly, M1, and the anterior temporal artery (white arrowhead). (**E**) Fusion MIP image of PETRA-MRA at 2 days after the procedure showing the blood flow in the stent (white arrowhead) almost as well as DSA. (**F**) The blood flow of the stented anterior temporal artery (white arrowhead) cannot be visualized on the fusion MIP image of TOF-MRA at 2 days after the procedure, and the caliber of stented M1 is small. DSA: digital subtraction angiography; MIP: maximum intensity projection; PETRA-MRA: pointwise encoding time reduction with radial acquisition-magnetic resonance angiography; TOF-MRA: time-of-flight-magnetic resonance angiography

VA were clearly visualized on PETRA-MRA images compared with TOF-MRA images and the stented PICA was slightly visualized (**Fig. 3E**).

Discussion

After coil embolization of intracranial aneurysms, follow-up by imaging is necessary to investigate signs of recurrence such as coil compaction. Using TOF-MRA images, evaluation is possible but only to a certain extent. Evaluation of the NR and BF may be insufficient due to magnetic susceptibility artifacts, suggesting that DSA is preferred for close evaluation.

The Silent MRA method was recently developed by GE healthcare and imaging with reduced magnetic susceptibility artifacts (to coils) has garnered attention.[10,11]

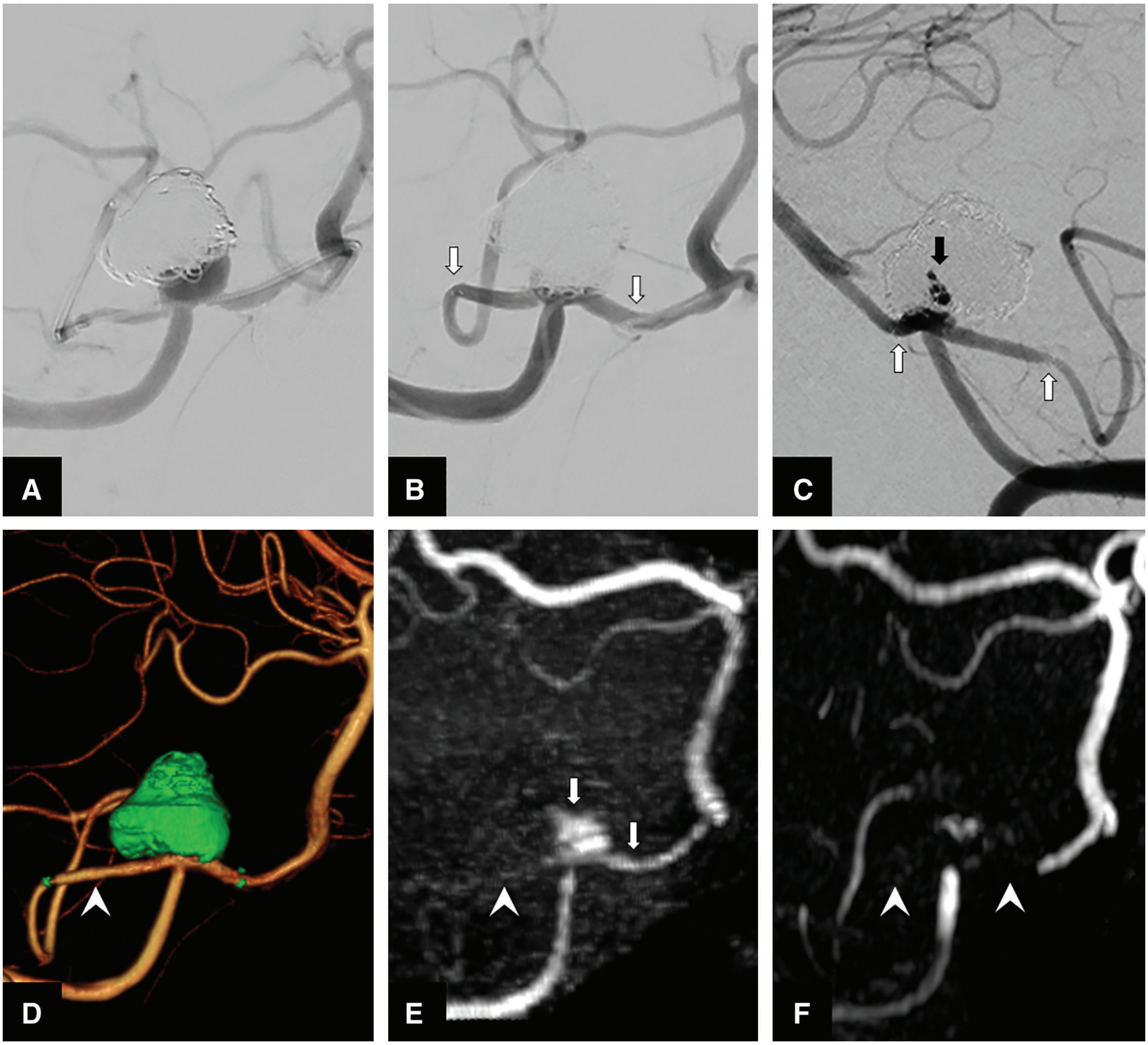

Fig. 3 (**A**) Preoperative working view on right vertebral angiography showing the remnant of the VA-PICA aneurysm. (**B**) Final angiography showing CO of the aneurysm. The white arrows show the stent from the PICA to VA. (**C**) Lateral view on 6-month follow-up angiography showing regrowth of the NR. The white arrows show the distal and proximal ends of the stent, and the patency of the PICA was good. (**D**) Fusion VR of DSA shows the PICA (white arrowhead) and the blood flow in the stent clearly. (**E**) MIP image of 9-month follow-up PETRA-MRA showing the blood flow in the stent at the PICA (white arrow head) slightly. It shows the blood flow in the stent at the right VA and the remnant of the aneurysm (white arrows) clearly. (**F**) The blood flow in the stent from the PICA to VA (white arrowheads) cannot be visualized on the MIP image of 9-month follow-up TOF-MRA. CO: complete obliteration; DSA: digital subtraction angiography; NR: neck remnant; PETRA-MRA: pointwise encoding time reduction with radial acquisition-magnetic resonance angiography; VA-PICA: vertebral artery-posterior inferior cerebellar artery

Silent MRA and PETRA-MRA commonly share acquisition of vascular images with reduced magnetic susceptibility artifacts utilizing the ultrashort echo time, but Silent MRA is a technique using MRA arterial spin-labeling,[9–12] whereas PETRA-MRA acquires signals through the in-flow effect (a phenomenon in which the signal intensity of arterial blood increases compared with that in the surrounding tissue when arterial blood not applied with a saturation pulse flows into the acquisition range), being different from Silent MRA.[13–15] In PETRA-MRA, the blood vessel is visualized by subtraction of the PETRA image from which the in-flow effect was removed by applying a saturation pulse to the blood in-flow region from the image acquired by the normal PETRA method including the in-flow effect.

Heo et al. reported that postoperative evaluation of anterior circulation intracranial aneurysms after stent-assisted coil embolization by PETRA-MRA was possible.[16] As in our study, the evaluation of occlusion status after embolization using PETRA-MRA images was consistent with that of using DSA images in five of the six patients. No difference was noted in the evaluation after embolization in either MIP or VR images from PETRA-MRA, but visibility was stereoscopically enhanced on VR and useful for morphological evaluation (**Fig. 1D–1F**). However, it is necessary to consider that measured values are not accurate when the vascular diameter is measured using MIP or VR, and DSA may be preferred for precise evaluation.

PETRA-MRA is not contrast-enhanced and non-invasive. It is advantageous for repetitive examination, but it requires an acquisition time of 10 minutes or more under the conditions employed at our facility because the image is acquired by digital subtraction via software. Moreover, images are greatly influenced by body movement artifacts. Patient cooperation is essential when addressing this weakness.

The blood flow within the stent was insufficiently evaluated in the patient with a VA-PICA aneurysm, but evaluations of occlusion status after coil embolization were visualized favorably in the patients with anterior circulation aneurysms. Insufficient visualization of the blood flow within the stent in the VA-PICA patient may have been due to the small diameter of the parent artery.

It has been reported that contrast-enhanced MRA was effective as follow-up imaging after stent-assisted coil embolization of intracranial aneurysms[17]; therefore, comparison between PETRA-MRA and enhanced MRA should also be performed.

The number of patients in this study was low and no low-profile visualized intraluminal support (LVIS; Microvention Inc., Aliso Viejo, CA, USA) stent was included. In future studies, it is necessary to investigate visualization differences of blood flow within the stent among different stents and many patients.

Conclusion

This study suggested that PETRA-MRA imaging is useful for postoperative follow-up and is advantageous to non-invasively evaluate occlusion status after embolization and the blood flow within the stent after treatment in patients with intracranial aneurysms treated by stent-assisted coil embolization.

Disclosure Statement

The authors declare no conflict of interest.

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