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MR Angiography

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1. Introduction

Diagnostic angiography was first performed in humans by Moniz in 1927 (Nath 2006), but did not achieve widespread adoption until Seldinger facilitated a safer method via flexible catheter access rather than direct needle access in 1953(Seldinger 1953). Since that time, invasive diagnostic angiography enjoyed rapid adoption, with further therapeutic interventions now performed in nearly every vascular bed. In 1974, the first reports of magnetic resonance imaging (MRI) were published(Macovski 2009), which soon added to the arsenal of the radiologist's tools to image the body and eventually its vessels. In recent years, noninvasive imaging (via ultrasound, x-ray computed tomography [CT], and MRI) has decreased the frequency of diagnostic angiography which is in many cases now reserved for high-risk patients, and situations with a certain or high likelihood of intervention (Saloner 1995). While the role of the diagnostic radiologist has therefore been redefined, this development has also contributed to the rise of subspecialisation in the field of interventional radiology, via improved planning and post-procedure management. Today magnetic resonance angiography (MRA) is widely available, and is the standard of care for many diagnoses in the neurologic system, and is rapidly becoming a first-line test in many centers for peripheral vascular imaging, imaging of the great vessels, and in some cases can even be applied to the beating heart, allowing noninvasive coronary MR angiography for selected applications. This chapter will review the basic forms of MRA as organized by pulse sequences and image types (technical considerations), and then review examples of these techniques as performed in each body system.

2. Technical considerations in MR Angiography

From its inception, MRI has allowed imaging of the vessels, by virtue of its cross-sectional nature. Although MRI initially presented an advantage over CT by its unlimited imaging planes, the advent of multidetector CT with isotropic resolution has slightly dampened this enthusiasm. MRI does however, enjoy the advantage of its lack of ionizing radiation, relative freedom to image large patients without image compromise, and ability to repeat acquisitions when necessary. Ultrasound remains the first line test for imaging flow velocity, but MRI can indeed quantitate blood flows and velocity with technically advanced sequences.

This section will first review the non-contrast enhanced (non-enhanced) techniques for imaging vessels, followed by pulse sequences requiring intravenous contrast. Image post-processing techniques for vascular imaging will briefly be reviewed. Contrast agents themselves, and relevant safety issues, will then be reviewed.

2.1 Non-enhanced MRA

Non-enhanced MRA can be achieved because the magnetic properties of flowing blood are inherently different than that of stationary tissue. This ranges from relatively simple "black blood" techniques, to phase-contrast imaging, and relatively modern inflow techniques. These techniques are advantageous because they do not require intravenous access, and can be repeated if necessary. They may be less robust for imaging diminutive vessels, and depending on the pulse sequence, may not be available on all scanners.

2.1.1 Black-blood techniques

Black blood techniques are produced via pulse sequences that null the signal from moving blood. While they are relatively simple (based upon spin echo techniques), they can take relatively long times to acquire. More recently fast spin-echo and single-shot techniques have decreased acquisition times. Although they are widely available and relatively robust, these techniques are often supplanted by more advanced pulse sequences. However, in cardiac imaging, they remain a basic staple, particularly when coupled with nulling techniques that decrease the signal from moving blood. Black blood techniques also are advantageous when imaging of surrounding soft tissue anatomy is desired. (Lee 2005)

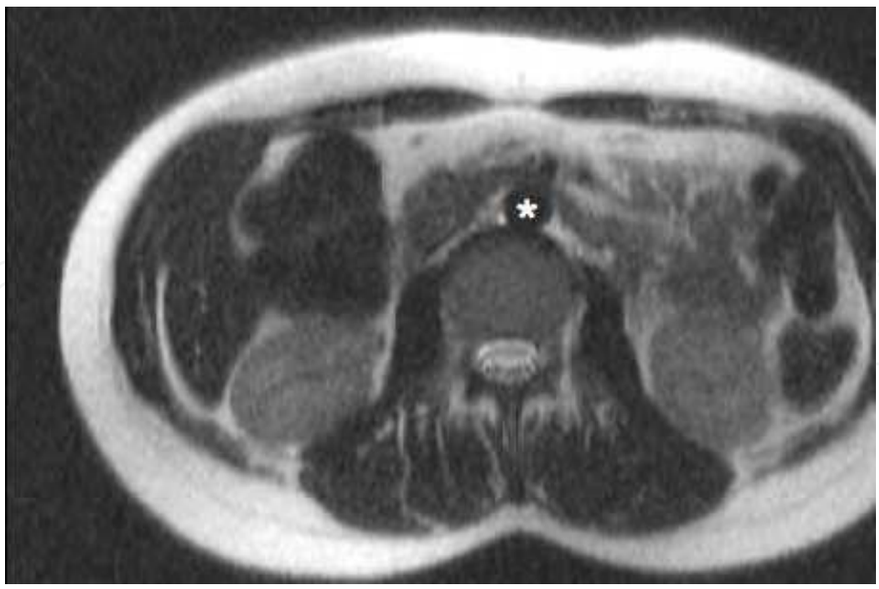


Fig. 1. Black blood effect. Fast spin-echo T2-weighted axial MRI image demonstrates a normal flow void within the abdominal aorta (asterisk). This pulse sequence can be obtained on any modern scanner, and takes advantage of the inherent lack of contrast in a flowing vascular bed when performing basic spin-echo acquisitions.

2.1.2 Bright-blood techniques

Gradient-recalled echo techniques improve dramatically the speed of acquisition that MRA can be performed. More modern iterations include balanced steady-state free precession imaging (aka. "white blood"), and have allowed cardiac MRI with cine imaging to be robust enough for routine use. These sequences can be used for localization and imaging of surrounding tissues (although they are less reliable for tissue characterization). (Lee 2005)

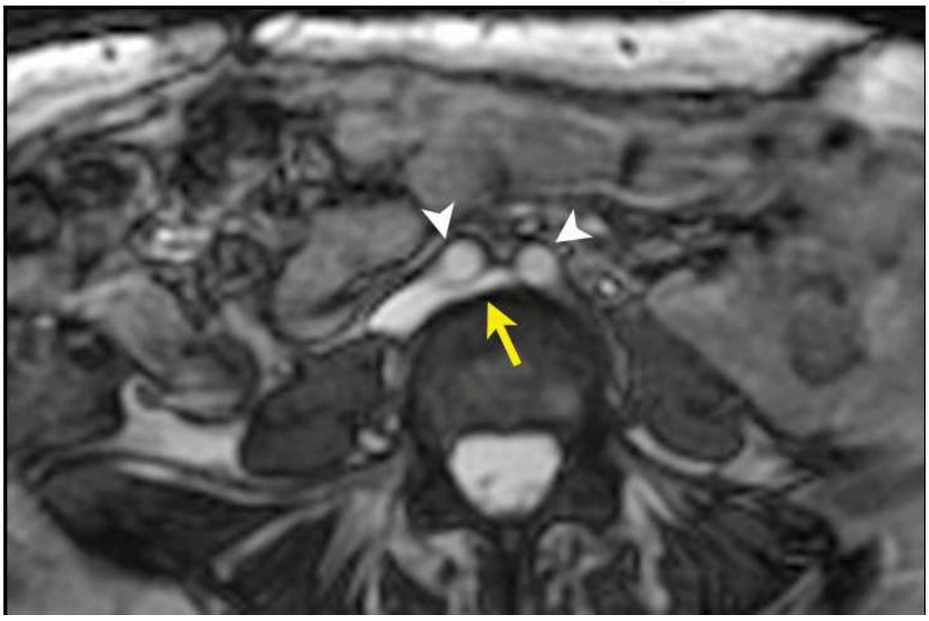


Fig. 2. Bright blood imaging. Balanced steady-state free precession image from an axial cine acquisition demonstrates narrowing of the left common iliac vein (yellow arrow) by the iliac arteries (white arrowheads) and the anterior surface of the L4 vertebral body. This patient had symptoms of May-Thurner syndrome, with recurrent left-sided deep venous thrombosis. Bright blood, or "white blood" imaging yields rapid high-resolution images, although the direction of flowing blood is not discernible.

2.1.3 Time-of-flight imaging of the vessels

Time-of-flight imaging techniques rely on flow-related enhancement to provide signal in the vasculature, and do not require intravascular contrast material. They can be performed via two-dimensional or three-dimensional acquisitions, and depending on the placement of saturation bands, can be tailored to image the arterial or venous system. By acquiring numerous overlapping slices, three-dimensional reformatting can be performed post-hoc to generate more desirable image planes. (Lee 2005)

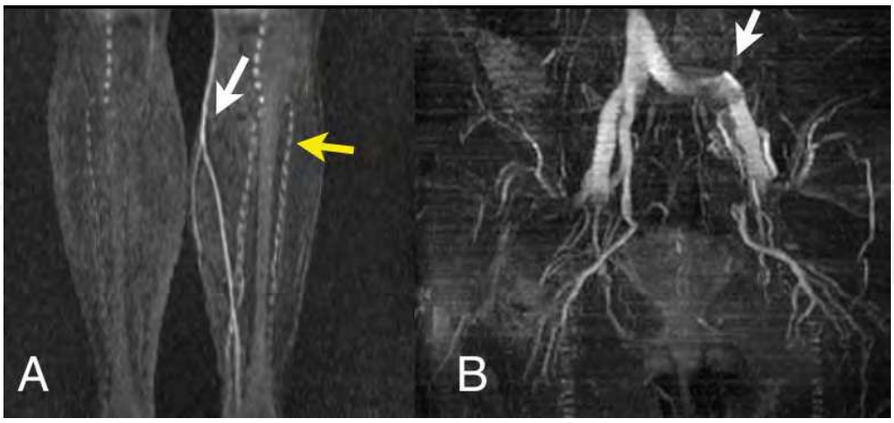


Fig. 3. Time-of-flight versus inflow imaging. Time-of-flight images of the lower legs (A) demonstrate visualization of the left-sided large saphenous veins (white arrow). Note the slab artifacts in the arterial tree which are faintly visualized due to pulsatile flow in the trifurcation vessels (yellow arrow). The patient was suspected of having a more proximal venous obstruction, and inflow techniques with SSFP readout were attempted, yielding a much more robust image of the pelvis (B), which demonstrated compression of the left common iliac vein (white arrow) and numerous small collateral vessels.

2.1.4 Cardiac and respiratory gating

Cardiac and respiratory motion can complicate imaging of the thorax, and even render some acquisitions nondiagnostic. (Boxerman et al. 1998) Certain applications such as cardiac angiography necessitate cardiac gating. This is also particularly true for accurate imaging of the aortic root. (Venkatesh & Ghoshhajra, 2011) Despite this challenge, modern sequences can be rapidly acquired via synchronization to the peripheral plethysmograph or the patient's electrocardiographic leads. Occasionally rapid "real-time" sequences can be used to mitigate cardiac motion without gating, although these images are less frequently acquired due to resolution constraints which render them inferior to gated exams. (Francone et al. 2005) Although breath-held exams are important for much of MRI in and around the thorax, by increasing the number of signal averages the effects of both cardiac and respiratory motion can be mitigated (at the expense of dramatically increased acquisition times). "Navigator-gated" sequences are also available in some cases to acquire bright-blood exams over numerous cardiac and respiratory via a repeated navigator slab which allows rejection of slices acquired during unfavorable respiratory excursions. This technique also dramatically increases acquisition times but again allows free respiration during the exam. (Sakuma et al. 2005)

2.1.5 Inflow imaging

Noncontrast MRA has enjoyed numerous recent technical advances in the form of modified steady-state free precession imaging, which can be tailored for the depiction of flowing

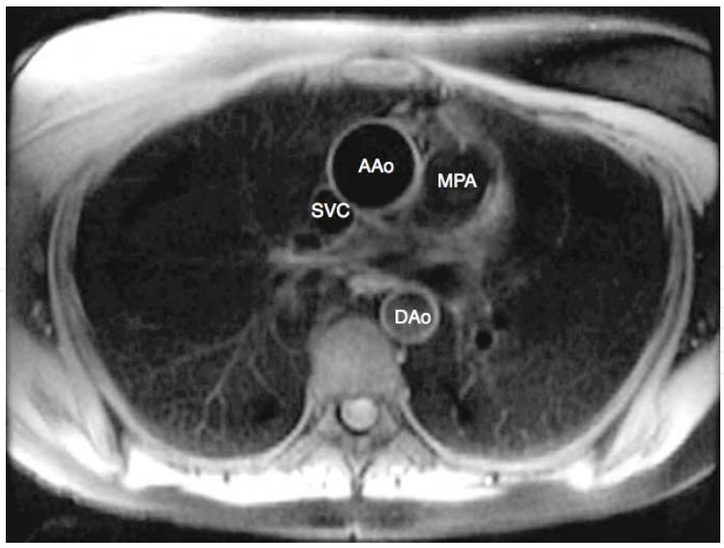


Fig. 4. Cardiac and respiratory gating. Axial black blood imaging of the ascending aorta was obtained with cardiac gating at suspended respiration. This image was obtained with blood suppression to ensure black blood technique, as well as chemical fat suppression. Note the precise depiction of the aortic wall, and motion-free images of the great vessels. The ascending aorta (AAo) has more rapid flow which is perpendicular to the plane of acquisition, and therefore superior blood suppression as compared to the main pulmonary artery (MPA). The superior vena cava (SVC) and descending aorta (DAo) are also well visualized without cardiorespiratory motion artifacts.

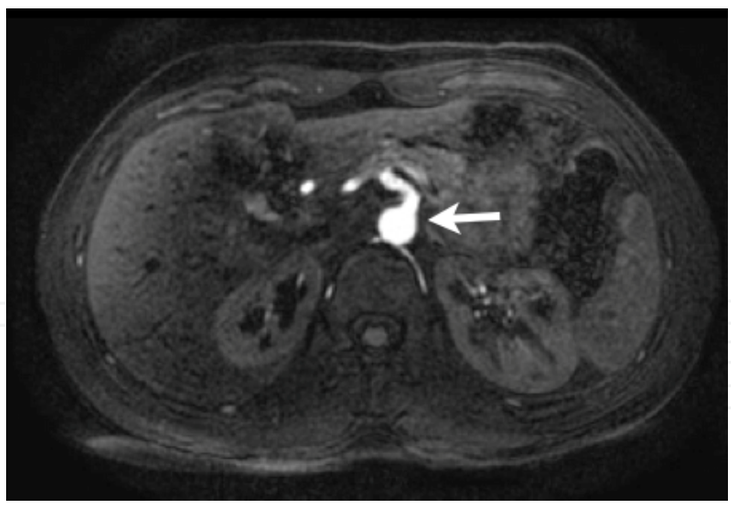


Fig. 5. Inflow imaging. Robust non-contrast MRA can be performed with advanced inflow techniques. In this unenhanced axial source image reconstructed from a three-dimensional steady-state free precession arterial labelled scan the arterial flow in the aorta at its junction with the superior mesenteric artery is well visualized. Note also the opacification of the small intrarenal branches, and relatively low signal from the background tissues.

blood in a rapid acquisition, with or without a directional component. These three-dimensional acquisitions can also be advantageous when the background signal and fat are

suppressed, yielding easily reformatted images consisting of moving blood only. These acquisitions can also be synchronized to the peripheral plethysmograph to provide images only in systole or both systole and diastole, thus allowing differentiation from arterial or venous flow in the extremities. (Glockner et al. 2010; Hartung & François, 2011)

3. Contrast-enhanced MRA

Contrast-enhanced MRA can be performed routinely at many centers. These techniques take advantage of the dramatic shortening of T1 relaxation times due to gadolinium's paramagnetic effects. By timing image acquisitions to the arterial or venous phases of circulation (best accomplished via power-injection at a high rate and rapid imaging sequences), the vascular system can be imaged with relative ease. (Lee, 2005) Two recent advances have provided further advantages to contrast-enhanced MRA. In addition to first-pass (arterial) or later phase (venous or equilibrium) timing, extremely rapid images can also be obtained at multiple time points (time-resolved MRA)(Cornfeld & Mojibian, 2009) or images can be obtained very slowly (to improve spatial resolution) when "blood pool" agents are injected, which remain in equilibrium circulation for hours rather than seconds to minutes. (Hansch et al. 2011; Makowski et al. 2011; Hartung & François, 2011)

3.1 Time-resolved MRA

Recent incremental advances in the spatial and temporal resolution of MRA have now allowed multiple rapid successive MRA acquisitions. These techniques have particular relevance when bolus timing is uncertain, or when imaging arteriovenous abnormalities such as arteriovenous malformations or fistulas. (Schanker et al. 2011)

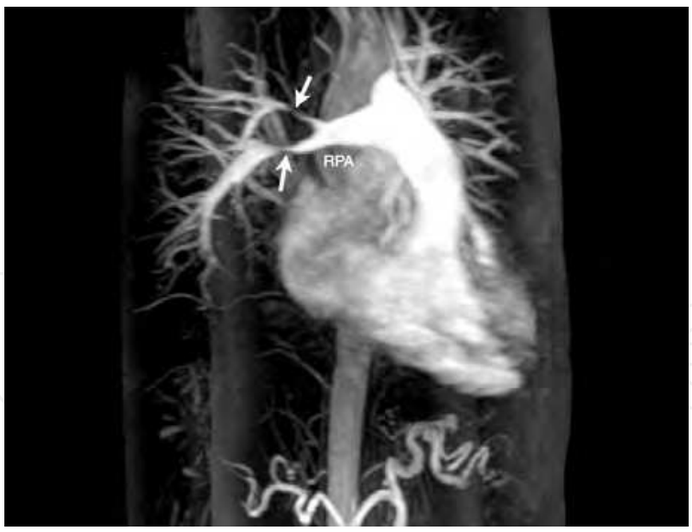


Fig. 6. Time-resolved MRA. Rapid time-resolved MRA is now possible, allowing acquisitions at several time points during the passage of contrast through the circulation. This patient with congenital heart disease suffered from severe stenosis in several branches of the right pulmonary artery (RPA, arrows). Note the relative paucity of contamination by pulmonary venous enhancement on this maximum intensity projection image, which allowed accurate visualization of the pulmonary arterial tree in this pulmonary arterial/early aortic phase image.

4. Image processing techniques for MRA

Most MRA imaging is acquired in coronal or sagittal planes (to decrease acquisition times and phase-wrap artifacts), although some techniques require axial acquisition to allow for flow-related signal acquisitions. A basic tenet of image acquisition is that of isotropic imaging, which then allows later reformatting and volume dataset interpretation. Many images can be reformatted at the scanner or in some cases by a dedicated post-processing laboratory; occasional direct post-processing by the radiologist is preferable. The most common formats are multiplanar reformatting (MPR), maximum-intensity projection reformatting (MIP), and three-dimensional volume-rendered imaging (VR). MPR images allow thin images to be generated from a volume dataset in any plane, whether body-specific planes such as axial images reformatted to coronal or sagittal planes, but also allows curved planar reconstructions along the course of the vessels themselves, which can allow viewing of the entire course of a tortuous vessel in a single image. MIP images are useful for "collapsing" a slab of a volume containing a tortuous vessel into a single image or set of images; this technique is useful but should be reserved as an adjunct to source or MPR images. This is particularly useful for long-axis views, and can be disadvantageous in short-axis reformatting, whereby stenosis can be eliminated from a slab of images. (Wehrschuetz et al. 2004; Regenfus et al. 2003)



Fig. 7. Volume-rendered imaging. Source images can be reconstructed in several ways. In this case, a three-dimensional volume-rendered image was created to demonstrate the location of an aortic dissection (asterisk). While the appearance can be striking, source and MPR images must be reviewed to ensure that all findings are visualized, since volume rendering only demonstrates the external surface of the enhanced vessels rather than the lumen.

5. Contrast agents for MRA

Gadolinium-based contrast agents have an excellent safety profile, although recent reports of nephrogenic systemic fibrosis (NSF) have dampened enthusiasm and rendered the agents contraindicated in cases of severe renal insufficiency. (Grobner 2005) In patients with normal renal function, these agents have been well tolerated and they enjoy a significantly lower rate of anaphylaxis versus iodinated CT contrast agents. Preserved diagnostic quality with decreased contrast doses can achieved in some cases with the use of high field strength imaging (via improved contrast-to-noise ratios at 3.0 Tesla versus 1.5 Tesla, the two most common field strengths). (Hartung, Grist, and François 2011) All gadolinium-based agents are comprised of paramagnetic chelates that shorten T1 and T2 relaxation times (via disturbance of the spin-lattice and spin-spin interactions). Other contrast agents with various mechanisms of action exist in MRI, but are not utilized routinely for MRA.

5.1 First-pass agents

Traditionally contrast agents in MRA have included gadodiamide, gadobenic acid, gadopentetic acid, and gadoteridol. These are excreted chiefly via renal clearance. Because they are rapidly excreted, timing is critical. (Hartung, Grist, and François 2011)

5.2 Blood pool agents

Recently gadolinium contrast agents have been developed for use in the vascular system, and are advantageous due to slower, predominantly hepatic clearance (gadofosveset).

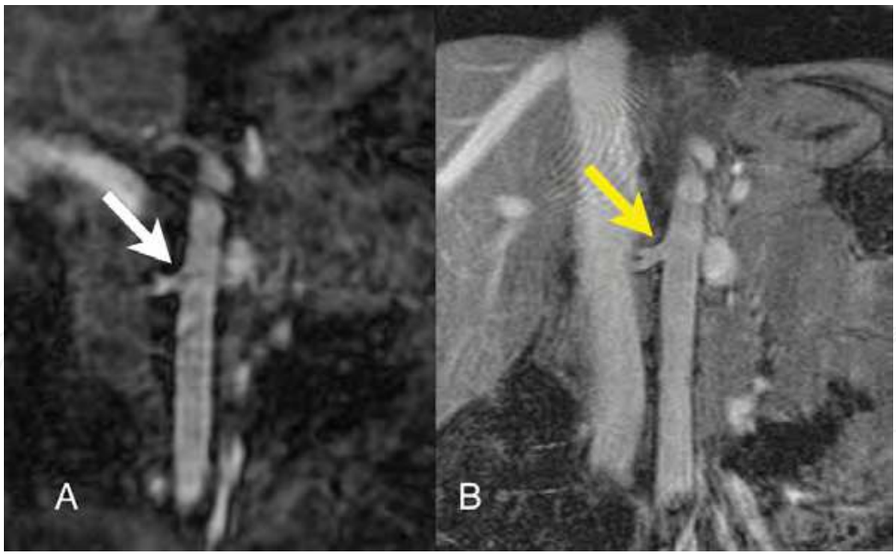


Fig. 8. Dynamic versus blood pool agent imaging. Dynamic first-pass MRA performed with bolus injection of gadofosveset demonstrates pure arterial imaging (A) and equilibrium phase imaging (B). While the arterial phase is not contaminated by venous enhancement, the reduced matrix necessary for rapid imaging (256 x 160 pixels) offers lower spatial resolution than that achieved by equilibrium phase imaging (512 x 224 pixels). The resultant finer voxels offer more robust of small vessel anatomy such as the early branching right renal artery (white arrow in A versus yellow arrow in B).

Although the advantage of such agents is that timing of acquisition is not critical (and can indeed be lengthened in order to image at higher spatial resolutions), by timing a rapid acquisition during the first pass of enhancement a pure arterial phase image set can be obtained prior to equilibrium phase. (Hartung, Grist, and François 2011; Makowski et al. 2011; Hansch et al. 2011)

5.3 Safety and nephrogenic systemic fibrosis

Nephrogenic systemic fibrosis is a disorder that has been associated with renal failure and linked to gadolinium administration. After the disease was identified, dramatic and rapid success in limiting the incidence of new cases was achieved by widespread adoption of guidelines to limit or forgo the use of gadolinium contrast agents in patients with limited renal function as defined by estimated glomerular filtration rates below 60 ml/min/m^2 and 30 ml/min/m^2 respectively. (Kanal et al. 2007)

6. MRA head to toe

Virtually no body part or vascular bed has been untouched by MRA. The pulse sequences, applications, challenges, and utility of MRA varies widely depending on the anatomy imaged. Below is a brief review of the basic MRA applications organized by body system, with a focus on clinical examples of common clinical applications and MRA-specific diagnoses.

6.1 Neurovascular MRA

MRA of the head and neck has rapidly become a mainstay of neuroradiologic practice, in part due to its simultaneous acquisition during MRI of the brain for stroke imaging and workup. The ability to rapidly and accurately screen the cerebrovascular system noninvasively has led to improved stroke care and treatment, and the availability of rapid imaging access defines the capabilities of a stroke center. MRI/MRA access indeed is though to have profound effects upon stroke treatment. Both the arterial and venous systems can be rapidly imaged with and without contrast.



Fig. 9. MRA of the Circle of Willis. Reformatted 3D MRA image demonstrates occlusion of the basilar artery in a patient with acute bilateral central infarcts (aka. “top of the basilar thrombosis syndrome”).

6.2 Thoracic MRA

Thoracic MRA plays an increasing role in the workup, diagnosis, and management of aortic disease. While the ease and availability of CT angiography sometimes relegates MRA to a second-line therapy (particularly in the acute setting), MRA of the thoracic vessels is a mainstay of imaging in those patients with a need for repeated longitudinal imaging, such as genetic disorders such as Marfan's syndrome or Loey-Dietz syndrome. The benefits of robust imaging without the need for ionizing radiation (and ability to image without contrast when necessary) makes this test useful for young patients.

6.3 Coronary MRA

Coronary MRA is finally realized as a potential application of cardiac MRI, but its relatively long exam times and inability to depict calcified lesions makes it a second or third choice test for ischemic heart disease. (Lima and Desai 2004) Nonetheless, coronary MRA has demonstrated similar results for the exclusion of significant stenosis to the current noninvasive standard, cardiac-gated CT angiography in small studies. In some applications such as the exclusion of anomalous coronary arteries, MRA has a role, particularly in younger population in whom atherosclerotic stenosis is unlikely.



Fig. 10. MRA of the aortic arch. Sagittal MIP (A) and 3D volume-rendered (B) images of the thoracic aortic arch demonstrate a large, saccular pseudoaneurysm in a patient whom developed a myocotic aneurysm due to immunosuppression by chemotherapy.

6.4 Abdominopelvic MRA

MRI/MRA is increasingly useful in many body imaging applications. The technique is useful for the workup of vascular hepatic lesions, and is robust for the imaging of large vessels such as abdominal aortic aneurysms. Although artifacts can limit the utility for imaging small vessels, MRA is often useful in young patients or patients whom are able to breath-hold and comply with the exam. In conjunction with anatomic imaging, MRA can be invaluable in certain workups, such as preoperative planning for uterine artery embolization.

6.5 Peripheral MRA

Limb ischemia is often a chronic disease requiring intense longitudinal follow-up, and imaging can play a central role. The utility of MRA in the management of peripheral vascular disease can be large, because the technique can obviate invasive arteriography and in many cases lead to shorter exam times when invasive angiography is deemed necessary. MRA, and in particular dynamic MRA, can be useful in the workup of more rare lesions such as vascular malformations.



Fig. 11. MRA of the aortoiliac vessels. Coronal MIP image from a contrast-enhanced MRA demonstrates multiple occlusions (white arrows) and right-to-left collaterals (yellow arrow) in a patient with severe atherosclerotic disease.



Fig. 12. MRA for abdominal aortic aneurysm. Oblique coronal MIP image from a contrast-enhanced MRA demonstrates a saccular infrarenal aortic aneurysm. MRA is particularly useful in patients whom need repeated imaging for longitudinal followup.

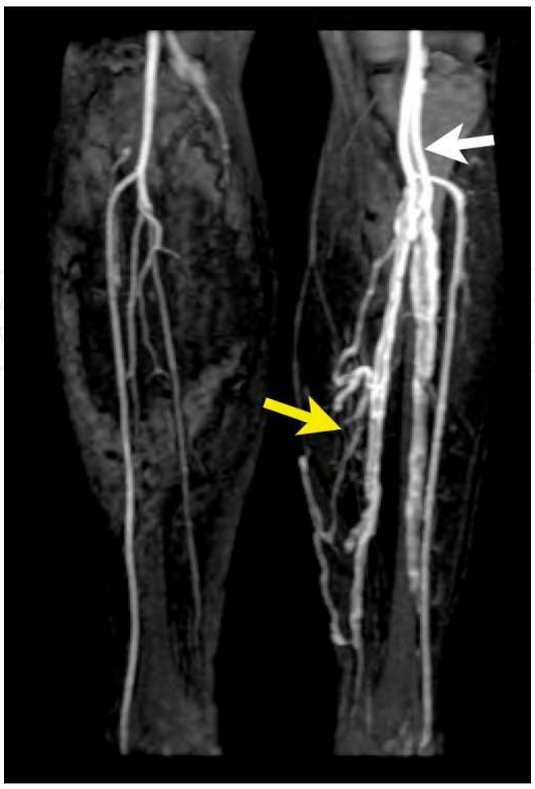


Fig. 13. MRA of the lower extremities. Coronal MIP image from a contrast-enhanced MRA demonstrates early filling of left-sided veins in a patient with claudication due to congenital arteriovenous malformations.

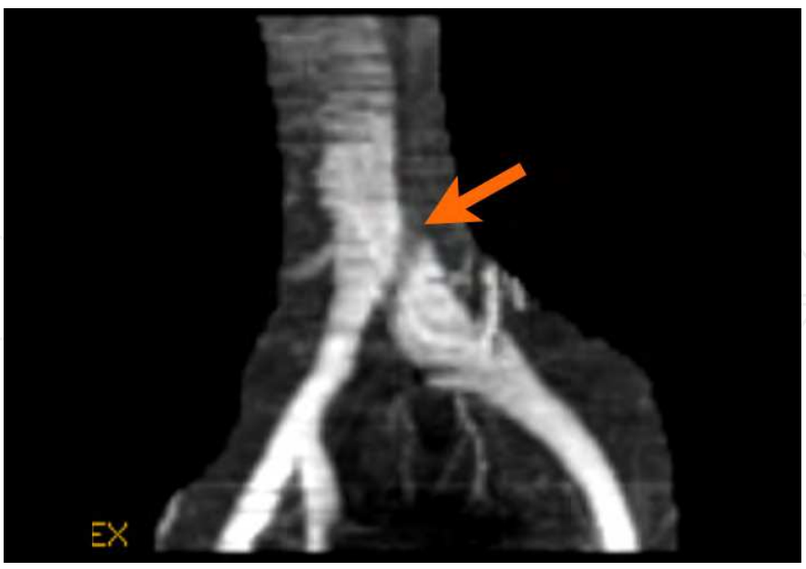


Fig. 14. MR venography of the pelvic veins. Reformatted image from a noncontrast inflow-based acquisition of the pelvic veins demonstrates compression of the left common iliac vein by the right common iliac artery in a patient with left to right venous collaterals and chronic left-sided deep venous thrombosis due to May-Thurner syndrome.

6.6 MR venography

In addition to the more common use of MRA for the arterial system, numerous venous beds can be reliably imaged with MRA. In the neurovascular system, the importance of venous thrombosis is now widely recognized, and in the pelvic circulation MRA plays a key role due to the ability to acquire multiple phases of imaging and image external compression on the veins in cases of May-Thurner syndrome. Although initial enthusiasm for MRA of the pulmonary arteries was high, trials have shown difficulties with MRA of thromboembolic disease in the chest and a high rate of nondiagnostic examinations. (Stein et al. 2008)

7. MRA artifacts

While the power and reach of MRA is impressive, the technique is not without difficulties. Artifacts can confound this robust technique, and each sequence carries with it its own technical pitfalls. The lack of standard appearances across multiple sequences, planes, and phases of contrast enhancement makes the task of the radiologist even more challenging. A vigilant eye and sceptical mind are essential. A rule of thumb in vascular imaging is to assume that all findings are artifactual until proven otherwise; if the presence of counfounding artifacts can be systematically excluded, then one can presume the findings are indeed real.

7.1 Motion artifacts

MRA sequences can be time-consuming, and the presence of motion artifact can be encountered as patients are unable to comply with a long acquisition (Figure 15), or due to normal cardiac or respiratory motion (Figure 16)

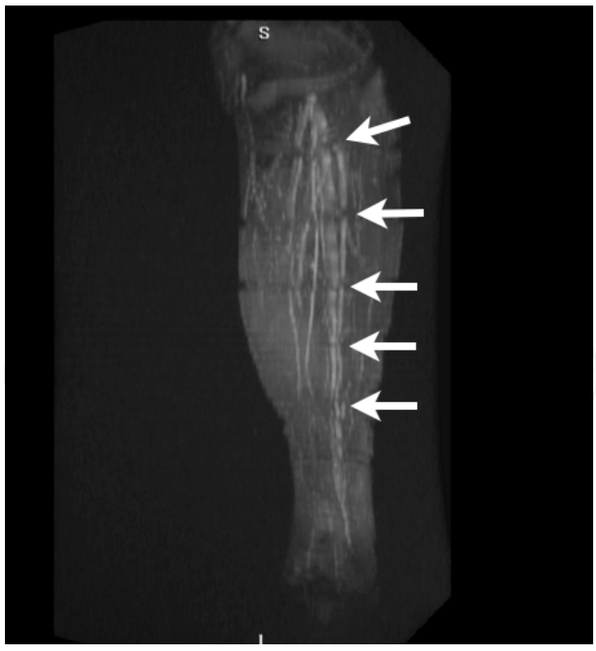


Fig. 15. Time-of-flight MRA of the lower extremity. Reformatted image from a noncontrast time-of-flight sequence obtained as multiple axial acquisitions (and later reformatted into this coronal view) demonstrates numerous banding artifacts (white arrows) which were introduced by patient motion during the exam.



Fig. 16. Contrast MRA of the Aortic Arch. Sagittal reformatted image from a bolus contrast-enhanced MRA performed to exclude aortic dissection shows motion artifact causing irregularity of the ascending thoracic aorta (white arrow). This is due to cardiac pulsation during acquisition.

7.2 Timing artifacts

MRA sequences performed during bolus contrast enhancement must be performed with proper timing in order to image the target vascular bed at the appropriate time. Improper timing can make interpretation difficult or impossible (Figure 17).



Fig. 17. Suboptimal bolus timing. Coronal reformatted image from a bolus contrast-enhanced MRA performed to exclude stenosis of the lower extremity arteries is confounded by venous contamination (blue arrow), which makes the highly diseased arterial system (red arrow) difficult to visualize. This was in part due to extremely poor cardiac function.

7.3 Difficult body habitus and positioning

MRI can be a challenge due to issues with large patients, whom may not fit into the bore of the magnet, or may be so large as to cause phase wrap artifacts affecting the vessel of interest (Figure 18).

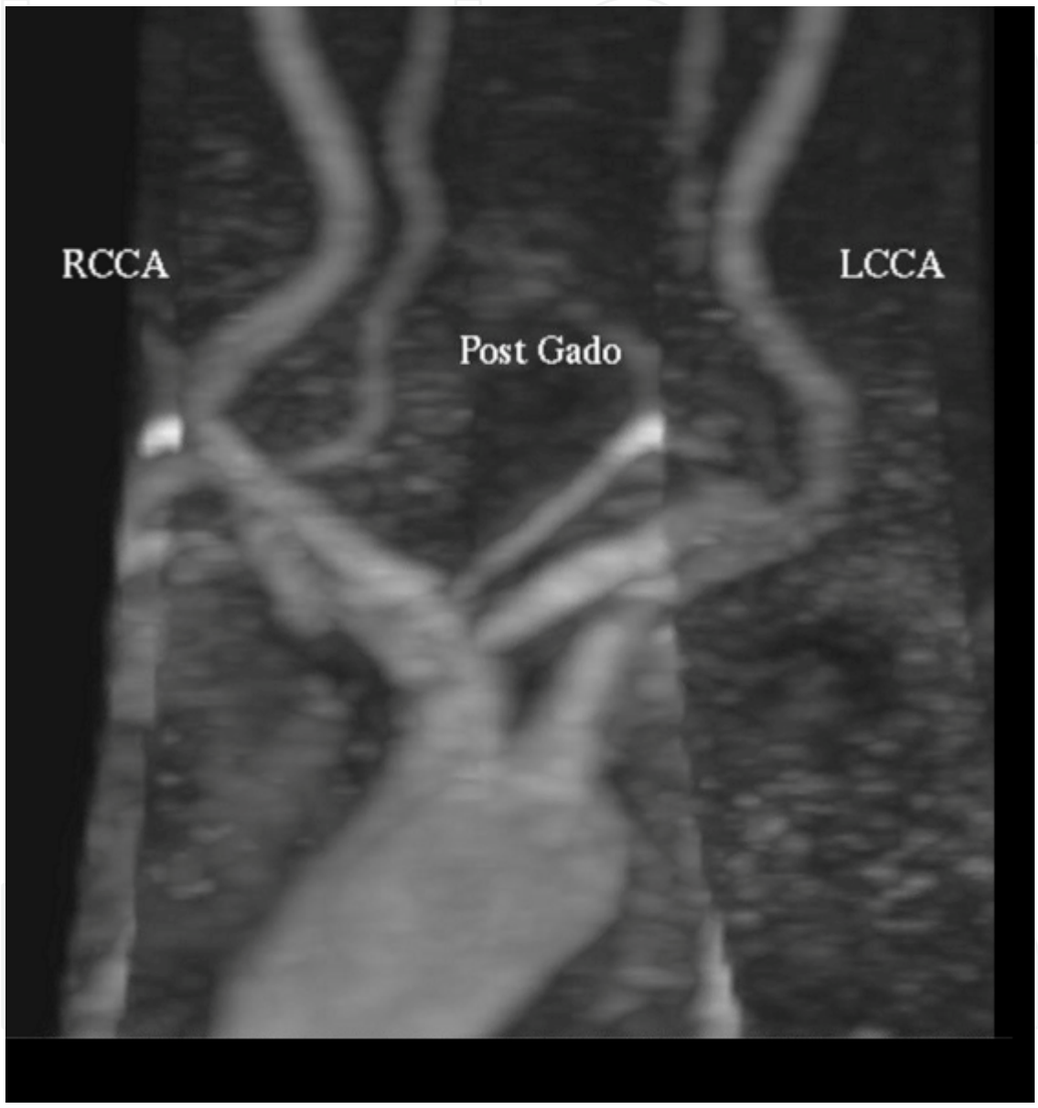


Fig. 18. Phase wrap artifact. This large patient's body habitus resulted in phase wrap of the right shoulder over the left common carotid artery; poor signal to noise ratio is therefore made worse at the site of the wrap artifact.

7.4 Metallic artifacts

MRI can also be a limited due to the radiofrequency shielding effects of metal in the body, particularly within stents (Figures 19 and 20).



Fig. 19. Metallic implant artifact (magnetic susceptibility artifact). This patient's right knee prosthesis caused apparent occlusion (white arrow) of the right popliteal artery (which was actually widely patent).



Fig. 20. Radiofrequency shielding artifact (magnetic susceptibility artifact). This patient's right common iliac stent created the appearance of arterial occlusion (white arrow); note the lack of collaterals and dephasing artifact (upper arrow) which are clues to the artifactual nature of the findings.

8. Conclusion

Magnetic resonance angiography is increasingly a part of the workup of vascular disease throughout the body, and is a central part of imaging for several diseases. The impact of MRA will continue in parallel to the development of newer and more robust pulse sequences.

9. Acknowledgment

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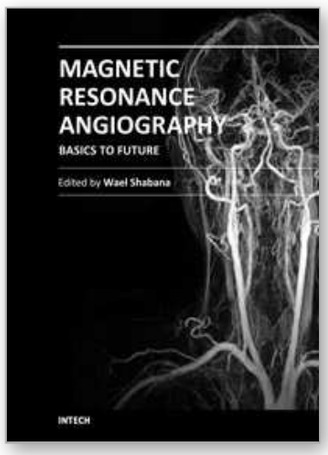
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Magnetic Resonance Angiography Basics to Future

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As MRI has paved its role in diagnostic angiography. MRA has the potential to provide more physiological and pathophysiological data over the disease in addition to the anatomical information. This book is divided into three sections. The first section discusses the basics of MRI angiography. It starts with focus on the contrast agents that are mainly used in MR angiography with detailed discussion of advantage and limitations of different types of contrast. The second chapter is oriented more towards the technical consideration that contribute to good quality examination, both the non contrast and contrast based sequences from black to bright blood imaging , contrast enhanced MRA, review of clinical application of MRA in different body systems and MR venography. The second section reviews the clinical application of MRI mainly in the head and neck and brain ischemia imaging. The new high resolution intracranial plaque imaging of the branch athermanous disease, to the hemodynamic of intracranial atherosclerotic stroke and quantitative MRA imaging in neurovascular imaging, are the topics in this section. Also this section covers the future prospective and the new frontiers MRI angiography is exploring. In the third section, MRA of aortic disease in children with emphasis on cardiac MRA.

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