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Review

Current Status of Magnetic Resonance Angiography

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The principles and clinical applications of the different magnetic resonance angiography (MRA) techniques that are available in clinical settings are described in this paper.

Time-of-flight (TOF) MRA is the most common MRA method, performed without the intravenous injection of any contrast material. The high diagnostic accuracy of brain three-dimensional TOF MRA in the detection of both steno-occlusive lesions and aneurysms is well-known. Therefore, MRA is usually performed first in suspected cases of these vascular lesions, with subsequent computed tomography angiography (CTA) or conventional angiography for further examination.

Phase-contrast MRA is another magnetic resonance technique that allows for the evaluation of flow directions and flow velocities, which is a specific advantage of MRA as compared with CTA.

In peripheral arteries, fresh blood imaging (FBI) or contrast-enhanced MRA is preferable because two-dimensional TOF MRA requires a long acquisition time. FBI is a novel and non-invasive MRA technique. However, this technique has been introduced relatively recently and is not available in many current magnetic resonance systems.

Key words: magnetic resonance angiography (MRA), Time-of-flight (TOF), Phase-contrast (PC), Fresh blood imaging (FBI)

1. Introduction

Magnetic resonance angiography (MRA) is the depiction and characterization of blood vessels and blood flow using magnetic resonance imaging (MRI). MRA encompasses a wide variety of magnetic resonance sequences that have been devised to provide angiographic contrast (Table 1). The technique's name suggests an equivalence to conventional angiography (i.e., digital subtraction angiography, DSA); however, MRA and DSA differ in many ways. Notably, one important advantage of MRA over both DSA and computed tomography angiography (CTA) is its non-invasiveness, or nonuse of irradiation. The second major benefit of MRA is that it can be performed without intravenous injection of contrast

Table 1. Imaging and post-processing reconstruction techniques of MRA

Imaging Techniques:
1. Non-contrast MRA
1.1. Time of Flight (TOF) MRA
1.2. Phase Contrast (PC) MRA
1.3. Fresh Blood Imaging (FBI)
2. Contrast-enhanced MRA
Post-processing Reconstr uction Techniques:
1. Maximum Intensity Projection (MIP)
2. Volume Rendering (VR)

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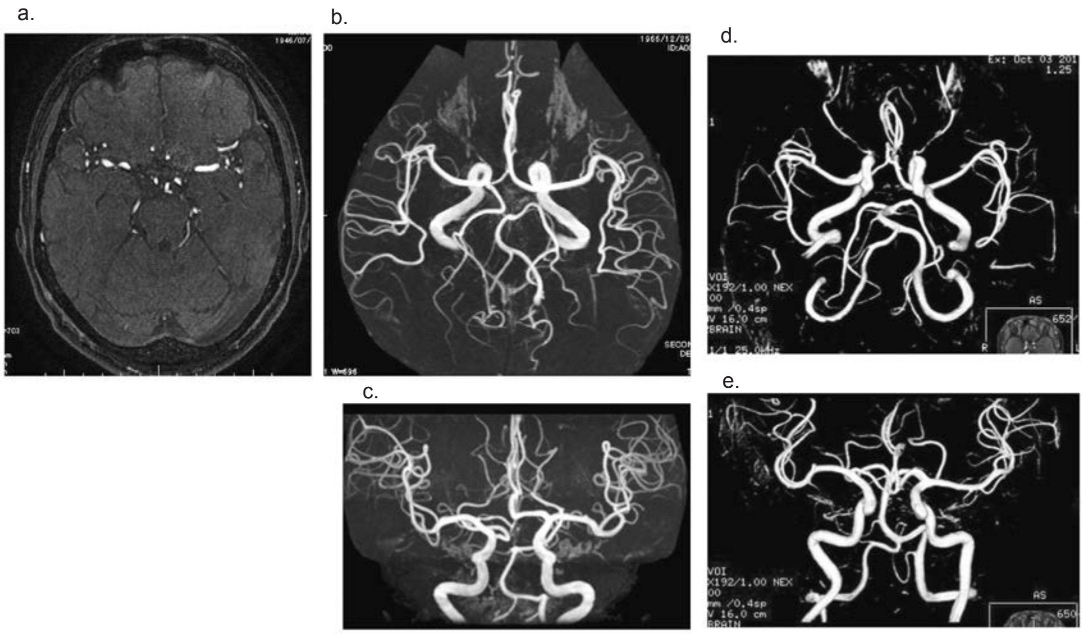

Fig. 1. Original axial image and MIP post-processing angiographic images.
a. Original axial image
b. MIP basal view
c. MIP frontal view
d. VR basal view
e. VR frontal view
From multiple original axial images, MIP or VR images are reconstructed in different directions. These images show no abnormal findings.

materials (non-contrast MRA). However, MRA does not always provide a precise anatomical depiction of the vessel lumen. Rather, it provides a functional representation of the vessels that reflects blood flow patterns and velocities[1]. The disadvantages of MRA include contraindications to MRI, noise, and long imaging time. Patients with "MR-unsafe" materials (e.g., MR-unsafe cardiac pacemaker, MR-unsafe aneurysmal clip) are contraindications to MRI. "Magnetic resonance-conditional" pacemakers are not widely used; therefore, most patients with cardiac pacemakers cannot be examined. Patients with metallic materials (e.g., artificial joints, metallic stents, and hemostatic clips) can generally undergo MRI, although regional image distortion is inevitable.

Regardless, in the case of any MRA technique, the obtained original images are reconstructed with maximum intensity projection (MIP) or volume rendering (VR) to obtain angiographic images (Fig. 1).

In this article, the main concepts and clinical applications of common MRA techniques will be described.

2. Time-of-flight (TOF) MRA

2.1. The principles of TOF MRA

TOF MRA is the most widely used MRA method in clinical settings, especially for the evaluation of the intracranial vessels (Figs. 1, 2).

The TOF MRA technique demonstrates contrast between flowing blood and stationary tissue. When repetition time is very short, the magnitude of the magnetization from the spins of stationary tissue is small because of the saturation effect, while the magnitude of the magnetization from the spins of flowing blood is high. In TOF angiography, radiofrequency pulses are applied only to a thin slice or slab of tissue within the patients. Only the volume of material that is pulsed becomes saturated. Blood that is outside of this area and that has not been pulsed is fully relaxed and possesses its full magnetization. As this relaxed blood enters the volume, it appears bright[2]. This leads to a high signal being present from moving spins, with background tissue signal suppression (representing a so-called "flow-related enhancement" or "inflow effect").

For a successful TOF angiography procedure to occur, blood must enter the chosen area with relatively high velocity and traverse it within a short amount of time. Notably, inflow will be at its greatest when the acquired slice of tissue is perpendicular to the axis of the blood vessels. If blood stays in the selected area for several pulses, it ultimately becomes saturated and loses its signal. Therefore, the vessels that flow parallel to the plane of acquisition (in-plane flow) may have no inflow effect and may not be visualized on MRA[2]. Therefore,

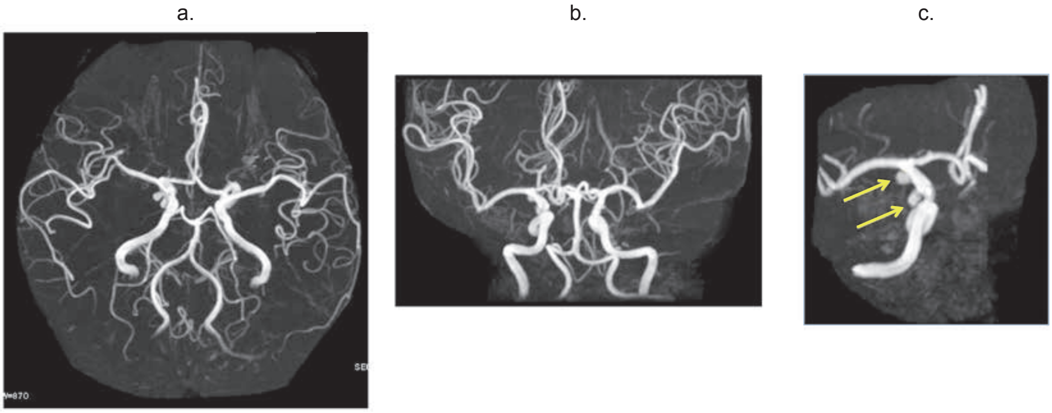

Fig. 2. Brain TOF MRA in patients with internal carotid aneurysms.
a. MIP basal view
b. MIP frontal view
c. MIP oblique view (target MIP)
The two saccular aneurysms of the right internal carotid artery are well delineated.

the axial slice setting is usually selected to maximize the flow signals because the main flow segments in the human body occur along the body's axis.

Often, a pre-saturation band is placed parallel to the acquired slice to remove any signals from vessels flowing in the opposite direction. For example, in carotid angiography, one may place a saturation band parallel and superior to the acquired slice to saturate the jugular vein[2].

The TOF angiogram can be acquired as a set of stacked two-dimensional (2D) slices, as three-dimensional (3D) sections, or as an overlapping stack of 3D segments (multi-slab 3D)[2].

In sequential 2D TOF MRA, a thin slice is acquired perpendicular to the axis of the blood vessel so that the blood travels across the narrow width of the slice. This yields a cross-sectional image with a dark background and bright flow signals. The 2D TOF MRA method is relatively sensitive to slow-flowing blood as compared with the 3D TOF MRA methods[2] and is sometimes used in the evaluation of peripheral arterial disease (PAD) (Fig 3.).

The resolutions of the projected images depend on slice thickness. In clinical practice, 3-4-mm-thick slices are often used because of the limited signal-to-noise ratio in the 2D TOF MRA method[2]. In patients with PAD, MRA techniques with longer scanning ranges, for example, from abdominal area to the feet, are usually required. However, for such a large scanning range, many imaging slices are typically needed and thus the scanning procedure can be complicated and time-consuming.

The significant advantage of 3D TOF MRA over 2D TOF MRA is its high signal-to-noise ratio, which allows for the inclusion of very thin slices of less than 1 mm, resulting in projections of very high resolution.

Fig. 3. Two-dimensional TOF MRA in patients with peripheral artery disease.
a. 2D TOF MRA
b. CTA (with contrast material)
The occlusion of the right superficial femoral artery and left femoro-femoral bypass graft is well depicted on MRA and CTA. Small collateral vessels are depicted better on CTA.

Unfortunately, the major limitation of 3D TOF MRA is that the observed blood flow of the distal portion of the slab tends to be low because of the saturation effect[2]. However, this problem can be overcome with multiple thin-slab 3D acquisition with a small amount of overlap between slabs or multiple overlapping thin-slab angiography[3] (Fig. 4). Because of the thin slabs used, there is little saturation of the blood present. The slabs need to overlap because partitions at the edges of a 3D

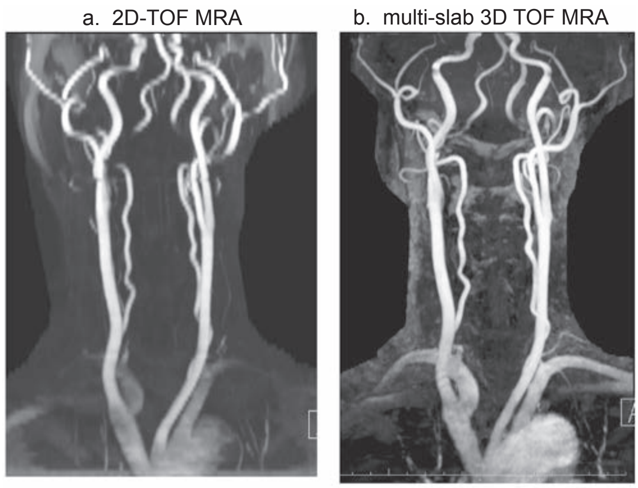

Fig. 4. Neck TOF MRA
a. 2D-TOF MRA
b. Multi-slab 3D TOF MRA
In 2D TOF MRA, the signal intensity decreases in tortuous vessels and in-plane flow. Multi-slab 3D TOF MRA shows better delineation.

image acquisition are darker than those in the middle.

2.2. Clinical applications of TOF MRA

As stated before, TOF MRA is the most widely used MRA technique; however, specifically in the evaluation of intracranial vessels, 3D TOF MRA is usually used (Figs. 1, 2).

The diagnostic ability of MRA at 3.0 T for the detection of intracranial steno-occlusive disease is considered high. A blinded study with a relative large population compared the accuracy of MRA and conventional angiography in the assessment of intracranial vascular stenosis and showed that the sensitivity and specificity of the five observers for the interpretation of MIP images were 85% and 96%, respectively[4)]. In another paper, it was reported that interpretations based on source partitions were more accurate than interpretations based on MIP images alone in the diagnosis of intracranial arterial stenosis. Of note, the specificity for high-grade lesions improved because several lesions that were not visible on MIP images could be measured on individual sections[5)]. A third paper showed that there is a strong linear relationship between the narrowest lumen diameter of the intracranial internal carotid artery and the percentage of stenosis. This study's results suggested that a single lumen diameter measurement on MRA allows for the attainment of accurate Warfarin-Aspirin Symptomatic Intracranial Disease stenosis measurements, which may affect risk stratification and treatment decisions[6)]. It is also reported that TOF MRA has a tendency to overestimate the degree of severe stenosis because of the disturbed pattern of blood flow within and beyond the stenotic lesion in some patients[7)]. Although this overestimation does not typically lead to a false-negative evaluation, it should still be kept in mind, and the results should be interpreted carefully.

MRA is also considered to have high diagnostic accuracy in the detection of intracranial aneurysms[8-12)] (Fig. 2). 3D TOF MRA at 3.0 T is reported to depict intracranial aneurysms better than 1.5 T TOF MRA[8)]. In another paper, it was reported that MRA at 3.0 T, specifically VR for 3D TOF MRA at 3.0 T, had an accuracy of 97.6%, sensitivity of 99.2%, specificity of 94.4%, positive predictive value (PPV) of 97.2%, and negative predictive value (NPV) of 98.3% in the detection of intracranial aneurysms in patient-based evaluations. Furthermore, the aneurysm-based evaluation yielded an accuracy of 98.3%, a sensitivity of 99.3%, a specificity of 96.9%, a PPV of 97.8%, and a NPV of 99.1%. Thus, the authors concluded that the use of VR for 3D TOF MRA at 3.0 T accurately identified the presence of intracranial aneurysms. Specifically, the high PPV and NPV findings indicated that VR for 3D TOF MRA at 3.0 T may replace DSA as a contrast-free, noninvasive, and non-radiation-based modality for the diagnosis and screening of intracranial aneurysms[9)]. Thus, the most recent guidelines for diagnostic imaging published by the Japanese Radiological Society recommend that MRA be used in the screening of unruptured intracranial aneurisms.

As described above, TOF MRA is mainly used in the evaluation of either intracranial vessels (Figs. 1, 2) or carotid arteries in the neck region (Fig. 4); however, it is often used in the examination of the peripheral arteries as well[12-14)] (Fig. 3). Although the small and tortuous collateral vessels are not very well demonstrated, the presence of severe stenosis or arterial occlusions can be evaluated using TOF MRA.

3. Phase-contrast (PC) MRA

3.1. The principles of PC MRA

The PC MRA technique derives contrast between flowing blood and stationary tissue. specifically by using the movement of transverse magnetization to produce image contrast[15, 16)]. Changes in the phase (phase angle) of transverse magnetization in flowing blood are induced within one or more magnetic field gradient. These phase shifts, which are directly related to spin position, can be reversed by applying a second gradient pulse of equal duration but opposite polarity. If the protons have not moved during the interval between the first and second gradient pulses, then the reversal of the phase shift will be exact, canceling the effect of the original phase shift and resulting in no net phase shift (zero changes in phase angle). This bipolar gradient is the called velocity-encoding gradient (VENC). Adequate VENC setting is essential to produce good PC MRA scans. To provide quantitative information, the VENC strength is set to the

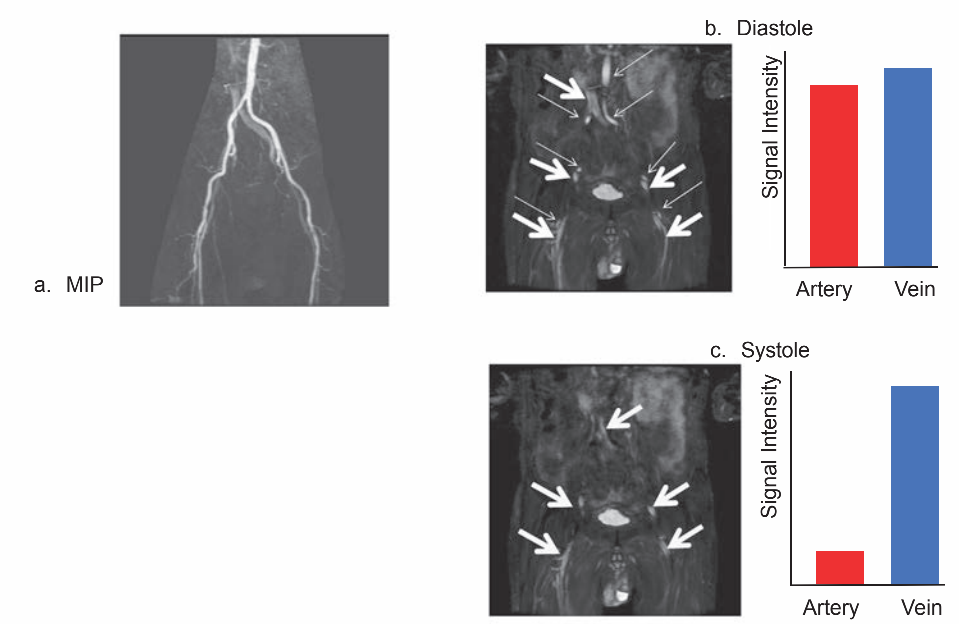

Fig. 5. The images and signal intensities of vessels on FBI.
a. MIP
b. an image and the signal intensity in diastole
c. an image and the signal intensity in systole
The MIP images (a) are reconstructed from subtraction images (i.e., subtraction of the systole image from the diastole images). In diastole, the signal intensity is high in the arteries and veins (b). However, the signal intensity of arteries is low in systole (c).
This image is modified from Fig. 2 in reference 18 with permission.

highest velocity encountered that will produce a phase shift close to but not exceeding ± 180° [3].

3.2. Clinical applications of PC MRA

PC MRA requires longer scanning times than does TOF MRA because of the necessity for repeated acquisitions with VENC in different axes. Thus, PC MRA is not usually used in clinical settings. Instead, it is mainly used in flow measurement: notably, flow direction and velocity can easily be evaluated using PC MRA.

4. Fresh blood imaging (FBI)

4.1. The principles of FBI

Flow-spoiled FBI is another non-contrast MRA method that allows for the depiction of arteries by utilizing the signal differences between systolic- and diastolic-triggered data[17-19]. The performance of FBI using an electrocardiogram (ECG)-gated 3D half-Fourier fast spin-echo (FSE) sequence relies on the presence of a signal difference between systolic and diastolic triggered acquisition. Specifically, this technique relies on the black arterial signal, or flow void, that may be present because of the spin-dephasing effects of fast arterial flow during systole. During diastole, arterial flow is slow and is thus depicted by a high signal. In contrast, venous blood is bright throughout the cardiac cycle because of its moderately constant slow flow[18] (Figs. 5, 6). Because this technique relies on the velocity of blood flow, ECG gating or peripheral-pulse gating is required for selectively acquiring the necessary data during the cardiac phases. The contrast of the image in half-Fourier FSE is

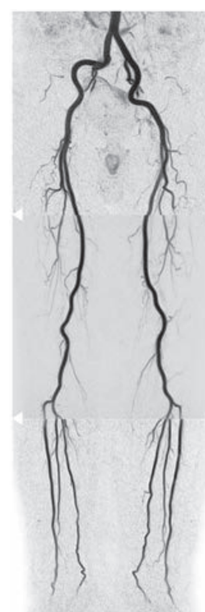

Fig. 6. Magnetic resonance angiography of the lower extremities (i.e., fresh blood imaging).
In the inverted MIP images, the entire vascular trees of the lower extremities are well delineated. (by courtesy of Aomori City Hospital)

determined by the effective echo time (TEeff); moderate to heavily T2-weighted images are obtained by selecting short or long TEeff values.

4.2. Clinical applications of FBI

Currently, although the FBI method is used in only a few facilities, interest in it is spreading. Its clinical applications are mostly in the peripheral arteries, including the aorta. In patients with PAD, a wide scanning range is required, and 2D TOF MRA is not ideal in such a situation. However, the use of FBI in PAD patients showed a high level of diagnostic performance, including a sensitivity of 97%, a specificity of 96%, an accuracy of 96%, a PPV of 88%, and a NPV of 99%[19].

In addition, in cases of arterial occlusion, segments distal to the recanalization sites have low signals because of low arterial blood pressure (i.e., less pulsatile flow). However, they do generate a signal and therefore can be clearly distinguished from total occlusion on FBI.

5. Contrast-enhanced (CE) MRA

5.1. The principles of CE MRA

In CE MRA, signal differences are achieved mainly by intravenously injecting a contrast agent into the vascular system to selectively shorten the T1 of the blood. By implementing a 3D T1 weighted imaging sequence during the first pass of the contrast agent, significant preferential arterial enhancement without the confounding effects of excessive venous or background tissue enhancement can occur[20]. Therefore, the CE technique is considered relatively insensitive to signal loss due to turbulence. Additionally, because the associated saturation effects are minimal, large fields of view within the coronal or sagittal planes can be imaged to demonstrate large vascular areas over a short acquisition time. For the evaluation of patients with PAD, the moving-bed technique is applied to elucidate entire vascular trees[21-24]. Data on the entire vascular tree of the lower extremities are usually acquired within two minutes. If it takes longer, the veins and stationary tissues might also be enhanced.

In CE MRA, the timing of the scan acquisition is a crucial point. If the data are acquired too early (i.e., before the arrival of the contrast agent), then the arterial enhancement may not be high enough. Conversely, if the data are acquired too late, then the arterial signal will be diminished and the veins and stationary tissues will be enhanced. To ensure proper timing of the acquisition, the use of triggering software or a test bolus technique is essential.

Fig. 7. Neck CE MRA
On CE MRA, tortuous segments of arteries are well delineated. The right subclavian vein is also delineated because of the contrast material remaining within the injection side vein.

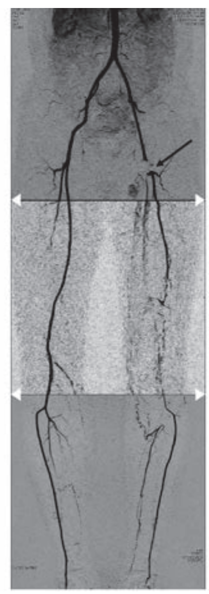

Fig. 8. Table-moving CE MRA of the lower extremities in patients with peripheral artery disease (inverted MIP).
Entire vascular trees of the lower extremities are well depicted on CE MRA. The occlusion of the left superficial femoral artery is well demonstrated. There is signal loss of the left common femoral artery because of metallic stent placement (→). The signal loss is limited to the placement region.

5.2. Clinical applications of CE MRA

CE MRA has been frequently applied in the neck or lower extremity arteries (Figs. 7, 8) and sometimes in the whole body, from brain to feet[26]. Because CE MRA is insensitive to signal loss resulting from saturation effects or turbulence, tortuous vessels are well-demonstrated on CE MRA. Additionally, overestimation of the stenosis on CE MRA is considered less prominent than that on TOF MRA.

The injection dose of the contrast material used in MRA is lower than the dose used in CT (e.g., iodinecontrast material) and the overall incidence of adverse reactions, such as nausea and vomiting, exanthema, and headache are less than 1% [27]. The only limitation in using gadolinium (Gd)-containing contrast agents had been that some patients have an allergy to Gd-containing contrast agents. However, since the relationship between the administration of a gadolinium (Gd)-containing contrast agent and the onset of nephrogenic systemic fibrosis (NSF) was first reported in 2006[28], the administration of a contrast material has been considered a risk factor for NSF in patients with renal deficiency. Renal deficiency has been added as a limitation of using Gd-chelates; thus, the indications for CE MRA have been reduced. Furthermore, even if the patient's renal function is good enough for the administration of a contrast agent, CTA is preferred. Generally, MRA is preferred for evaluating stenotic lesions only in cases of severe calcification; therefore, CE MRA is only indicated in patients with severe calcification, without renal deficiency.

6. Post-processing Reconstruction Techniques

With any magnetic resonance method, the angiographic images were obtained from images acquired by either MIP or VR post-processing. Images are usually acquired at every 15º to 30º rotation. There is evidence that VR more accurately depicts three-dimensional relationships, while MIP may not because of the particularities of the processing in the MIP algorithm. VR also allows for greater definition of the surrounding soft tissues, muscle and bone, while these are eliminated on MIP. However, MIP may display smaller branch vessels better than VR. There is thus room for the use of both projections in the evaluation of intracranial aneurysms[10]. Inverted images may be used with MIP (Figs. 6, 8). It is also recommended that the physicians examine not only MIP or VR images but also original images for a more accurate evaluation of the patient[5].

7. Conclusions

MRA is now widely used, and its significant diagnostic value has been established. However, MRA should only be applied with knowledge of its principles, to maximize its applicability.

Conflict of Interest Disclosure

The author declares that I have no conflict of interest.

References

1. Anderson CM. What is MRA? In: Anderson CM, Edelman RR, Turski PA, editors. Clinical magnetic resonance angiography. New York: Rave Press; 1993. p. 1–10.
2. Anderson CM and Lee RE. Time-of-flight angiography. In: Turski PA, editors. Clinical magnetic resonance angiography. New York: Rave Press; 1993. p. 11–42.
3. Link KM, Lesco NM. Magnetic resonance angiography: Great vessels and abdomen. In: Stark DD and Bradley Jr WG, editors. Magnetic Resonance Imaging. 3rd ed. St. Louis: Mosby; 1999. p. 373–84.
4. Korogi Y, Takahashi M, Mabuchi N, Miki H, Shiga H, Watabe T, et al. Intracranial vascular stenosis and occlusion: diagnostic accuracy of three-dimensional, Fourier transform, time-of-flight MR angiography. Radiology. 1994;193:187–93.
5. Korogi Y, Takahashi M, Nakagawa T, Mabuchi N, Watabe T, Shiokawa Y, et al. Intracranial vascular stenosis and occlusion: MR Angiographic Findings. AJNR Am J Neuroradiol. 1997;18:135–43.
6. Baradaran H, Patrl P, Gialdini G, Al-Dasuqi K, Giambrone A, Kamel H, et al. Quantifying intracranial internal carotid artery stenosis on MR angiography. Am J Neuroradiol. 2017;38(5):986–90.
7. Urchuk SN, Plewes DB. Mechanisms of flow-induced signal loss in MR angiography. J Magn Reson Imaging. 1992;2:453–62.
8. Gibbs GF, Huston J, Bernstein MA, Riederer SJ, Brown RD Jr. Improved image quality of intracranial aneurysms: 3.0-T versus 1.5-T time-of-flight MR angiograph. Am J Neuroradiol. 2004;25(1):84–7.
9. Li MH, Li YD, Tan HQ, Gu BX, Chen YC, Wang W, et al. Contrast-free MRA at 3.0 T for the detection of intracranial aneurysms. Neurology. 2011;77(7):667–76.
10. Yamanadala V, Sheth SA, Walcott BP, Buchbinder BR, Buckley D, Ogilvy CS. Non-contrast 3D time-of-flight magnetic resonance angiography for visualization of intracranial aneurysms in patients with absolute contraindications to CT or MRI contrast. J Clin Neurosci. 2013;20(8):1122–6.
11. Sailer AM, Wagemans BAJM, Nelmans PJ, de Graaf R, van Zwam WH. Diagnostic intracranial aneurysms with MR angiography systematic review and meta-analysis. Stroke. 2014;45(1):119–26.
12. Edelman RR, Hochman MG. Body magnetic resonance arteriography. In: Anderson CM, Edelman RR, Turski PA, editors. Clinical magnetic resonance angiography. New York: Rave Press; 1993. p. 1–10.
13. Owen RS, Carpenter JP, Baum RA, Perloff LJ, Cope C. Magnetic resonance imaging of angiographically occult run-off vessels in peripheral arterial occlusive disease. N Engl J Med. 1992;326:1577–81.
14. Saito Y, Takekawa S, Yodono H, et al. MR angiography of the lower extremities in arteriosclerosis obliterance. JJMRM.1993;13:347–53. Japanese.
15. Dumoulin CL, Hart HR Jr. Magnetic resonance angiography. Radiology. 1986;161:717–20.
16. Saito Y, Takekawa S, Yodono H, et al. Phase contrast MR-angiography of the lower extremities with Use of 0.5T MRI unit. JJMRM. 1989;9:38–44. Japanese.
17. Miyazaki M, Sugiura S, Tateishi F, Wada H, Kassai Y, Abe H. Non-contrast-enhanced MR angiography using 3D ECG synchronized half Fourier fast spin echo. J Magn Reson Imaging. 2000;12:776–83.
18. Miyazaki M, Takai H, Sugiura S, Wada H, Kuwahara R, Urata J. Peripheral MR angiography: Separation of arteries from veins with flow-spoiled gradient pulses in electrocardiography-triggered three-dimensional half-Fourier fast spin-echo imaging. Radiology. 2003; 227:890–6.
19. Nakamura K, Miyazaki M, Kuroki K, Yamamoto A, Hiramine A, Admiraal-Behloul F. Noncontrast-enhanced peripheral MRA: Technical optimization of flow-spoiled fresh blood imaging for screening peripheral arterial diseases. Magn Reson Med.

2011;65(2):595–602.

20. Prince MR. Gadolinium-enhanced MR aortography. Radiology. 1994;191(1):155–64.

21. Ho KY, Leiner T, de Haan MW, Kessels AG, Kitslaar PJ, van Engelshoven JM. Peripheral vascular tree stenoses: evaluation with moving-bed infusion-tracking MR angiography. Radiology. 1998;206:683–92.

22. Hayashi H, Yuasa Y, Amano Y, Tanimoto A, Saito Y, Yoshioka K, et al. Arterial visualization by contrast-enhanced moving-table MR angiography: crossover comparison of 0.1 and 0.2 mmol/kg Doses of Meglumine Gadopentetate in normal volunteers. J. Magn Reson Imaging. 2008;28:783–90.

23. Madhuranthakam AJ, Kruger DG, Riederer SJ, Glockner JF, Hu HH. Time-resolved 3D contrast -enhanced MRA of an extended FOV using continuous table motion. Magn Reson Med. 2004;51:568–76.

24. Saito Y, Yodono H. Non-invasive Evaluation of peripheral vessels: Diagnostic radiologist's viewpoint. J Jpn Coll Angiol. 2006;46:211–16. Japanese.

25. Saito Y, Sasaki T, Itabashi Y, Miura H, Noda H, Yodono H. Contrast-enhanced MR Angiography of the neck with elliptical centric view ordering: Evaluation of the imaging delay and imaging contrast. J Jpn Coll Angiol. 2006;43:289–92. Japanese.

26. Ruehm SG, Goyen M, Barkhausen J, Kröger K, Bosk S, Ladd ME, et al. Rapid magnetic resonance angiography for detection of atherosclerosis. Lancet. 2001;357:1086–91.

27. Ishiguchi T, Takahashi S. Safety of gadoterate meglumine (Gd-DOTA) as a contrast agent for magnetic resonance imaging: results of a post-marketing surveillance study in Japan. Drugs R D. 2010;10(3):133–45.

28. Grobner T. Gadolinium – a specific trigger for the development of nephrogenic fibrosing dermopathy and nephrogenic systemic fibrosis? Nephrol Dial Transplant. 2006;21(4):1104–8.