New Techniques and Applications for Magnetic Resonance Angiography

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Abstract

Recent technological advances in magnetic resonance imaging have transformed the field of magnetic resonance angiography (MRA) from a research tool into an important clinical examination that is gaining acceptance as the screening modality of choice in evaluation of vascular disease. This article describes some of the new techniques and applications of MRA in clinical practice today.

Key Words: Magnetic resonance angiography.

Introduction

THE INTRODUCTION OF contrast-enhanced magnetic resonance angiography (CE-MRA) has catapulted tomographic magnetic resonance angiography (MRA) from an occasional adjunct examination into a robust tomographic imaging modality that plays an important role in the day-to-day evaluation of patients with vascular disease. CE-MRA follows the paradigm of X-ray angiography. Imaging is obtained after intravenous administration of a contrast agent as is done in X-ray angiography. The advantages of magnetic resonance angiography compared to X-ray angiography include:

- Noninvasiveness — instead of requiring intra-arterial injection of contrast (as in X-ray angiography), the agent is injected intravenously.
- Lack of ionizing radiation.
- Lack of a nephrotoxic contrast agent.

Noninvasive imaging, including MRA, is increasingly replacing diagnostic X-ray angiography in screening for vaso-occlusive disease. MRA is being used more widely in vascular imaging to provide a preoperative roadmap. In our institution, MRA is the sole preoperative modality used in imaging the arterial and venous vasculature for renal and liver transplant donors.

Contrast-Enhanced MRA — Imaging Technique

Contrast-Enhanced MRA versus Time-of-Flight MRA

Before the advent of CE-MRA, the major MRA technique was time-of-flight (TOF) imaging. CE-MRA overcomes many of the limitations and artifacts inherent in TOF-MRA. These include lack of artifacts due to cardiac pulsation, insensitivity to in-plane flow, and the lack of respiratory artifact since imaging is acquired within a breath-hold. If done correctly, contrast-enhanced CE-MRA is a much more robust technique than TOF-MRA. High-quality MRA images are obtained in more than 95% of examinations (1).

Contrast-Enhanced MRA versus Computed Tomography Angiography

Both contrast-enhanced computed tomography (CTA) and CE-MRA employ similar imaging paradigms, i.e., imaging the vessel lumen after the administration of an intravenous contrast agent. The advantages of MRA over CTA

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is the lack of radiation, the use of an agent which is non-nephrotoxic, increased signal-to-noise ratio, and easier 3D postprocessing. Advantages of CTA over MRA include increased spatial resolution and easier image acquisition (CT is technically easier to perform than MR).

Imaging Pulse Sequence

Contrast-enhanced MRA is performed utilizing 3D spoiled gradient-echo imaging sequence. The advantage of this sequence is that it is a 3D sequence and reconstruction can be obtained in any plane. 3D as opposed to 2D gradient-echo images permits thinner, higher resolution images to be obtained within a breath-hold.

Contrast Agent

Gadolinium, one of the “rare earth” elements is a paramagnetic agent which increases the magnetic field adjacent to the gadolinium molecule. This shortens the T1 relaxation time of any substance in the region of the gadolinium molecule and enhances the MR signal intensity of blood on the T1-weighted postcontrast images. This contrast mechanism creates true anatomic images of vascular lumen, analogous to conventional angiography. There is no detectable toxicity to gadolinium and it can be used in patients with renal failure (2, 3). The dosage of gadolinium ranges from 0.1 – 0.3 mMol/kg IV (4). Gadolinium is excreted by the kidneys, and its half life is 1.5 hours.

Contrast Administration

Optimal contrast of arterial vasculature is produced by timing the acquisition of the MR images with the arrival of the contrast bolus in the arterial vasculature being imaged. A tight contrast bolus is improved by using a power injector (2 – 2.5 mL/sec).

Timing of Contrast Administration

The importance of accurately timing the delivery of the contrast bolus with image acquisition cannot be overemphasized. If imaging is begun too early, no contrast will be seen in the vessel. If imaging is begun too late, the contrast will already have washed out of the vessel being imaged and the venous system will be visualized. Multiple methods are available to optimize timing, and a considerable amount of research is being conducted to perfectly match the contrast bolus with data acquisition. Timing bolus techniques include:

- The “best guess” method — where an educated guess is made as to when contrast arrives in the vascular territory being imaged. The accuracy of this technique is on the order of 85%.
- Automated timing bolus — image acquisition begins when the contrast bolus is automatically detected in the vessel to be imaged. The success of this technique in our experience is about 85%.
- Timing bolus — 2 mL of gadolinium is injected at a prescribed injection rate using a power injector, followed by a 20 mL saline flush. Axial imaging is performed in the middle of the imaging volume using a fast gradient-echo sequence at an imaging rate of one frame per second. The time from the start of contrast injection to the peak arterial contrast is then calculated and used as the delay time for scanning to begin (5).

3D Reconstructions

One of the strengths of CE-MRA is acquired images are thin enough so that 3D reconstructions can be obtained. This allows rotation of the imaging volume in space. In order to rotate the volume without image distortion, images need to be acquired as an isometric imaging volume with resolution equal in all planes.

Optimization of 3D Gradient-Echo Imaging Parameters

The most common causes of a failed CE-MRA examination include:

- inability to maintain a breath-hold
- poor arterial phase timing, and
- inadequate coverage of the necessary imaging volume.

The ideal scan time of 15 – 20 sec allows most patients to maintain breath-hold. The following imaging parameters need to be optimized for each examination. Time to repetition and time to echo in spin (TR/TE) is minimized in order to maximize imaging speed. If one maintains a fixed scan time of less than 20 seconds while imaging a fixed volume one must compromise between higher image resolution and lower signal-to-noise ratio in adjusting the following parameters:

1. **Slice thickness** — thinner slices yield higher resolution but increase the number of

slices needed to cover the necessary volume, and decrease the signal-to-noise ratio per voxel. We try to maintain slice thickness of 3 mm or less.

2. **Matrix** — the higher the matrix, the higher the resolution, but the longer the scan time. We try to maintain matrices of 256 X 192 or 256 X 160.

3. **Bandwidth** — increasing bandwidth decreases scan time but also decreases signal-to-noise (S/N) ratio.

Advanced Concepts in CE-MRA

Understanding Basic K-Space

K-space is a very difficult concept for the non-physicist to understand. Simply, K-space is a spatial representation of the acquired MRI data. These MRI data can be acquired with different acquisition strategies which can and do affect the resultant image. After the MRI is performed, the K-space map is converted to an image by performing a mathematical process called a Fourier transformation which determines the spatial frequency features of the image. Each row of data in K-space represents an echo at a particular phase encoding step. The low-amplitude gradients, those with values near the center, provide the greatest contrast and signal.

Low spatial frequency information in the data within the center of K-space, determines image contrast. To have an arterial phase image in which arteries are bright and veins are dark, it is essential that the low spatial frequency data are acquired when a tight gadolinium bolus is present within the arteries being imaged and that the adjacent veins are dark.

High spatial frequency data at the periphery of K-space determines image detail. The presence of contrast is not as important for acquisition of peripheral K-space data, and this portion of K-space may be acquired before or after the contrast bolus is present within the arteries being imaged.

K-Space Artifacts

An important property of 3D gradient-echo imaging is its ability to alter the timing as to when the low-amplitude frequency data and the high-amplitude frequency data are being collected within the imaging sequence (6, 7).

1. **Early-timing artifact.** Hollow vessel or “ringing” artifact occurs when the low-frequency central portion of K-space is collected before the contrast bolus has reached its peak concentration and contrast concentration is still rapidly changing. The peripheral, high-frequency lines of K-space that determine the vessel edge, are less affected by the contrast bolus. The high-frequency data shows the vessel wall. The low-frequency contrast information shows a hollow vessel. This artifact is most common when using elliptical centric and centric ordering of K-space, since these acquisition strategies have a smaller window for acquiring the central low-frequency data of K-space. The tighter the contrast bolus (which occurs with faster injection of contrast and the shorter the imaging time), allows for a smaller the window for catching the contrast bolus at peak concentration. The hollow vessel artifact occurs when there is a mismatch in acquiring the central portion of K-space and the peak arterial contrast bolus of the vessel being imaged (3).

2. **Late-timing artifact.** If the central portion of K-space is imaged after the peak arterial phase has passed, venous contamination and lower signal to noise ratio will be seen in the image.

K-Space Acquisition Strategies

These techniques can be thought of as various strategies to adjust the “window” in time when the low-frequency data of K-space is collected. The scan delay must then be adjusted so that the tight contrast bolus is imaged at the precise time when the low- frequency data of K-space is collected.

1. **Sequential-phased-encoding ordering of K-space.** This is the traditional, most frequently used ordering of K-space acquisition. In this method lines of K-space are acquired sequentially. The central low-frequency data of K-space is acquired at the mid-portion of the image acquisition. The advantage of this method is that it is most forgiving and causes the least number of timing artifacts. When using sequential phased-encoded ordered K-space, the imaging delay can be calculated as follows (8):

Imaging delay = (contrast travel time) + $\frac{1}{2}$(injection time – imaging time)

2. **Centric-phased-encoding ordering of K-space.** In this strategy, the center low-frequency lines of K-space are acquired at the beginning of the scan. The advantage of this ordering of K-space is that if the patient breathes after 50% of the data has been collected, there will be less motion artifact. The arterial image should also have less venous contamination. When using centric-phased encoding ordering of K-space, the imaging delay is equal to the contrast travel time — the time from injection to when the contrast is first seen. This requires no additional calculation. The disadvantage of centric ordering of K-space is that it is more prone than sequential-phased-encoding ordering to mistiming artifacts (7).

3. **Elliptical-centric-phased-encoding ordering of K-space.** In this strategy, the center low-frequency lines of K-space are acquired at the beginning of the scan in an elliptical rather than linear manner. The advantage of this technique is that it covers the center of K-space very quickly with the least chance of venous contamination. For this reason, this technique is used in contrast-enhanced carotid MRA and moving-table-bolus chase peripheral MRA. When using elliptical-centric-phased-encoding ordering of K-space, the imaging delay is equal to the contrast travel time — the time from injection to when the contrast is first seen. The disadvantage of elliptical-centric-phased-encoding ordering of K-space, is that it is very sensitive to timing artifacts due to its very small temporal window during which K-space data are acquired. For this reason, we add one to two seconds to the contrast travel time (9).

4. **Reverse elliptical-phased-encoding ordering of K-space.** In this strategy, the low-frequency center lines of K-space are acquired at the end of the image acquisition.

5. **3D time-resolved imaging of contrast kinetics.** An increasing number of clever strategies are being developed to take advantage of the fact that it is not necessary to collect the entire portion of K-space in order to reconstruct an image. 3D time-resolved imaging of contrast kinetics (TRICKS) is a very clever technique which takes advantage of the fact that in a dynamic angiographic image the vessel edges or periphery of K-space do not change with time. What changes are the center low-frequency lines of K-space as the contrast bolus passes through the examined artery. In this technique the center portion of K-space is updated every 2–8 seconds, with the periphery of K-space being filled in at a later time. This has led to the term “time resolved” MRA. In this stratagem precise bolus timing is not necessary because the image is updated every 2–8 seconds. A “perfect” arterial phase should be present during at least one acquisition. The other advantage of this technique is that it begins to approach angiography in providing dynamic images in the flow of contrast (10).

Other Advanced MRA Techniques

1. **Time-resolved contrast-enhanced MRA.** New fast imaging techniques are available to increase the acquisition technique of a 3D MR angiogram to from 0.3 – 5 seconds. Though this technique is performed at lower spatial resolutions, the enhanced temporal resolution has advantages. At this temporal resolution, information regarding the temporal filling of vessels can be obtained. Initial studies have shown this technique is useful in evaluating patients with congenital heart disease, aortic stent-graft endoleaks, and peripheral vascular disease (2, 10).

2. **Moving-table-bolus chase MRA.** Moving-table-bolus chase MRA was introduced as a concept paralleling conventional angiography. In this technique, after acquiring a 3D CE-MRA of one vascular bed, the table is moved and imaging of a second vascular bed is performed while the contrast agent is still in the arterial bed. This strategy is routinely used in peripheral vascular MRA. We have also been using this technique in imaging of the entire aorta, to allow visualization down to the iliac vessels (11) (Fig. 1).

3. **Black blood imaging.** As opposed to CE-MRA, where flowing blood within a vessel is bright, in “black blood imaging” the signal intensity of flowing blood is suppressed, producing an image where the vessel lumen is black (12). Since the vessel lumen is black and the vessel wall is bright, black blood imaging allows for excellent imaging of the vessel wall. This is useful in evaluation of aortic dissection, intramural hematoma, penetrating ulcer, aortitis and

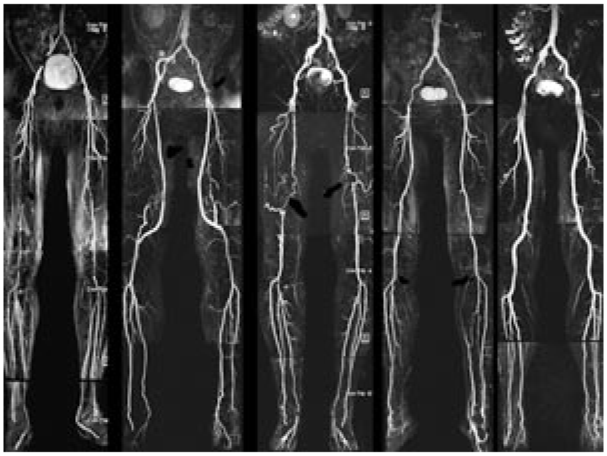

Fig. 1. Five examples of moving-table-bolus chase peripheral MRA. illustrate how a contrast bolus can be followed from the aortic bifurcation to the feet while minimizing venous contamination.

atherosclerotic plaque. The current limitation of black blood techniques is the increased duration of the examination. New sequences for multislice black blood imaging are being developed by different vendors.

4. **Bright blood imaging.** Bright blood image is especially useful for imaging of the vessel lumen (13). CE-MRA is a bright blood imaging technique. Steady-state free procession imaging (SSFP) is a new technique which produces high resolution bright blood imaging without administering intravenous contrast agent. This technique can be used to provide high temporal and spatial resolution images of a vessel or of the heart. These images can be viewed in a cine mode which allows for visualization of cardiac contraction. Bright blood SSFP also provides high resolution cine imaging of the vessel wall. These images are useful in evaluation of dissection and aortic aneurysms.

Applications of CE-MRA

Coronary artery disease and peripheral vascular disease are two major causes of morbidity, mortality and rising health costs in this country. Atherosclerosis appears to be the common link between these two disease processes. Remodeling of the vascular wall secondary to the atherosclerotic process results in the development of aneurysmal changes. Traditionally, surgery has been the treatment of choice for the correction of aneurysms of the aorta and peripheral arteries. Advances in minimally invasive and endovascular therapy have provided additional avenues of treatment and have potentially reduced morbidity, mortality, lengths of stay in the hospital, and costs to the already overburdened health care system. Due to the diffuse nature of the atherosclerosis process, many patients also have associated vascular complications such as diffuse atherosclerotic plaques and renal insufficiency. A noninvasive and nonnephrotoxic imaging technique for the pre- and post-interventional evaluation of the diseased vessels and the placement of the endovascular stent-grafts will greatly reduce the potential risks and dangers associated with conventional X-ray contrast angiography. Magnetic resonance imaging (MRI) has emerged as a highly attractive imaging modality for the routine follow-up evaluation of patients with peripheral vascular disease.

Clinical Indications for MRA

1. To screen for vaso-occlusive disease — carotid arteries, arch vessels, renal arteries, peripheral vessels.
2. To evaluate the anatomy of the aortic valve and origin of the coronary arteries.
3. Preoperative planning for repair of abdominal aortic aneurysms.
4. Postoperative follow-up of aortic aneurysm repair.
5. Preoperative planning to repair thoracic aortic aneurysms.
6. Postoperative follow-up of thoracic aortic aneurysm repair.
7. To image aortic dissection.
8. To image vasculitis.

Screening for Vaso-occlusive Disease

1. **Carotid artery stenosis.** Currently, digital subtraction angiography (DSA) is considered the best for detecting and grading carotid stenosis, but the associated risk of stroke is between 0.7 – 1.0% (14). For this reason, noninvasive imaging would be desirable. The sensitivity of MRA in detection of carotid artery stenosis ranges from 75 – 100%, while its specificity ranges from 59 – 99% (10, 15, 16). Recent studies have suggested that CE-MRA improves the sensitivity and specificity for detection of carotid artery stenosis over that of time-of-flight imaging. Cosottini et al. have shown that while CE-MRA still overestimates stenosis, the results indicated that it had limited value as a tool for preoperative evaluation of carotid artery stenosis (17).

2. **Arch vessels.** MRA and CTA are accepted screening modalities for the carotid arteries and arch vessels (18, 19) (Fig. 2).

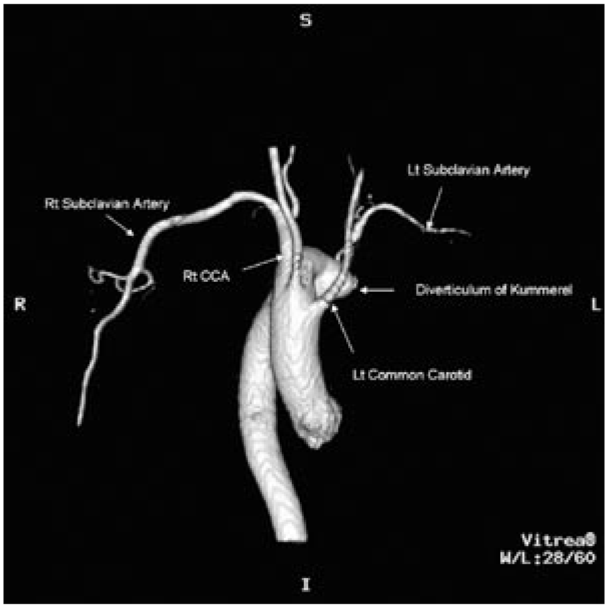

Fig. 2. Contrast-enhanced MRA of aberrant left subclavian artery with diverticulum of Kummerel.

3. **Renal arteries.** CE-MRA has special advantages over DSA or CE-CTA in evaluation of renal artery stenosis (RAS) in that the contrast agent is nonnephrotoxic and can be used to study patients with renal failure. Clinical indications for CE-MRA of the renal arteries are renal transplant donors, uncontrollable hypertension and ischemic renal nephropathy (Figs. 3 and 4). CE-MRA compares favorably to DSA in many studies showing a sensitivity of greater than 96% in most studies with specificity greater than 92% (20–23). In many centers, MRA is the screening modality of choice for suspected RAS.

4. **Peripheral vasculature.** Prevalence of peripheral vascular disease is about 7% for people older than 50. The most common symptoms of peripheral vascular occlusive disease are claudication (pain with exercise) or rest pain, depending on the distribution of the disease. Therapeutic interventions include angioplasty, stenting, surgical revascularization and bypass grafting. Flow-limited stenosis can occur anywhere between the aorta and foot. The goal of noninvasive imaging is to provide a "roadmap" for the vascular surgeon or interventional radiologist. The challenge of imaging the peripheral vasculature is the large territory that must be covered. Imaging from the aortic bifurcation to the trifurcation vessels can be obtained routinely. High resolution imaging of the feet without venous contamination using a single injection technique is more challenging.

Evaluation of the Aortic Valve and Origin of the Coronary Arteries

Breath-hold cine images may be obtained in two planes for evaluation of the aortic valve. We perform this routinely in the work-up of as-

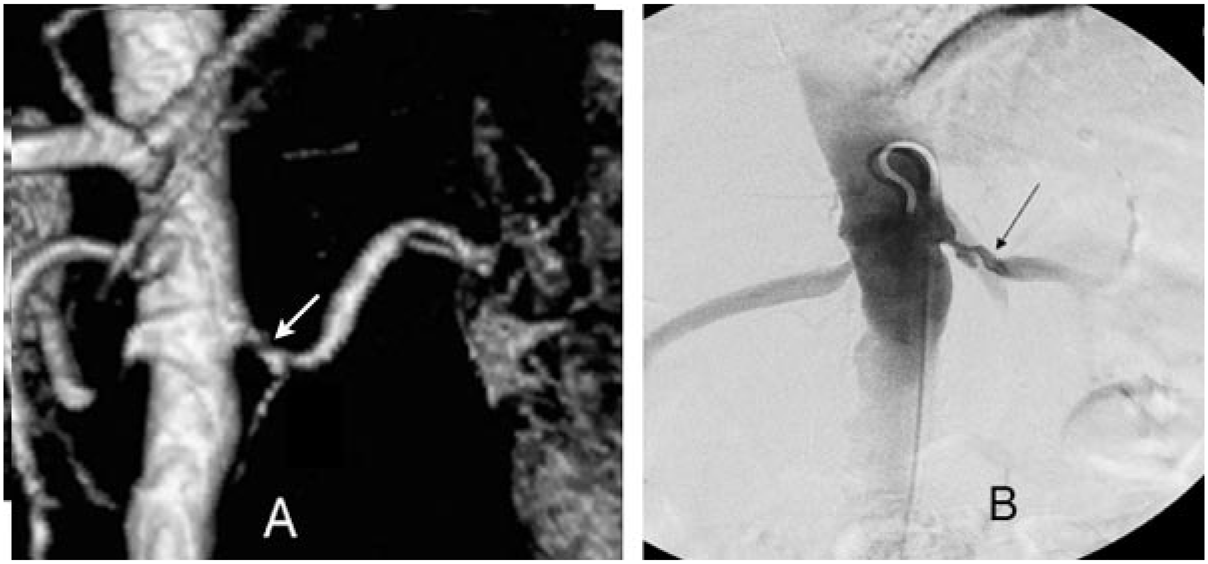

Fig. 3. (A) MRA left renal artery stenosis (arrow). **(B)** Corresponding X-ray angiogram shows left renal artery stenosis (RAS) (arrow).

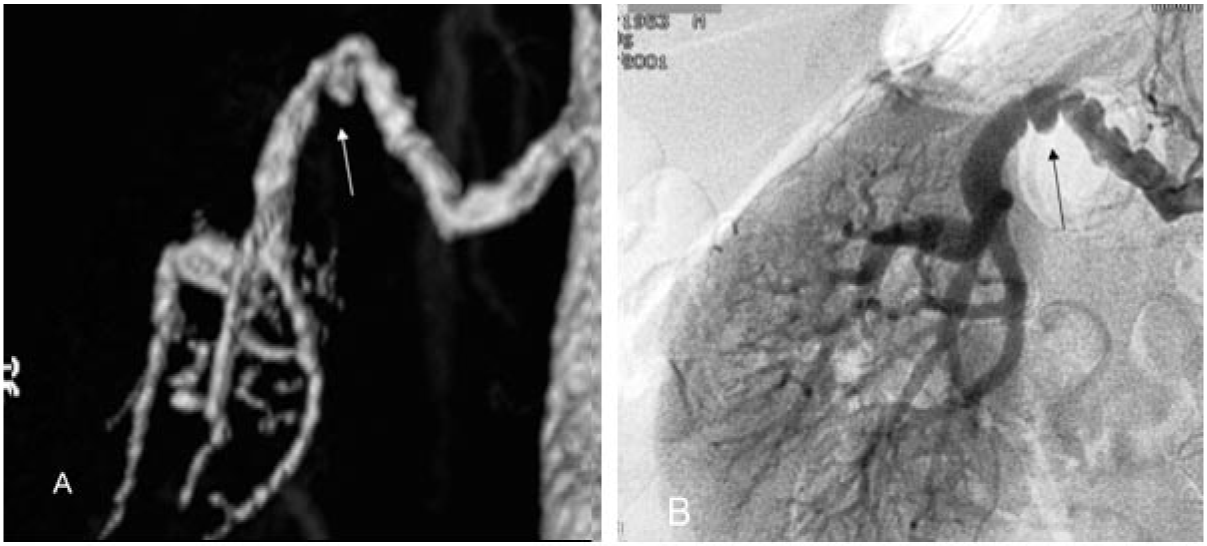

Fig. 4. (A) CE MRA, shows heading of the right renal artery in a patient with fibromuscular dysplasia (FMD). **(B)** Corresponding X-ray angiogram in the same patient.

cending aortic aneurysm to rule out a bicuspid aortic valve. Fast cine imaging allows visualization of jets produced in aortic regurgitation or stenosis. The aortic valve is also routinely imaged in type A aortic dissection. High-resolution black blood imaging of the coronary arteries is obtained for all type A aortic dissections as well as postoperative imaging of the ascending aorta.

Pretreatment Planning of Abdominal Aortic Aneurysms

In 1995, Parodi (24), in Argentina, first described endovascular repair of an abdominal aortic aneurysm. Imaging for preoperative aortic endograft design requires precise measurements. The consequences of small errors in graft sizing include endoleaks and graft migration. Currently, most centers employ both conventional angiography and CTA for pretreatment design of aortic endografts. Recently, some centers have shown good results in pretreatment planning of aortic endografts using either CTA or MRA alone (Figs. 5, 6) as well as facilitating the design of aortic endografts to be used. Measurements for endograft design include:

1. Aneurysm length measurements from the level of the lowest renal artery to the iliac bifurcation bilaterally. CE-MRA is acquired as a true 3D dataset with slices thin enough to approach true isotropic volumes. Similar data reconstruction algorithms can be applied to MRA which have been used for CTA.

Fig. 5. Contrast-enhanced MRA of abdominal aortic aneurysm.

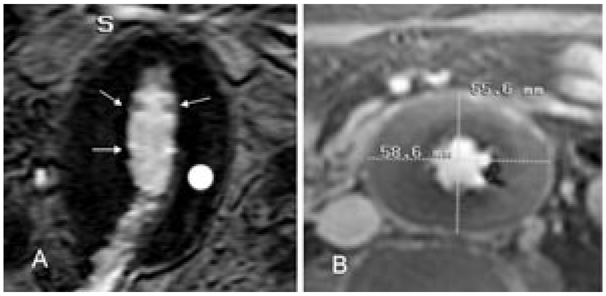

Fig. 6. (A) The arrows point to the artifact from the aortic stent-graft. **(B)** Measurement of AAA.

2. Accurate measurements of the diameter of the aorta at the level of the superior neck of the aneurysm and both common iliac arteries proximal to the iliac bifurcation are necessary. Precise measurements are crucial for the endovascular surgeon in endograft design. Diameter measurements should be performed in the vessel at a true orthogonal to the centerline of the vessel. This is best accomplished from reconstruction of MRA datasets.

3. Accurate visualization of the visceral vessels is important in determining stenosis of these vessels. This is important in planning endograft vs. open repair.

Post-aortic Stent-Graft Deployment for Abdominal Aortic Aneurysm

It is preferable to perform follow-up imaging with a noninvasive test such as MRA or CTA. Standard follow-up is recommended at one month and 6 months after stent placement. The majority of endoleaks are of Type 2, which may be caused by backfilling of the aneurysm sac by either the lumbar arteries or the inferior mesenteric artery (Fig. 6). Recent studies suggest that MRA is more sensitive for detecting Type 2 endoleaks than is CTA, and suggest that this is due to the increased sensitivity of MRI to contrast enhancement (25 – 28).

MR Artifacts of Endovascular Stents

1. Aortic stent-grafts (AneuRx, Talen) produce minimal artifact from the nitinol within the stent-graft. While this causes local distortion of the post-contrast images, vessel patency and endoleak can be visualized (Fig. 6).

2. The Wallstent, a cobalt-based alloy, causes major artifacts, obscuring visualization of vessel patency (Fig. 7).

3. Palmaz stent, a stainless steel stent, causes major artifacts, obscuring visualization of vessel patency.

4. Embolization coils cause major distortion artifacts, obscuring all adjacent organs, as well as vessel lumen patency (Fig. 8).

5. The platinum stent, a recently available stent for iliac or renal artery stenting, causes minimal artifact and allows for visualization of vessel patency (Fig. 9).

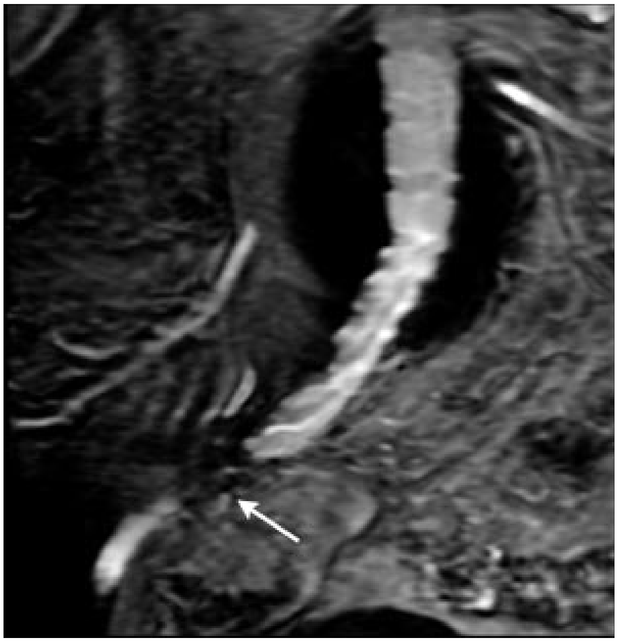

Fig. 7. AAA repaired with a stent-graft. The arrow points to the artifact from the right iliac artery Wallstent, which can be mistaken for an occlusion.

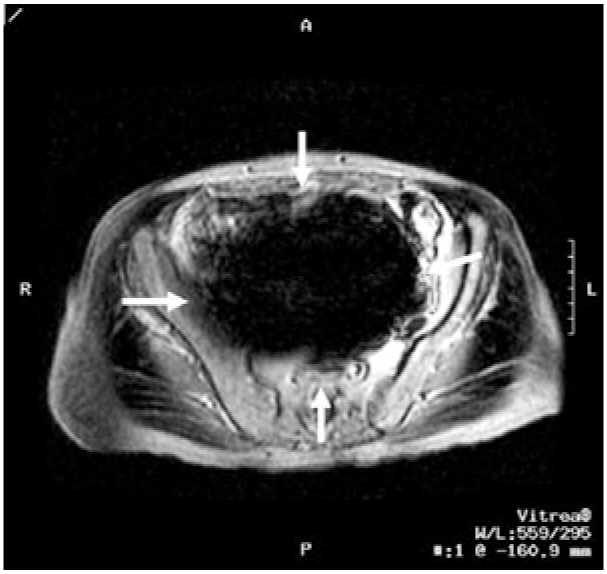

Fig. 8. Susceptibility artifact (arrows) from stainless steel embolization coils.

Research in the development of non-artifact-producing endovascular stents is ongoing (28, 29).

Pre- and Post-treatment Planning for Aortic Arch Aneurysms

Causes of aneurysmal dilatation of the aortic arch include atherosclerosis, trauma, arteri-

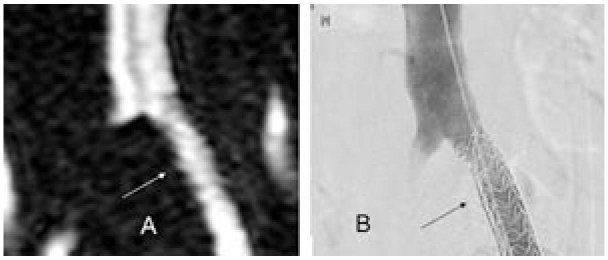

Fig. 9. (A) The arrow points to the minimal artifact which is caused by a platinum stent in the left iliac artery on MRA. **(B)** Digital subtraction angiogram of the same platinum stent in the left iliac artery (arrow).

tis, infection, connective tissue disease, aortic stenosis and congenital variants. Preoperative imaging of the aorta should include high-resolution imaging of the aortic wall, and cine imaging of the aortic valve and the aortic aneurysm. 3D CE-MRA of the aorta and 2D T1 weighted post-contrast images of the aorta are obtained. We have found 3D imaging useful in displaying the relationship of the aneurysm to the arch vessels in cases of complex anatomy (Fig. 10). Black blood imaging is useful for visualizing inflammation and thickening of the aortic wall. Cine imaging is useful for imaging the aortic valve and examining the distensibility of the aneurysm. Post-contrast 2D T1-weighted images are useful for visualizing thrombus and pseudoaneurysms. Measurements important for the endovascular surgeon are length of the aneurysm, diameter of the vessel before and after the aneurysm, and relationship of the aneurysm to the origin of the great vessels off the arch.

Pre- and Post-treatment of Aortic Dissection

Aortic dissection is the most common non-traumatic aortic pathologic condition (Fig. 11).

Fig. 10. (A) Arrows point to thoracic aortic aneurysm seen on CE-MRA. **(B)** Arrows point to artifact from aortic stent-graft repair of the thoracic aortic aneurysm in **(A)**.

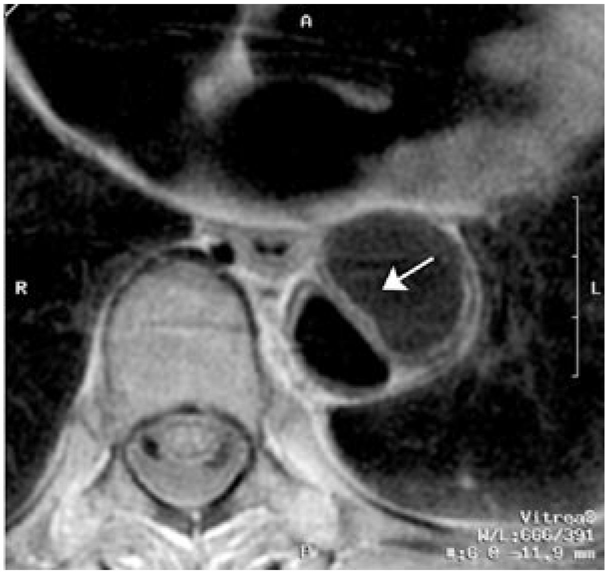

Fig. 11. Dissection in midthoracic aorta (arrow) using black blood MRA.

Imaging for aortic dissection must include identifying the origin of the intimal flap and its relationship to the arch vessels. In the case of a Stanford Type A left main dissection, imaging should include the aortic valve and the origin of the right and left coronary arteries. In the case of a Stanford Type B dissection, imaging should identify the origin of the visceral vessels from either the true or false lumens, and the distal extent of the flap. Our imaging protocol includes electrocardiographic-gated single-shot true fast imaging with steady-state precession (FISP) images through the entire aorta. 3D CE-MRA images can be obtained through the entire aorta to visualize vessel origins.

Pre- and Post-treatment of Takayasu's Arteritis

Takayasu's arteritis is the most common arteritis and usually occurs in young women of Asian descent. 3D CE-MRA imaging must include the entire aorta, including the arch vessels, in order to identify stenosis and aneurysmal dilatation. CE-MR imaging is useful in identifying aortic wall thickening, which we have found to be suggestive of active disease, and in assessing treatment response and flare-ups (Fig. 12).

Pre-and Post-treatment of Thoracic Aortic Aneurysms

High-resolution black blood or bright blood imaging can identify an intimal flap or pene-

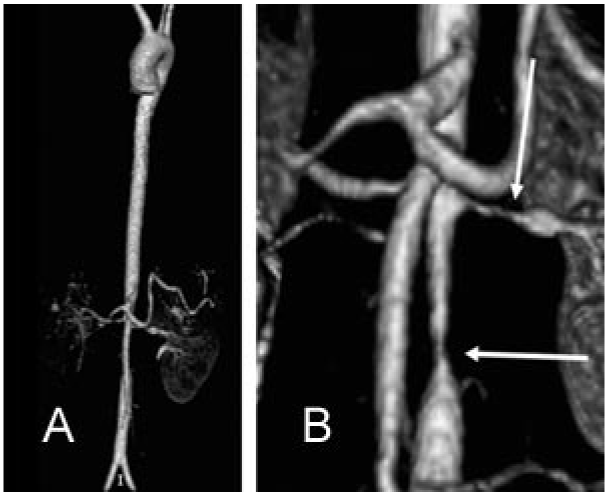

Fig. 12. (A) CE-MRA of the entire aorta in a patient with Takayasu's arteritis. **(B)** Arrows point to a high-grade stenosis in the left renal artery and the distal abdominal aorta.

trating ulcer. For proper endograft design, it is necessary to have accurate measurements of the aorta before and after the aneurysm as well as the length of the aneurysm. Imaging of the entire aorta is necessary to rule out abdominal aortic aneurysm. MRA of the iliac arteries should be included to aid the endovascular surgeon in pre-deployment approach of the stent-graft (30).

Conclusion

Contrast-enhanced MRA has made great advances over the last decade and is an increasingly useful and utilized examination for the noninvasive evaluation of vascular disease.

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