**MRI for Technologists**

**4712-204**

# Clinical Magnetic Resonance Angiography

## PROGRAM INFORMATION

***MRI for Technologists*** is a training program designed to meet the needs of radiologic technologists entering or working in the field of magnetic resonance imaging (MRI). These units are designed to augment classroom instruction and on-site training for radiologic technology students and professionals planning to take the review board examinations, as well as to provide a review for those looking to refresh their knowledge base in MR imaging.


**Original Release Date:** **October 2006**
**Review Date** **June 2018**
**Expiration Date:** **January 1, 2022**


*This material will be reviewed for continued accuracy and relevance. Please go to www.icpme.us for up-to-date information regarding current expiration dates.*

## OVERVIEW

The skill of the technologist is the single most important factor in obtaining good quality diagnostic images. A successful MRI examination is the culmination of many factors under the direct control of the technologist.

***Clinical Magnetic Resonance Angiography*** introduces the learner to concepts and techniques required for obtaining high quality magnetic resonance angiography (MRA). This unit familiarizes the learner with basic physics of MRA, the role of contrast–enhanced MRA, bolus detection techniques, and MRA image and data postprocessing techniques. MRA of the body and magnetic resonance venography (MRV) will also be covered.

After completing this educational material, the reader will be able to:

- Describe the role of gadolinium-based contrast agents in vascular imaging
- Explain the role of phase contrast and time-of-flight imaging to create images using magnetic resonance angiography
- Discuss bolus detection techniques and timing methods
- Recognize patient risk factors and respond to the most common adverse patient reactions to MRI contrast media
- Identify common postprocessing reconstructions used in MRA
- List the imaging techniques used in MRA and MRV for various portions of the vasculature, including those that benefit from the use of contrast enhancement
- Describe how peripheral run-off images are acquired with contrast media using a stepping table

## EDUCATIONAL CREDIT

This program has been approved by the American Society of Radiologic Technologists (ASRT) for 2.0 hours ARRT Category A continuing education credit.

## HOW TO RECEIVE CREDIT

Estimated time to complete this activity is 2.0 hours. The posttest and evaluation are required to receive credit and must be completed online.

- In order to access the posttest and evaluation, enroll in the online course at icpme.us.
- Read the entire activity.
- Log in to your account at icpme.us to complete the posttest and evaluation, accessible through the course link in your account.
- A passing grade of at least 75% is required to be eligible to receive credit.
- You may take the test up to three times.
- Upon receipt of a passing grade, you will be able to print a credit certificate of credit from your online account.


## ACKNOWLEDGMENTS

Our appreciation goes to Thomas Schrack, BS, ARMRIT for his review and update of this material. We would also like to acknowledge the original authors of this material:

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# FDA Drug Safety Communication: FDA warns that gadolinium-based contrast agents (GBCAs) are retained in the body; requires new class warnings

https://www.fda.gov/Drugs/DrugSafety/ucm589213.htm Accessed June 14, 2018.

**05-16-2018 Update**

In addition to approving the updated prescribing information concerning the gadolinium retention safety issues described in the Drug Safety Communication below, FDA has also approved new patient Medication Guides for all GBCAs.

Health care professionals and patients can access the patient Medication Guides according to the GBCA drug name* on the Medication Guides webpage, or the latest prescribing information by searching in Drugs@FDA.

All MRI centers should provide a Medication Guide the first time an outpatient receives a GBCA injection or when the information is substantially changed. In general, hospital inpatients are not required to receive a Medication Guide unless the patient or caregiver requests it. A health care professional who determines that it is not in a patient's best interest to receive a Medication Guide because of significant concerns about its effects may direct that it not be provided to that patient; however, the Medication Guide should be provided to any patient who requests the information.†

*The brand names of the GBCAs can be found in Table 1 below.
†For more information on distribution of Medication Guides, see the Guidance Document, the Drug Info Rounds Video, or the Code of Federal Regulations at 21 CFR 208.26.

This is an update to the FDA Drug Safety Communication: FDA identifies no harmful effects to date with brain retention of gadolinium-based contrast agents for MRIs; review to continue issued on May 22, 2017.

**12-19-2017 Safety Announcement**

The U.S. Food and Drug Administration (FDA) is requiring a new class warning and other safety measures for all gadolinium-based contrast agents (GBCAs) for magnetic resonance imaging (MRI) concerning gadolinium remaining in patients' bodies, including the brain, for months to years after receiving these drugs. Gadolinium retention has not been directly linked to adverse health effects in patients with normal kidney function, and we have concluded that the benefit of all approved GBCAs continues to outweigh any potential risks.

However, after additional review and consultation with the Medical Imaging Drugs Advisory Committee, we are requiring several actions to alert health care professionals and patients about gadolinium retention after an MRI using a GBCA, and actions that can help minimize problems. These include requiring a new patient Medication Guide*, providing educational information that every patient will be asked to read before receiving a GBCA. We are also requiring manufacturers of GBCAs to conduct human and animal studies to further assess the safety of these contrast agents.

GBCAs are used with medical imaging devices called MRI scanners to examine the body for problems such as cancer, infections, or bleeding. GBCAs contain gadolinium, a heavy metal. These contrast agents are injected into a vein to improve visualization of internal organs, blood vessels, and tissues during an MRI, which helps health care professionals diagnose medical conditions. After being administered, GBCAs are mostly eliminated from the body through the kidneys. However, trace amounts of gadolinium may stay in the body long-term. Many GBCAs have been on the market for more than a decade.

**Health care professionals** should consider the retention characteristics of each agent when choosing a GBCA for patients who may be at higher risk for gadolinium retention (see Table 1 listing GBCAs). These patients include those requiring multiple lifetime doses, pregnant women, children, and patients with

inflammatory conditions. Minimize repeated GBCA imaging studies when possible, particularly closely spaced MRI studies. However, do not avoid or defer necessary GBCA MRI scans.

**Patients, parents, and caregivers** should carefully read the new patient Medication Guide* that will be given to you before receiving a GBCA. The Medication Guide explains the risks associated with GBCAs. Also tell your health care professional about all your medical conditions, including:

- If you are pregnant or think you might be pregnant
- The date of your last MRI with gadolinium and if you have had repeat scans with gadolinium
- If you have kidney problems

There are two types of GBCAs based on their chemical structures: linear and macrocyclic (see Table 1 below). Linear GBCAs result in more retention and retention for a longer time than macrocyclic GBCAs. Gadolinium levels remaining in the body are higher after administration of Omniscan (gadodiamide) or OptiMARK (gadoversetamide) than after Eovist (gadoxetate disodium), Magnevist (gadopentetate dimeglumine), or MultiHance (gadobenate dimeglumine). Gadolinium levels in the body are lowest after administration of Dotarem (gadoterate meglumine), Gadavist (gadobutrol), and ProHance (gadoteridol); the gadolinium levels are also similar across these agents.

*The Medication Guide will be posted once it is approved.

**Table 1. FDA-Approved GBCAs***

| Brand name | Generic name | Chemical Structure |
|---|---|---|
| Dotarem† | gadoterate meglumine | Macrocyclic |
| Eovist | gadoxetate disodium | Linear |
| Gadavist† | gadobutrol | Macrocyclic |
| Magnevist | gadopentetate dimeglumine | Linear |
| MultiHance | gadobenate dimeglumine | Linear |
| Omniscan‡ | gadodiamide | Linear |
| OptiMARK‡ | gadoversetamide | Linear |
| ProHance† | gadoteridol | Macrocyclic |

*Linear GBCAs result in more gadolinium retention in the body than macrocyclic GBCAs.
†Gadolinium levels remaining in the body are LOWEST and similar after use of these agents.
‡Gadolinium levels remaining in the body are HIGHEST after use of these agents.

To date, the only known adverse health effect related to gadolinium retention is a rare condition called nephrogenic systemic fibrosis (NSF) that occurs in a small subgroup of patients with pre-existing kidney failure. We have also received reports of adverse events involving multiple organ systems in patients with normal kidney function. A causal association between these adverse events and gadolinium retention could not be established.

We are continuing to assess the health effects of gadolinium retention in the body and will update the public when new information becomes available. We are requiring the following specific changes to the labeling of all GBCAs:

- A *Warning and Precaution*
- Changes related to gadolinium retention in the *Adverse Reactions, Pregnancy, Clinical Pharmacology*, and *Patient Instructions* sections

We urge patients and health care professionals to report side effects involving GBCAs or other medicines to the FDA MedWatch program.

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# Clinical Magnetic Resonance Angiography

*Please note: items in **bold** can be found in the glossary.*

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## BASIC PHYSICS OF MRA

### Introduction

Vascular magnetic resonance imaging (MRI) is a valuable tool in the evaluation and diagnosis of circulatory system pathology. Since the establishment of magnetic resonance **angiography** (MRA) using **time-of-flight** (TOF) methods in the 1980s, manufacturers and academic institutions have strived to develop techniques to enhance quality by removing the ambiguities inherent in the techniques applied by early MRI systems.

With advancing technology and a desire to improve patient care, the relatively noninvasive techniques of MRA are widely used by clinicians worldwide. Hardware modifications including ultrafast gradients have shortened scanning times, allowing for complete image acquisitions in a reasonable breath-hold. Ultrafast gradients also permit shorter **echo times** (TE) than previously obtainable, producing high quality images. Short TEs are important in MR angiography because they reduce spin **dephasing** in flowing blood, and maintaining phase coherency in flowing spins provides more accurate visualization of blood vessels. In addition, the use of paramagnetic contrast agents and power injectors provide consistent, reliable, diagnostic exams. Areas amenable to MRA diagnosis include but are not limited to the evaluation of the carotid arteries, intracranial arteries, aortic arch and thoracic aorta, abdominal aorta and its major tributaries, and peripheral vascular tree - essentially any major arterial or venous structure. In order to fully elucidate these techniques, the basic physics applied are discussed first. Specific explanation of how MRA is practiced in each body region follows.

## Basic Physics

The basic physics of MR angiography can be demonstrated by the principle of simple flow dynamics.

### Flow Dynamics and Time-of-Flight Imaging

The basic physics of flow as it relates to MRA in the body play an important role when performing angiographic examinations. Flow effects can produce a range of visual phenomena. For example, fast moving blood produces flow voids; blood flowing into the outer slices of an imaging volume produces high signals; and pulsatile flow creates ghost images of the vessel in the phase-encoding direction. Noncontrast MRA has taken advantage of these artifacts to create predictable image contrast.

**Factors affecting the appearance of flowing blood include velocity, acceleration, pulsation, vortices, and flow direction.**

Time-of-flight image contrast is primarily created by flow within the vessel **lumen**, although the vessel wall itself is not visualized. Factors affecting the appearance of flowing blood include velocity, acceleration, pulsation, vortices, and flow direction. TOF imaging provides robust images that can address a range of clinical questions.

Time-of-flight imaging is a gradient echo-based sequence with a short **repetition time** (TR) and high **flip angles** to saturate stationary tissue. T1 recovery of the background tissue is prevented by repeated rapid excitations, and therefore only fresh inflowing unsaturated blood spins will give a signal. Flow-related enhancement principles provide that stationary spins within the slice become heavily saturated and thus appear hypointense, while fresh spins from flowing blood have not been subjected to the rapid RF pulses that the stationary spins have been. Therefore, flowing spins are unsaturated and exhibit hyperintense signal characteristics. Flow-related enhancement is the main principle behind non-contrast TOF imaging.

As mentioned earlier, the TE must also be short so that the spins will not lose **phase coherence**. TOF techniques typically use short TR sequences acquired as slices perpendicular to the direction of blood flow. Flowing blood that runs parallel to slice orientations (**in-plane flow**) risk becoming saturated as it is are exposed to rapid **radiofrequency** (RF) pulses, as are the stationary spins. The effect of flow-related enhancement yields a high signal from blood moving into the slice, making the vessels stand out bright against a gray background. Maximum flow signal is achieved when a totally new column of blood enters the slice during every TR period. **Saturation bands** can be placed adjacent to the slices to selectively destroy MR signal from blood flowing into the imaged volume from one side of the slice. As an example, a superior saturation band can be used to void venous flow in the jugular veins when performing MRA of the carotid arteries. Depending upon where the saturation band is placed, either venous or arterial signal can be suppressed, allowing a flow direction-sensitive technique useful for creating **arteriograms** or **venograms**.

**A limitation of TOF MRA is its vulnerability to artifacts.**

Time-of-flight MRA is acquired with sequential 2D slices, 3D slabs, or multiple overlapping thin 3D slabs. A limitation of TOF MRA is its vulnerability to artifacts. These include complex or turbulent flow that can cause spin dephasing and the resultant signal loss, which can be improved but not eliminated by reducing TE. An example of turbulent flow is the carotid bulb at the bifurcation of the internal and external carotid arteries. Because of the dephasing of spins in the bulb, TOF techniques tend to overestimate a **stenosis**. In-plane flow, rather than **through-plane flow**, results in signal loss from saturation of the blood pool signal. Tissues with short T1s, such as fat, blood, and gadolinium-enhanced regions, can appear bright like flow and thus obscure vessels. See examples of time-of-flight imaging later in this material.

Furthermore, the inherent geometry of acquisitions can produce inefficient coverage of long vessel segments, resulting in a long scan time, significantly increasing patient motion, and degrading image quality. Contrast-enhanced MRA techniques offer solutions to these challenges.

### PHASE CONTRAST IMAGING

Phase contrast (PC) MR angiography is a 2D or 3D imaging technique that relies on gradient manipulation to produce MRA data rather than the flow-related enhancement principles used in TOF imaging. Phase contrast imaging manipulates the accumulated phase shifts of the spins in flowing blood by the application of **bipolar gradient** pulses to produce angiographic images against a dark background of stationary tissue.

The advantages of phase contrast imaging are:

- visualization of slow-flow blood
- excellent background suppression
- “encoding” flow in specific directions
- quantification of flow direction and velocity

To appreciate the mechanism behind phase contrast MRA, recall that spins are placed in the transverse magnetization plane x, y following the initial excitation pulse. Stationary spins do not accumulate phase shifts. However, moving spins accumulate phase shifts as the spins move from one local gradient field to the next. The application of controlled gradient fields takes advantage of the movement of flowing spins, as well as the non-movement of stationary spins. This is accomplished by the application of bipolar gradients, gradient pulses applied in equal but opposite magnitudes.

When subjected to a gradient field of a given magnitude and direction, spins undergo a phase shift in accordance with the Larmor Equation $\acute{\omega} = \gamma ß_0$, where $\acute{\omega}$ is the **Larmor frequency**, $\gamma$ is the gyromagnetic ratio, and $ß_0$ is the strength of the local magnetic field. That phase shift is proportional to the magnitude and direction of the gradient field. As an arbitrary reference point, that phase shift can be given a value of +1. Assuming the spin is stationary, subjecting it to a second gradient field equal in magnitude but in the opposite direction, the phase shift will become -1. When the phase shifts of the spin are combined, the net phase shift will yield no signal. In this way, phase contrast MRA provides excellent background suppression **(Figures 1 – 2)**.

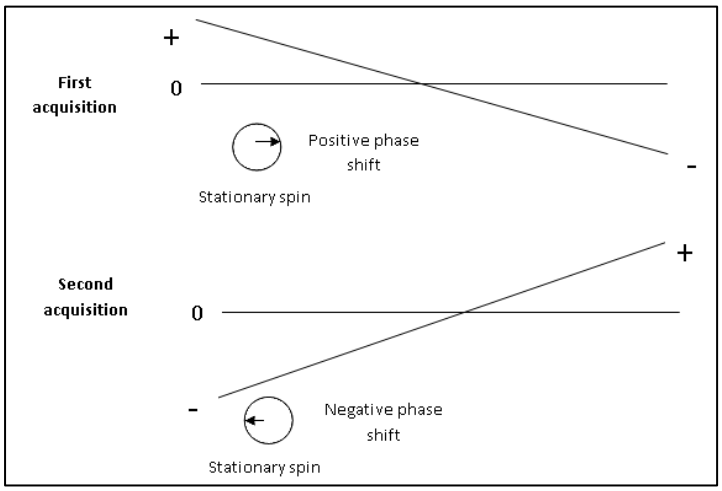



**Figure 1.** The first acquisition uses a bipolar gradient field to induce a *positive* phase shift on a stationary spin. The second acquisition is an equal but reversed gradient field to induce a *negative* phase shift. When the two acquisitions are combined, the new phase shift equals 0, yielding no signal.

*Illustrations courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

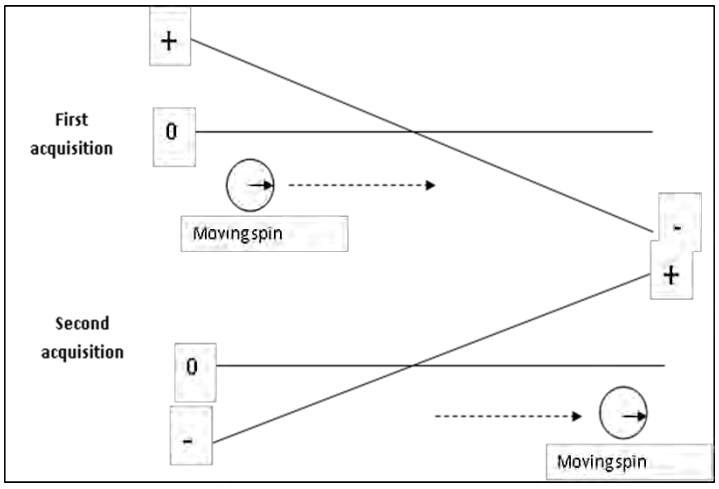



**Figure 2.** However, the results are different when dealing with a *moving* spin. In the case of flowing blood, the spin accumulates a phase shift from the first gradient acquisition to the second. When the two acquisitions are combined, the phase shifts of the flowing spin have a positive net phase shift in the transverse magnetization plane. When the data sets of the first and second acquisitions are combined, the only signal produced is that of the flowing blood.

It is the combined image that displays signal from flowing blood, but in the individual acquisitions, information can be obtained and displayed that yields directional flow. For example, if the flow-encoding gradient used is the x-gradient, the flow that is encoded is left/right flow. Using y- and z-gradients subsequently yields anterior/posterior and superior/inferior flow directions. When evaluating complex multi-directional flow in clinical practice, eg, intracranial vasculature, all three gradient directions are used. However, for quick localization purposes, often the gradient that corresponds to the blood flow direction is the only one used, eg, for carotid artery localization using the z-gradient for the S/I flow.

As stated above, spins of flowing blood accumulate a phase shift when the bipolar flow-encoding gradients are applied. The amount of phase shift produced is proportional to the velocity of the flowing blood. In order to correctly encode spins from flowing blood to produce the highest signal, the amplitude of the flow encoding must be optimally set. This is accomplished via the velocity encoding value or VENC. The VENC value is set to the highest estimated flow velocity of the vasculature in question. For example, the normal maximum velocity for the common carotid artery in an adult is 80cm/sec. Therefore the proper VENC to gain maximum signal in the carotid arteries in a phase contrast MRA is 80cm/sec. If the VENC is too low, for example, set to 50cm/sec for carotid artery evaluation, flow that is greater than 50cm/sec will be **aliased** as slower flow. When the VENC is set too low, flowing spins can accumulate a phase shift that is greater than $180^0$. As an example, a phase shift of $+200^0$ is the same as a phase shift of $-160^0$. Not only will this signal appear as slower flow but will also seem to flow in the opposite direction. See **Table 1** for examples of typical large vessel velocities.

| Vessel | Flow Velocity (cm/sec) |
|---|---|
| Ascending Aorta | 100 |
| Descending Aorta | 100 |
| Common Carotid | 80 |
| Middle Cerebral Artery | 60 |
| Basilar Artery | 50 |
| Femoral Artery | 80 |
| Popliteal Artery | 40 |
| Vena Cava | 40 |
| Portal Vein | 10 |

**Table 1.** Typical large vessel velocities.

*See* Schneider G, Prince MR, Meany JFM, eds. *Magnetic Resonance Angiography: Techniques, Indications and Practical Applications.* Springer: 2005.

As stated earlier, phase contrast imaging has the ability to characterize not only flow *direction* but also flow *velocity*. The brightness of the flowing blood signal is directly proportional to the amplitude of the flow-encoding gradient. When the optimal VENC is used, flow velocity that most closely matches the amplitude of the flow-encoding gradient exhibits the brightest **voxel** signal. Slower flow is displayed as less bright, and retrograde flow is displayed as dark voxels. Since the brightness of the signal is proportional to the VENC used, it is possible to quantify phase contrast MRA flow velocity.

2D/3D phase contrast MRA, vastly different than 2D/3D TOF, offers useful diagnostic techniques for the evaluation and quantification of the body's vasculature. The excellent background suppression of PC MRA creates maximum intensity pixel projection (MIP) images that more closely resemble x-ray angiographic images. However, one disadvantage of PC MRA is the potential for longer scan times when complex multi-directional flow needs to be evaluated since all three gradient planes must be obtained as separate acquisitions **(Figures 3–5)**.

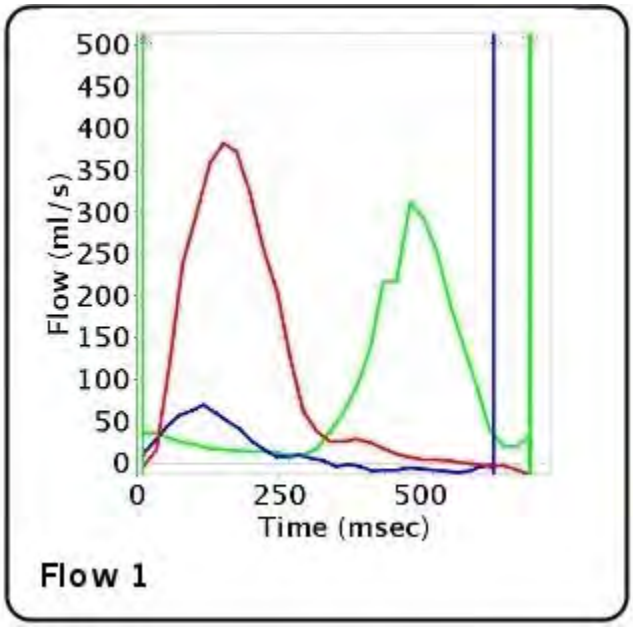
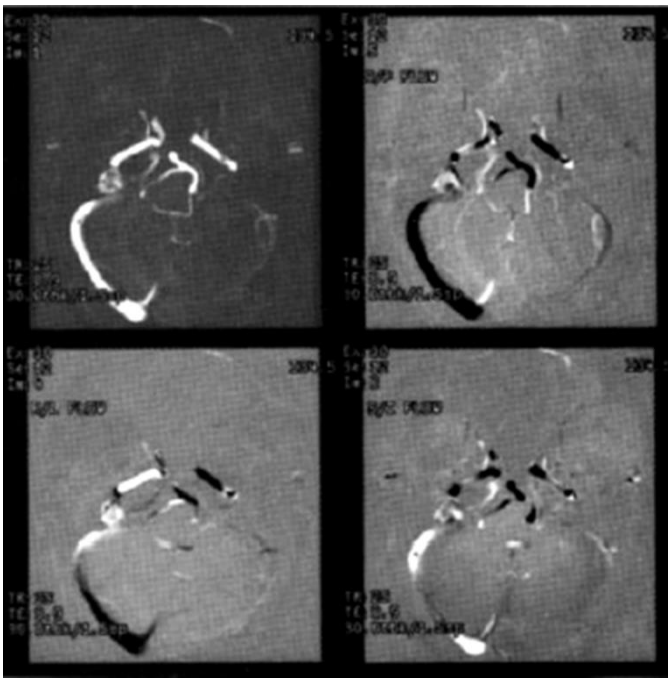



**Figure 3.** 15-year-old-male with decreased capacity in the right lung. Flow map of the main pulmonary artery (red), the left pulmonary branch (green), and the right pulmonary branch (blue).

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*



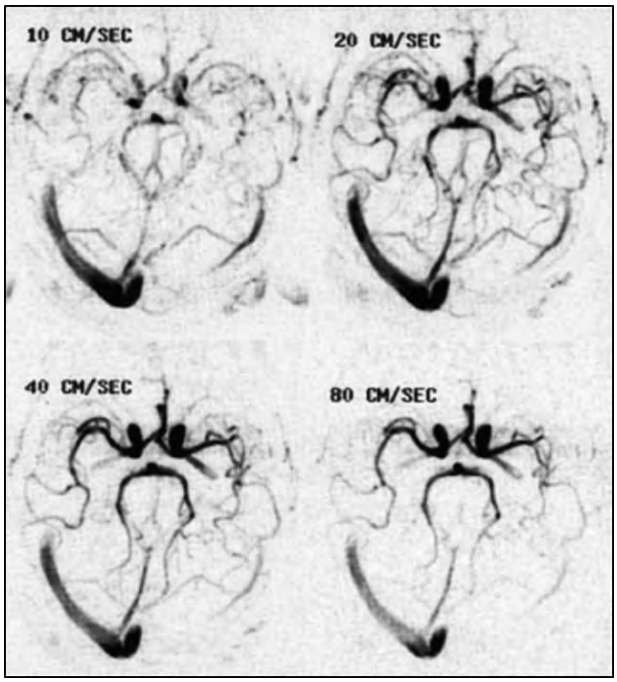



**Figure 4. (Left)** Phase contrast MRA images. Upper left is the combination of the acquisitions in all three planes (x, y, and z). The upper right is the A/P flow image. Lower left is the L/R flow and lower right is the S/I flow image.

**Figure 5. (Right)** The effect of VENC on phase contrast imaging. Each image was acquired with a differing VENC value of 10cm/sec – 80cm/sec. Note that the lower VENC values encode slower flow (venous) more optimally, while higher VENCs favor faster flow (arterial).

*See Turski P. Vascular Magnetic Resonance Imaging. GE Healthcare:1994;3:103.*

## THE ROLE OF CONTRAST-ENHANCED MRA

### Bolus Detection Techniques with Time-of-Flight Imaging

The use of a gadolinium-based contrast agent (GBCA) for imaging the vascular system changed the way MRA examinations were performed. Until the mid-1990s, the vast majority of MRA scanning was done using noncontrast-enhanced 2D or 3D TOF imaging with the scanning sequence of a gradient echo series in the plane most perpendicular to the flow direction of interest. For example, if the carotid arteries were the vessels of interest, the scan plane was typically in the axial direction, perpendicular to the flow as the carotid arteries run inferior to superior. In this example, imaging would create contrast in the image based on the flow-related enhancement of flowing blood into an axial slice plane, where magnetization of the blood is at its greatest. The resultant images showed darker (non-flowing) stationary tissues against very bright flowing blood. Images were then postprocessed into MIP projections in a 3D display.

While 2D and 3D TOF imaging is robust, there are disadvantages:

- TOF can overestimate the degree of stenosis
- Flow that is not perpendicular to the imaging plane can become saturated with RF energy, appearing dark and falsely resembling a stenotic vessel
- Flow that is slow also may become saturated with RF and appear dark
- Long scan times (4–6 minutes for a 2D TOF and 6–9 minutes for a 3D TOF) increase the risk of patient motion and consequent blurry images

Specific to body applications, noncontrast-enhanced images of the lower extremities are often badly smeared due to naturally occurring **tri-phasic flow** velocities where arterial flow moves in three distinct phases: fast forward, short reverse, then fast forward again. See **Figures 6 and 7** for examples of flow-related enhancement and 3D TOF.

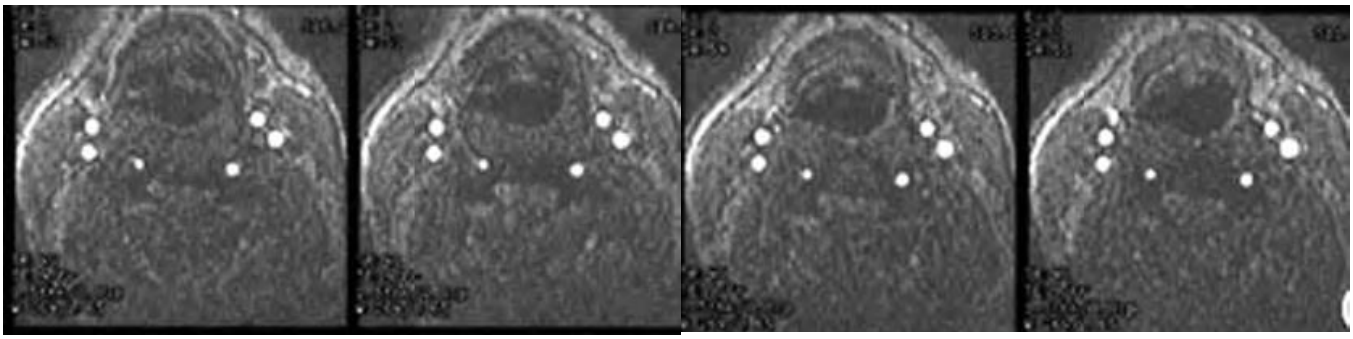


**Figure 6.** Axial view of 4 images acquired perpendicular to the carotid and vertebral arteries. A short TR and a high flip angle ensure heavy saturation of stationary tissues while providing maximum flow-related enhancement of the carotid and vertebral arteries. These "source" images are then postprocessed into a 3D MIP projection.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

## Role of Gadolinium Contrast in Vascular Imaging

The introduction of GBCAs in vascular imaging dramatically altered the methods used to perform most MRA examinations. Because gadolinium is **paramagnetic**, contrast-enhanced MRA (CE MRA) offers advantages that TOF MRA cannot:

- CE MRA does not depend on flow-related enhancement to provide bright (high) signal
- CE MRA does not require the slice orientation to be perpendicular to the flow
- CE MRA enables the use of ultrafast 3D gradient sequences which significantly reduces scan time, allowing higher spatial resolution
- GBCAs do not saturate from multiple RF pulses, eliminating flow-related artifacts found in TOF sequences, ie, the overestimation of stenosis

The technical challenge of using contrast was the ability to deliver the **bolus** of contrast at the exact moment of imaging, timing the acquisition to obtain images of the vessels of interest precisely upon arrival of the contrast agent.

**Figure 7.** Collapsed MIP projection of the intracranial arteries. This noncontrast 3D TOF image takes advantage of the flow-related enhancement of the fast-flowing blood. The individual source images are displayed as a singular MIP projection to visualize the entire vasculature.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

**Gadolinium contrast bolus timing in MRA applications is critical to the success of the exam.**

Gadolinium contrast bolus timing in MRA applications is critical to the success of the exam, and CE MRA comprises a large component of MRA applications. Body MRA applications include ascending, thoracic, and abdominal aorta; renal arteries; superior mesenteric artery; and MRA “runoffs” (abdominal, iliac, femoral, popliteal, lower leg, and feet arteries). Neurological MRA applications include carotid and intracranial vascular imaging. Musculoskeletal MRA includes upper and lower extremities and joint areas. Bolus timing for each of these areas must be precise, and a discussion about differing bolus detection and timing techniques follows.

## BOLUS DETECTION TECHNIQUES

### Specific Bolus Techniques

Methods for predicting or detecting the arrival of a bolus of contrast into the vessel of interest typically fall into one of three categories:

- Manual timing
- Computer-aided detection
- Visual detection



#### MANUAL TIMING

Manual timing is quite effective in determining bolus arrival, allowing facilities without dedicated bolus detection software to acquire a high quality MRA. The technologist sets up a scanning series so that a single slice is prescribed to be imaged multiple times. This multiphase series is performed while a small amount of contrast (2–3 mL) is injected over two to three seconds. After the series is complete — typically ~1 minute— the technologist reviews the images to determine which image has the greatest degree of contrast in the vessel of interest by using a region-of-interest (ROI) tool that displays the actual **pixel** values of the contrast entering the vessel. Once a specific image is identified, the technologist calculates the time it took for the bolus to arrive by looking at the time stamp on the image that is provided on all MR systems. The challenges of the manual timing technique are correctly calculating timing and determining if the test bolus has lingered in the venous system obscuring arterial vessels. However, a well-timed, manually calculated test bolus series is indistinguishable from the more automated methods.

#### COMPUTER-AIDED DETECTION

MRI is a versatile imaging modality, capable of analyzing signal data from the patient in near-real time. The ability to perform real-time data processing is extremely useful in the MRA application for determining when a contrast bolus arrives at the area of interest.

The automated bolus detection method requires the technologist to prescribe a small-volume area of interest (10mm x 10mm x 15mm) on a scout image – such as the abdominal aorta for renal MRA – and the fully prescribed area to be scanned when the contrast is delivered.

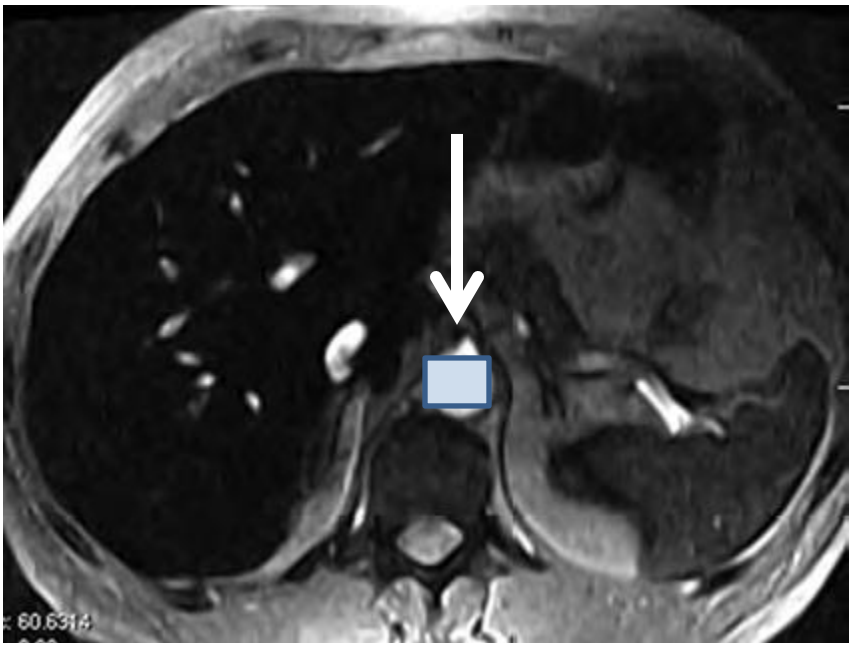


**Figure 8.** Axial image showing abdominal aorta with a graphically prescribed 3D "tracker" pulse cube. The area inside the cube is monitored in real time for rapid increases in pixel signal intensity resulting from gadolinium in-flow. When a set threshold of signal increase is reached, data acquisition of the 3D MRA begins.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

The scanner begins the imaging sequence and analyzes the pixel intensity from the small volume, often called the **tracker (Figure 8)**. Once the system determines the average pixel value of the volume (the baseline of pixel values), the technologist injects the contrast. The system continues to monitor the tracker volume. When the bolus arrives in the area of interest, the pixel values from the tracker quickly increase in dramatic fashion, signaling the MR system that the bolus has arrived. The system then launches the ultrafast gradient echo sequence for the contrast MRA series **(Figure 9)**.

Automated computer-aided bolus detection methods are highly effective, producing excellent contrast MRA studies. The technique is automated, with little outside intervention and no manual calculations required. There is no contamination of the images from small amounts of test bolusing in the venous system.

The challenge of the automated computer-aided bolus detection method is that it requires precise placement of the tracker volume. If the tracker is misplaced or the patient moves between the time of placement and the time the scan actually begins, the bolus may not be detected or may be detected too late, yielding non-diagnostic images. Also, the central ***k*-space** line of the MRA sequence must be filled first to meet the arrival of the contrast bolus.

**Visual detection methods combine the best of manual timing and computer-aided bolus detection techniques.**

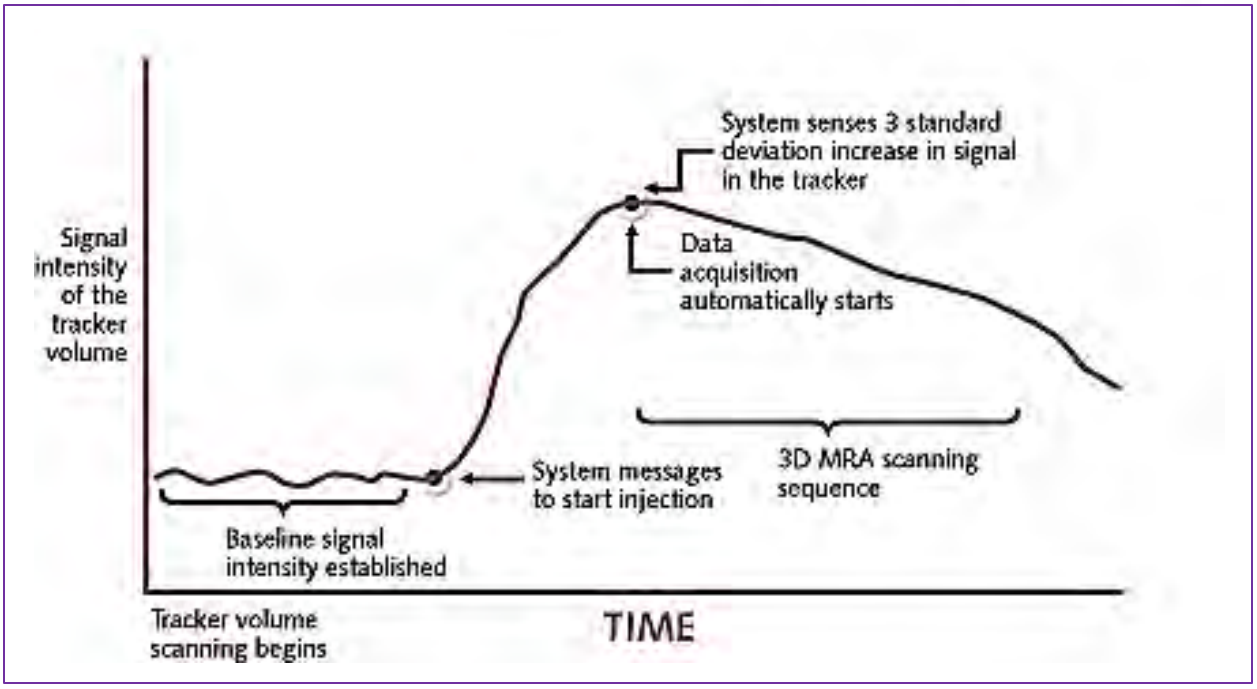



**Figure 9.** Time course of events in an automated bolus detection technique.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

### VISUAL DETECTION

Visual detection methods combine the best of manual timing and computer-aided bolus detection techniques. Visual detection integrates the real-time display of image data from the automated computer-aided bolus detection with the visual cues of the manual timing method. Visual detection is often referred to as “fluoro-triggered MRA.” The area of interest is first scanned with a very low-resolution technique so that the images are displayed in near-real time — thus, the use of the term “fluoro” as in real-time x-ray imaging. The injection is made during the display of the images in real time, and the technologist can often watch the patient’s breathing during an abdominal MRA. The technologist visually inspects the images to note the arrival of the contrast bolus. Once the bolus is seen, the technologist switches the imaging parameters in real time to a higher resolution scan, which produces excellent contrast MRA results.

The advantage of the visual detection method is that the technologist is in control of the start of the scan, eliminating the need for a test bolus, and breathing commands can be tailored to individual needs. The only potential drawback is that the technologist must be vigilant in watching the images in order to track the arrival of the bolus. Again, as mentioned above, the central *k*-space lines need to be sampled first in order to meet the arrival of the contrast bolus.

## Ultrafast Scanning Can Eliminate Bolus Timing

Ultrafast scanning is available on many high-end MR scanners. Referred to by various manufacturer names (GE-TRICKS; Siemens -TWIST, TREAT; Philips - 4D-TRAK), this rapid technique is finding its way into the mainstream. It requires very fast and high performance gradients (to acquire the data quickly) and very fast array processor reconstruction engines. In less than five minutes, 1,000 or more individual images can be acquired, making ultrafast reconstruction processors an absolute requirement.

**In less than five minutes, 1,000 or more individual images can be acquired, making ultrafast reconstruction processors an absolute requirement.**

Ultrafast scanning is image scanning so fast that:

- entire 3D volumes are acquired as fast as a single slice
- one simply prescribes the required 3D volume of interest and then tells the system how many times to scan this volume
- the course of a bolus of contrast is captured as it progresses through the vasculature of interest
- it does not matter when the bolus arrives because the scanner is already acquiring the data before, during, and after peak enhancement
- this technique takes no longer than the typical 3D time-of-flight sequence

In essence, the technologist prescribes the 3D volume of interest of, for example, the patient's lower legs. The technologist determines the number of times the volume will be scanned. Each of these scans is referred to as a "phase." The technologist must then balance the spatial resolution with the necessary temporal resolution, that is, how fast each 3D volume must be acquired. Remember that as spatial resolution increases, temporal resolution decreases. Once set, the technologist simply injects and starts the scan at the same time as the injection. As each 3D volume is acquired, usually in a matter of seconds, it is quickly reconstructed and processed into a MIP that is then displayed on the screen while the subsequent 3D volume is acquired. Each 3D MIP displays an increasing, then decreasing amount of contrast in the vasculature **(Figure 10)**.

**Remember that as spatial resolution increases, temporal resolution decreases.**

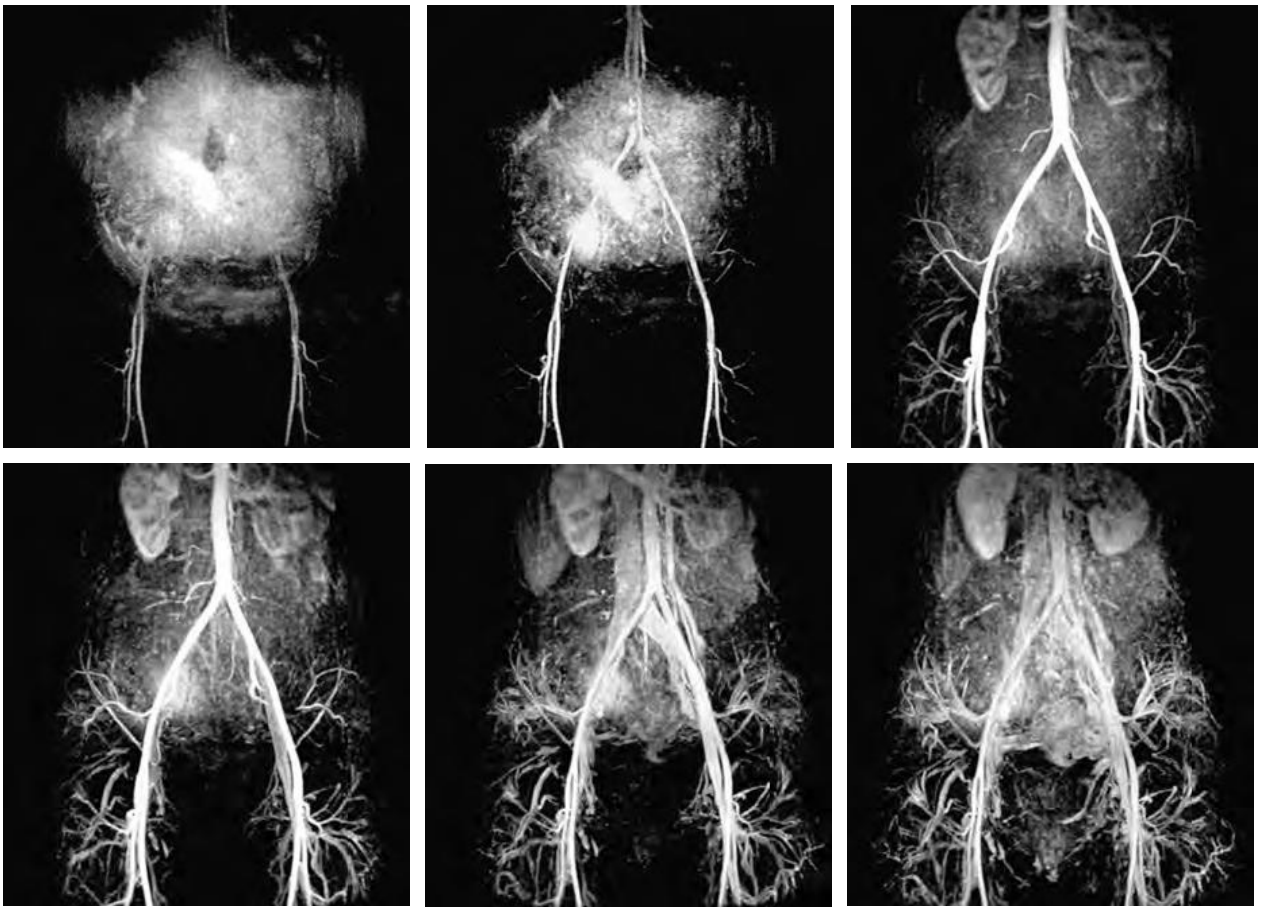


**Figure 10.** Selected MIP phases of a multiphase multi-3D pelvic MRA/MRV of a 35-year-old female with pelvic pain. Top left: early arterial phase. Top right: peak arterial phase. Bottom left: early venous phase. Bottom right: late venous phase. Note the extensive and prominent pelvic veins consistent with venous pelvic congestion.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

## NOTES

## MRA IMAGE AND DATA PROCESSING

### Maximum Intensity Pixel Project Reconstructions and Subvolume MIP Reconstructions

MIP and subvolume MIP reconstructions are commonly used to postprocess MR angiograms. With newer and more advanced software applications and enhanced magnetic gradients, far more MRA studies (renal, peripheral, aortic, and carotid) are being performed using 3D techniques with intravenous contrast media. Three-dimensional MRA data sets acquired before and after intravenous contrast contain information about blood vessels, as well as enhancing and nonenhancing stationary tissues. To review these data, the technologist or radiologist scrolls through the slices of raw data in sequence. However, vascular structures are better displayed and evaluated by taking advantage of the sharp contrast between the brightly enhanced vessels and the surrounding stationary tissues.

MIP is a postprocessing technique that mathematically filters the strong vascular signals from a 2D/3D volume data set and projects these signals into an operator-selected plane. The MIP technique is simple and fast. MIP postprocessing gives MRA images the appearance of a conventional radiographic angiogram. MIP and subvolume MIP reconstructions help illustrate and record vascular structure or morphology.

MIP images are produced using a ray-tracing **algorithm**. This algorithm, which is incorporated into the standard software of all MR systems, essentially creates a 2D image projection from 3D image data. To understand this algorithm, consider a straight line or “ray” coursing in a specific direction through the many voxels in a 3D volume. Each voxel has a different signal intensity value. Rays are projected through the 3D imaging volume in the user-defined plane. Of all the voxel signals encountered along each ray, only the *highest* signal value (*maximum* pixel intensity) is retained and assigned to the relevant pixel in the 2D projection image **(Figures 11-15)**. Because flowing or contrast-enhanced blood generates high signal, the 2D projection of the brightest voxels effectively produces an image of the vascular system. Vessels are visualized while surrounding tissue is suppressed into the background.

When performing this postprocessing technique, it is helpful to complete several MIP reconstructions and slightly change the direction of the projection each time. This technique yields projections that demonstrate the vessels at slightly different angles. The projections can be displayed in **cine** mode, and the vessels will appear to rotate in space. If one vessel overlaps or covers another vessel in one projection, the projection angle can be changed until the vessel of interest is easily visualized.

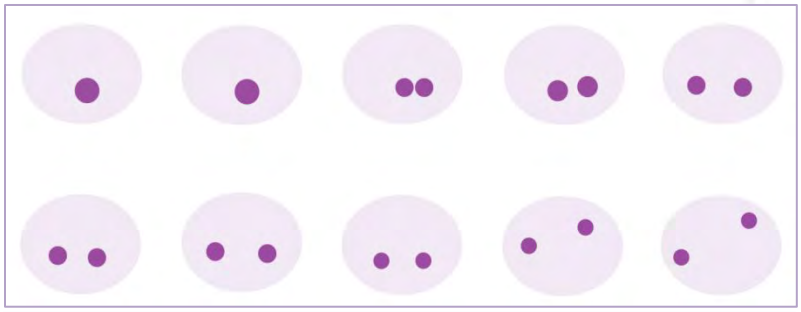


**Figure 11.** Individual axial images showing bright vascular flow.

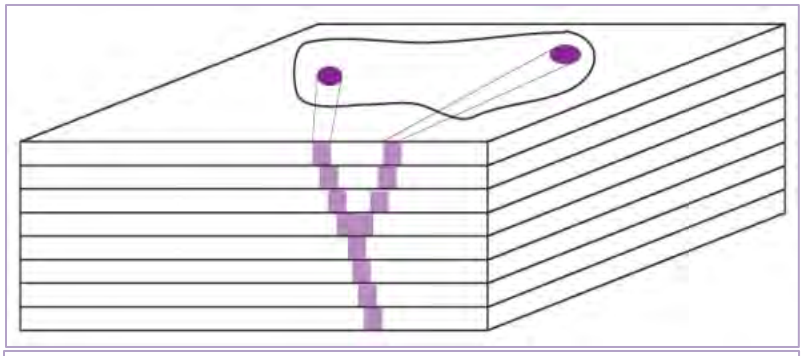


**Figure 12.** When the axial images are "stacked," the bright vessels are displayed in any direction.

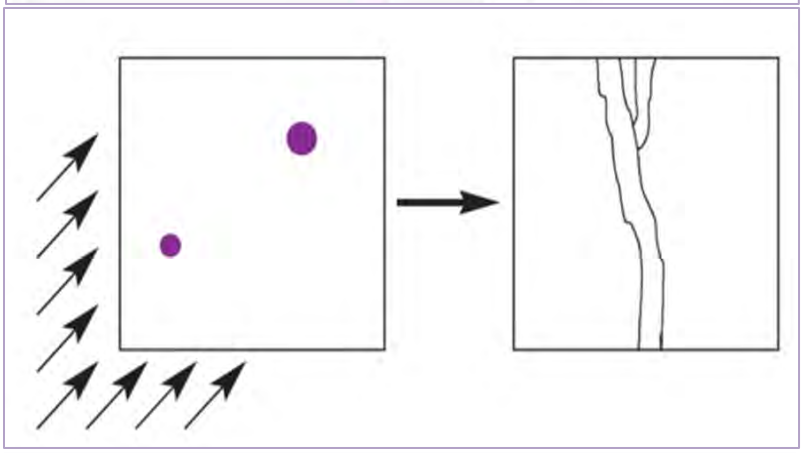


**Figure 13.** Here the ray is projected from a 45-degree angle. Note the orientation of the resulting MIP.

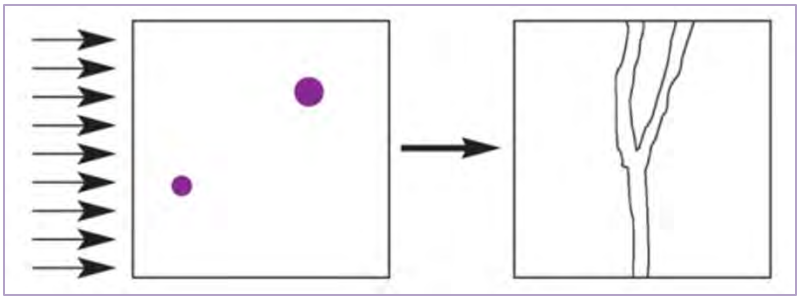


**Figure 14.** The MIP process "looks through" the data to project the brightest pixels along the direction of the ray. The user selects the best direction(s); in this figure, the ray is coming directly from the left side.

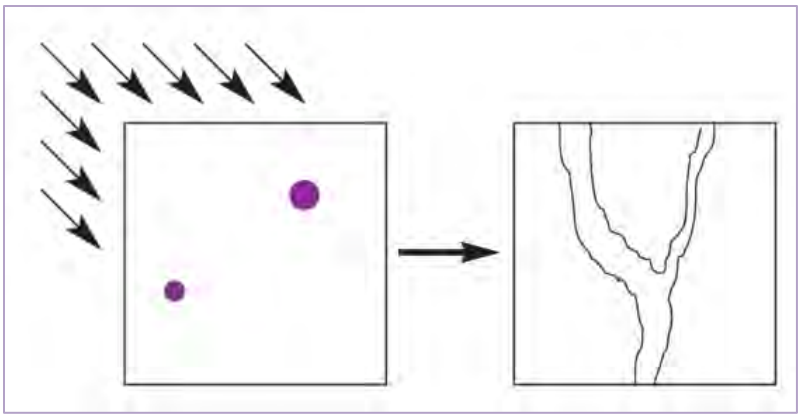


**Figure 15.** In this figure the ray is projected from the opposite 45-degree angle. Note the orientation of the resulting MIP now.

*Illustrations courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

The MIP algorithm does have limitations including:

- loss of information due to selection of the brightest voxel
- failure to visualize a small **thrombus** in a vein
- obstruction of vessels by bright objects included in the MIP volume
- inability to determine the proximity of a vessel to the viewer
- corruption of MIP reconstructions by venous overlap

Each of these limitations can be reduced or even eliminated through careful and complete postprocessing by performing a targeted MIP.



### Targeted Maximum Intensity Pixel Projection

A targeted (subvolume) MIP will improve image quality and significantly reduce reconstruction time. When using this technique, only a limited portion of the acquired data is used that includes only the vessels of interest. The advantage of targeted MIP is that the projection contains fewer noisy background pixels, such as high signal fat, and overlapping vessels can removed. The only signals considered in the targeted MIP algorithm are those the user chooses to include within the ROI. This technique is used to isolate specific vessels of interest from others in the projection path, keeping the image uncomplicated. Targeted MIP reconstructions are especially helpful for depicting tortuous, overlapping vessels or vascular pathology at vessel origins and branch points.

"Trimming" the area in a targeted MIP yields sharper delineation of vessels by eliminating bright volumes that could superimpose areas of interest. The areas of interest are typically drawn by hand so they can be tailored to the unique anatomy of the patient for optimal visualization. Note in **Figure 16** how the brighter tissue, eg, fat, interferes with visualizing the vessels behind it. Removing this unwanted bright signal clearly improves the quality of the vascular structure visualization. Whether the technologist utilizes a MIP or subvolume MIP, the source images must always be analyzed and presented.

### Minimum Intensity Pixel Projection Reconstructions

Minimum intensity pixel projection (MinIP) reconstructions are analogous to MIP reconstructions, except that the MinIP algorithm retains the voxel of *lowest* signal intensity along each ray and assigns it to the relevant pixel in the 2D projection image. MinIP reconstructions are rarely used in daily practice; however, their value is evident in situations that require 2D projectional displays of low signal intensity structures, such as the air-filled lumen of the tracheobronchial tree or metallic vascular and biliary stents. These low signal intensity structures would be hidden by high signal intensity voxels in the 3D volume on routine MIP reconstructions.

However, MinIPs can be used in susceptibility-weighted imaging (SWI) of the brain, an application used to improve visualization of areas of dephasing in the brain due to the presence of hemosiderin. Hemosiderin is the resultant iron-based by-product of hemorrhagic stroke. When imaged using a gradient echo pulse sequence, thin-slice acquisitions produce images displaying highly hypointense vessels along with signal voids where hemosiderin is present. The slice stack is postprocessed using MinIP reconstruction to further visualize very dark vessels in contrast to the hemosiderin. While not an MRA/MRV application per se, SWI does employ MinIP processing.

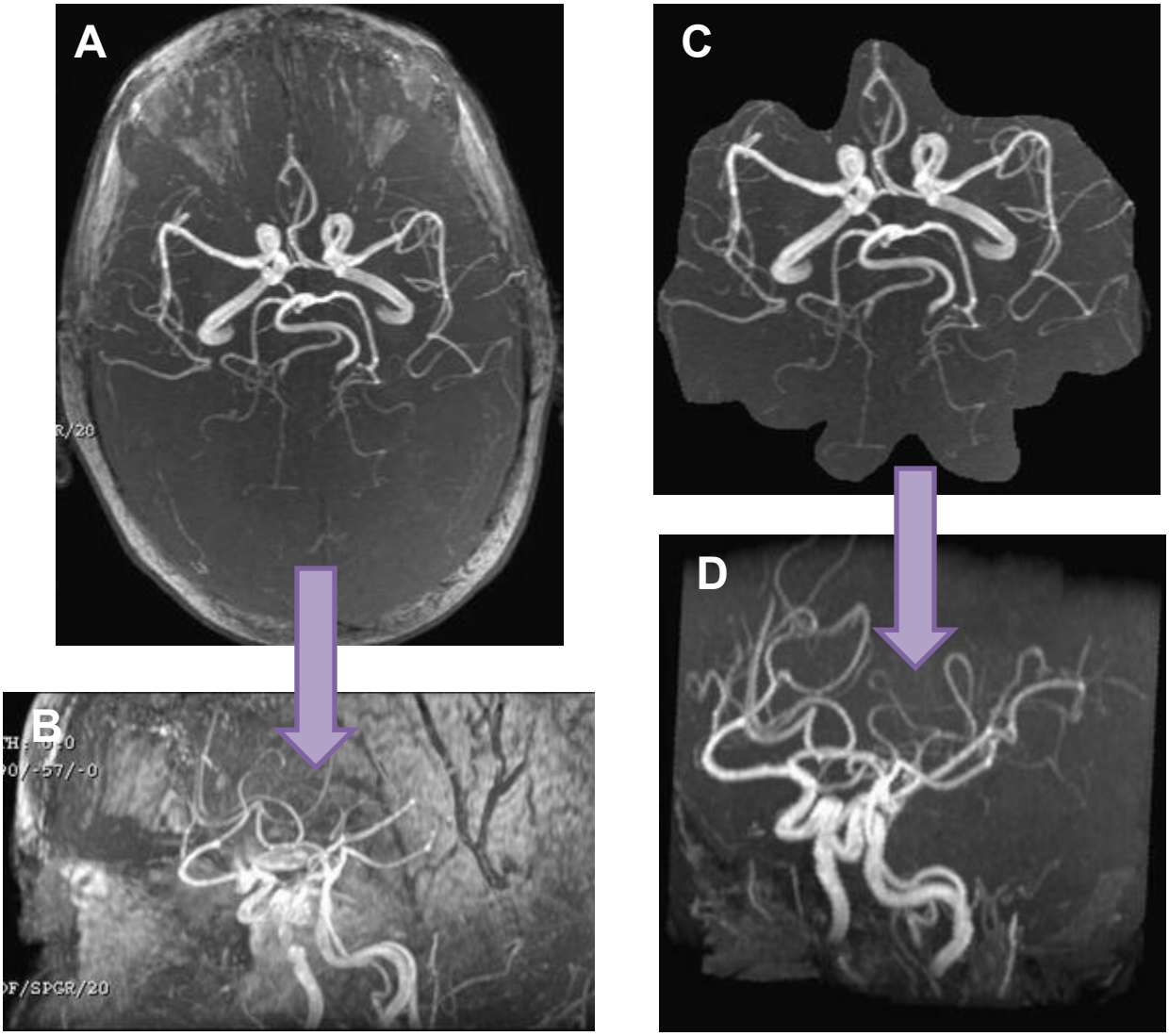



**Figure 16 A-D. (A)** Axial MIP of a 3D TOF image, untrimmed. Since this MIP is performed in the same direction as the acquired slices (in the axial plane), it is commonly referred to as the "collapsed" MIP. **(B)** The same MIP image rotated to an anterior sagittal view. Note how the bright signal obscures the vasculature and the smaller cerebral arteries are not seen at all. **(C)** This image shows the collapsed MIP with the bright signal trimmed away. **(D)** This image shows the same rotation as in (B). Note the increased visibility of the vasculature, including the clarity of the smaller cerebral arteries.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

## Applications of Image Subtraction in MRA

Image subtraction is a postprocessing technique that eliminates unwanted background tissues or signals. The most common method of implementing image subtraction consists of "subtracting" precontrast images from postcontrast images. Image subtraction is very useful in a variety of MR applications.

Image subtraction in gadolinium-enhanced MR imaging can be used with any field strength magnet. It is a quick technique that does not add examination time for the patient. Image subtraction is a way to obtain fat suppression that avoids the potential limitations arising from magnetic field **inhomogeneity** or low field strength.

The subtraction postprocessing technique increases the conspicuity of enhancing lesions, tissues, organs, and vessels, especially against a background that is hyperintense on unenhanced T1-weighted sequences, such as fat, proteinaceous fluid, and subacute blood products. From a technical standpoint, image subtraction requires some of the imaging parameters — such as FOV, slice thickness, and pixel dimensions — to be identical on both pre- and postcontrast images. Patient motion and **spatial misregistration** between pre- and postcontrast data sets must be kept to a minimum. An IV should be placed before moving the patient into the magnet to minimize the likelihood of patient motion between the pre- and postcontrast image acquisitions.

When using breath-hold acquisitions for chest and abdominal MRI and MRA, patients should hold their breath at the same phase in the respiratory cycle, either in full inspiration or expiration, as long as both pre- and post-imaging series are the same. This breath-holding technique yields the best reproducibility of organ location during repeated scans.

After MR scanning is completed, the image subtraction software and pre- and postcontrast data sets are selected. Scanners from some vendors provide image subtraction options as part of their pulse sequence setup menus. In this case, image subtraction is performed automatically after both data sets are acquired. The most widely used subtraction algorithms are performed slice-by-slice. Alternatively, complex subtraction can be performed before image reconstruction. Complex subtraction includes effects due to phase differences between the pre- and postcontrast images. The computer creates a new series from the subtracted images that can be viewed on the console, printed, or sent to the picture archiving communication system (PACS). It is imperative that both pre- and postcontrast pulse sequences have identical parameters. The entire subtraction technique can be performed in a relatively short period of time, depending on the type of software available **(Figure 17)**.

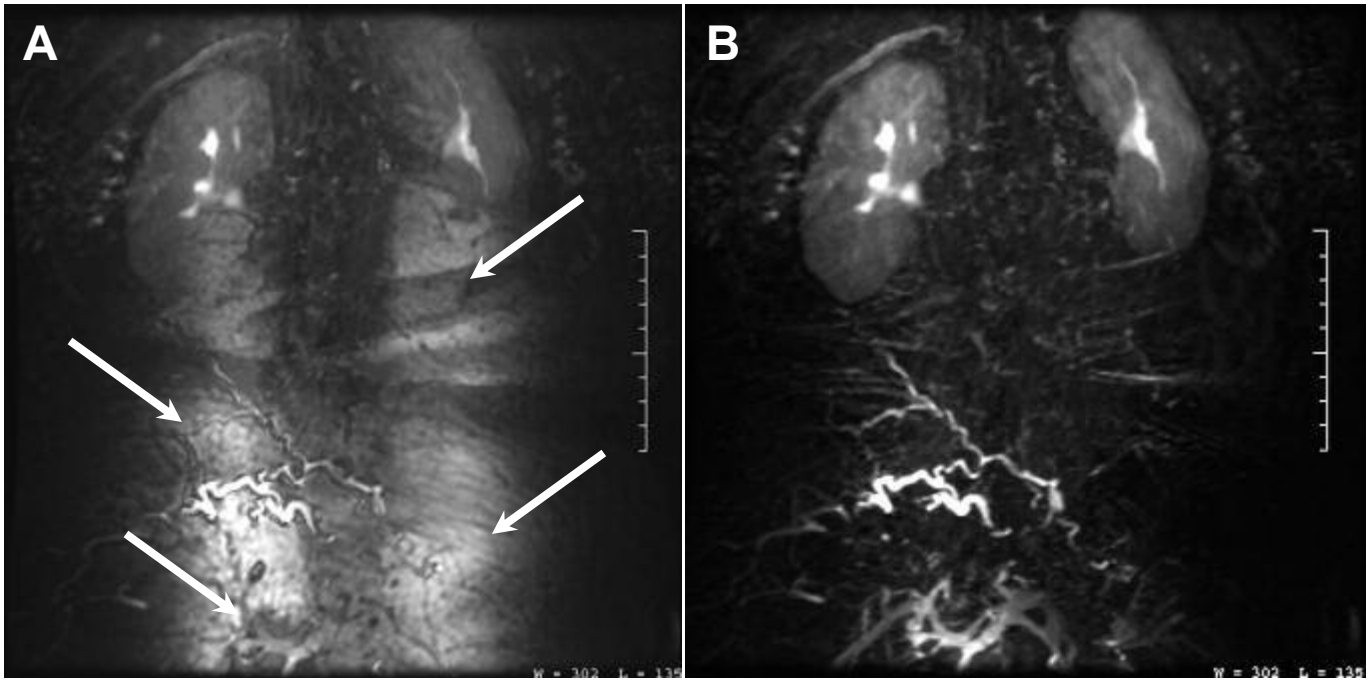



**Figure 17 A-B. (A)** An unsubtracted image in the coronal plane of the posterior lumbar region following contrast injection to visualize a suspected arteriovenous malformation (AVM). Note the bright signal from fat due to the close proximity of the surface coil, even with the use of fat saturation techniques (arrows). **(B)** The subtracted image using a precontrast image as a mask. Note the greatly increased visualization of the AVM in the subtracted image.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

Image misregistration is a potential limitation of subtraction techniques. Misregistration occurs when the patient changes position or moves between the pre- and postcontrast image acquisitions or, in the case of breath-held acquisitions, the breathing is held differently from pre- to postcontrast image. Constant vigilance is required to detect evidence of image misregistration because it decreases the diagnostic utility of the subtracted images. Several vendors have developed software that attempts to correct misregistration in either rigid or deformable motion.

## Image Subtraction Techniques in MRA

Image quality in gadolinium-enhanced 3D MRA benefits from subtraction postprocessing. When obtaining an MRA, image subtraction can help to:

- eliminate background signal and improve depiction of small vessels
- eliminate signal folding (aliasing) of nonenhancing background structures onto the angiographic image

Blood vessels that are reconstructed using the MIP algorithm can potentially be obscured by bone marrow, soft tissue, or fat having high signal on T1-weighted sequences. These high signal background structures can limit the conspicuity and evaluation of small vessels in the distal extremities and narrowed or diseased vessels. If the FOV is too small, an overlapping appearance of the vessels of interest may occur, displaying an aliasing artifact. Subtracting the image sets can eliminate the aliasing and allow better visualization of the vessels of interest. Subtraction imaging allows optimal visualization of blood vessels and obviates the need for fat suppression techniques.

**Subtraction imaging allows optimal visualization of blood vessels and obviates the need for fat suppression techniques.**

### HEAD AND SPINE IMAGING

Subtraction techniques can aid in defining the patterns and degree of enhancement of central nervous system (CNS) tumors and complex tumors at the base of the skull. It also assists in depicting and defining residual tumor and distinguishing between tumor and hemorrhage or radiation changes, which can also appear as high signal. In the spine, subtraction imaging can be helpful in defining meningeal disease, extension of tumor into neural foramina and epidural and paraspinal areas, as well as distinguishing between nonenhancing herniated disc and enhancing epidural fibrosis in postoperative cases.

### BODY IMAGING

Subtraction imaging is also useful for evaluating solid and complex cystic masses. For example, renal or ovarian masses that contain hemorrhagic or proteinaceous fluid often exhibit increased signal on precontrast T1-weighted images. Such masses may be difficult to assess for internal enhancement which, if present, is frequently a harbinger of malignancy. Conversely, the absence of internal enhancement suggests a benign etiology. Subtraction postprocessing helps determine the presence or absence of enhancement **(Figure 18)**.

Subtraction postprocessing is useful for assessing the extent of tumor necrosis and residual viable tumor in hepatocellular carcinoma or liver metastases after chemoembolization or radio-frequency ablation. Subtraction imaging can serve as an indicator for the success of therapy and can also help to localize residual or recurrent viable tumor in cases of suspected therapeutic failure. Subtraction imaging can also be used to distinguish between viable and nonviable tumor and to help localize areas for biopsy.

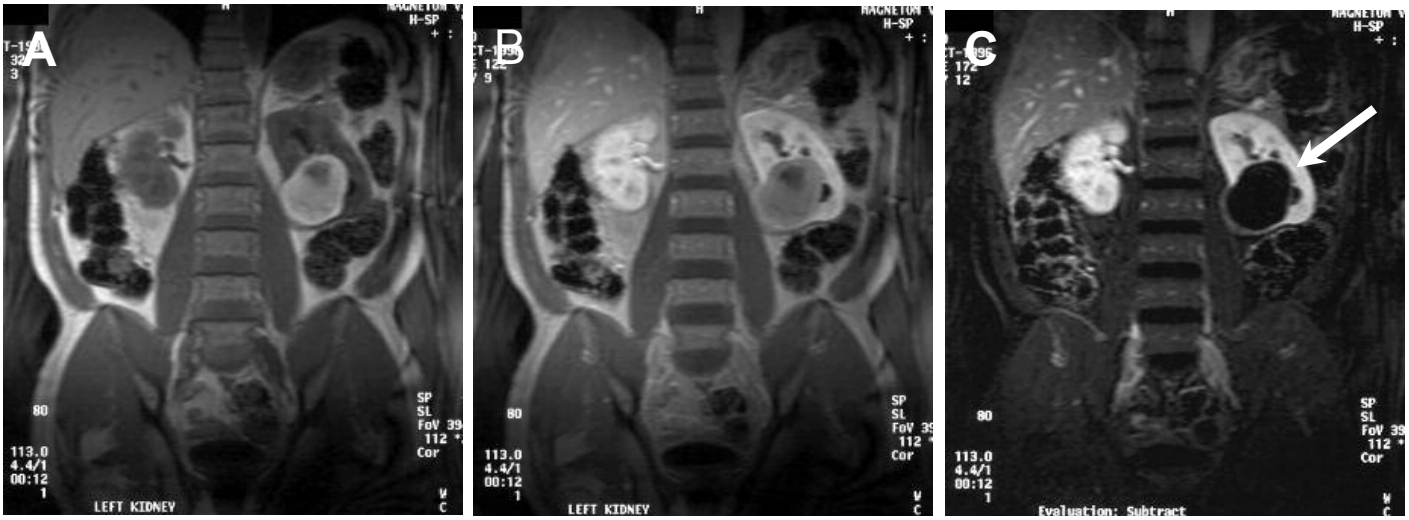



**Figure 18 A-C. (A)** Coronal T1 FLASH breath-hold non-contrast image through the kidneys. Complex mass in the left kidney. **(B)** Coronal T1 postgadolinium T1 FLASH breath-hold image. Complex mass in the left kidney. **(C)** Subtraction (postgadolinium minus pregadolinium) T1 FLASH image. Complex renal mass shows no internal enhancement.

*Courtesy of Mark Flyer, MD, Maimonides Medical Center.*

Subtraction postprocessing can be combined with opposed-phase imaging to increase the conspicuity of fat content in lesions that contain both fat and water, such as adrenal adenomas and fatty liver. In these cases, intravenous contrast is not required. To perform subtraction postprocessing, out-of-phase T1-weighted gradient echo images are subtracted from in-phase images acquired with identical imaging parameters (except for the echo time). Most scanner manufacturers now offer a dual-echo gradient echo sequence, which enables the in-phase and out-of-phase images to be acquired without the possibility of image misregistration.

### MUSCULOSKELETAL SYSTEM

In the evaluation of bone marrow and soft tissues in the musculoskeletal system, subtraction imaging can improve the definition of tumors and inflammatory lesions, fluid collections, and soft tissue or **osseous tissue** involvement by suppressing high signal fat in bone marrow and in soft tissues. Subtraction imaging can also confirm the presence or absence of contrast enhancement in lesions.

## MR ANGIOGRAPHY OF THE BRAIN AND NECK

MR angiography has become a mainstay of brain imaging. MRA is typically performed either in the neck for examination of the carotid and vertebral arteries or intracranially to examine the Circle-of-Willis and the main cerebral arteries that arise from it **(Figures 19 and 20)**. In the neck, contrast-enhanced MRA takes advantage of improved software and increased gradient strengths to allow reduction in MRA imaging time, as well as more precise timing of the injected bolus to capture the actual passage of contrast through the carotids in the arterial phase. Many radiologists believe contrast MRA is superior to non-contrast 2D or 3D TOF sequences, particularly in patients who have significant disease.



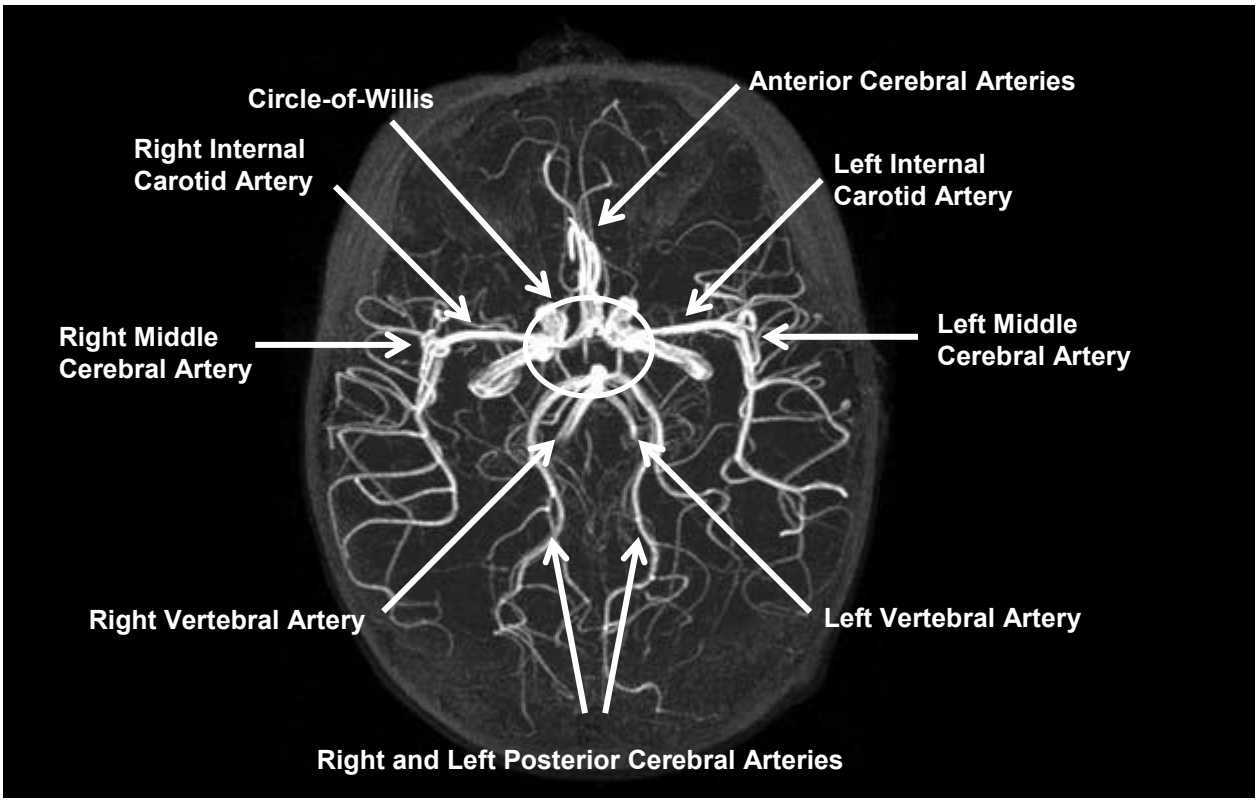



**Figure 19.** Axial MIP 3D TOF of intracranial arterial tree showing normal vascular anatomy.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

### MRA of the Brain

Indications for MRA of the brain include history of known **aneurysm**, severe headache, ischemic symptoms and stroke, loss of vision, **tinnitus**, etc. In short, a variety of neurological symptoms can arise from intracranial ischemia.

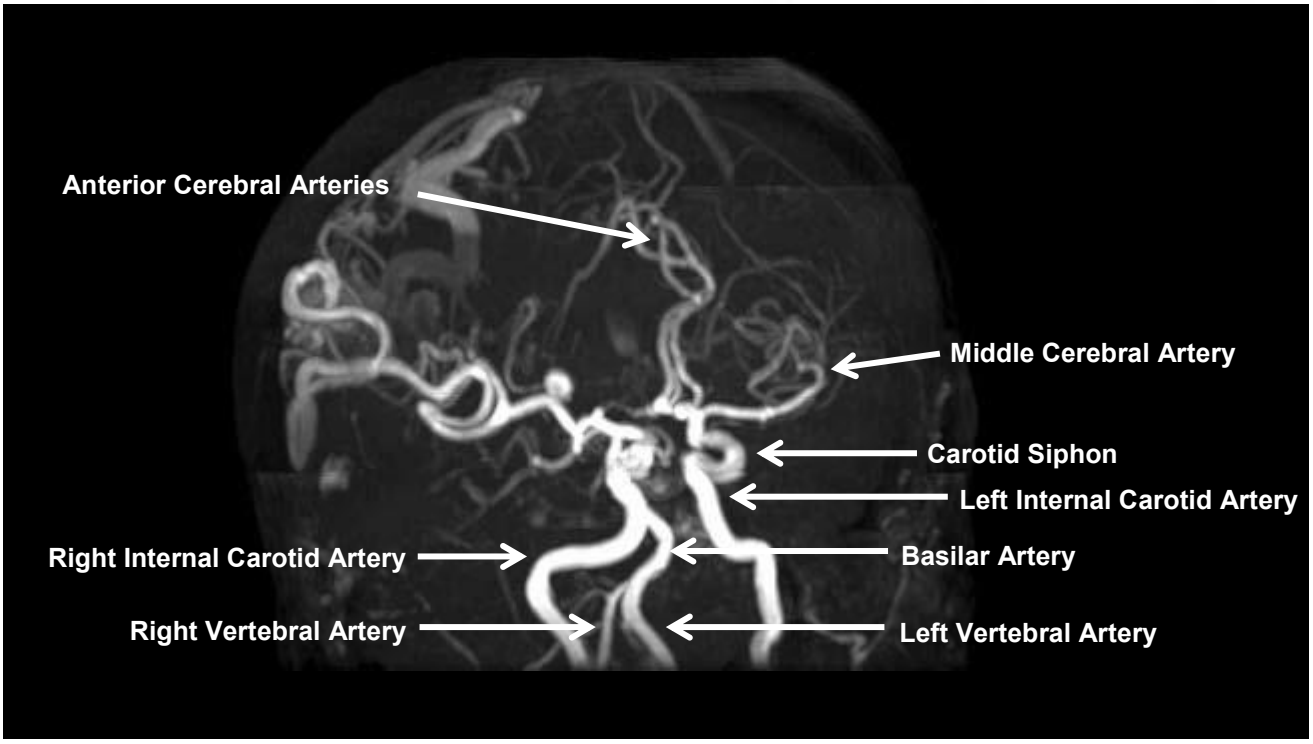



**Figure 20.** MIP projection 3D TOF of intracranial arterial tree showing vascular anatomical landmarks. Note large posterior colloid cyst.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

MR angiography is particularly useful in the evaluation of **ischemia** and **infarction**. In the evaluation of arterial infarction, conventional 3D TOF MRA covering the Circle-of-Willis is useful. This technique will not depict small penetrating arterial thrombosis but can detect thrombosis involving larger vessels, such as the middle cerebral artery (MCA), anterior cerebral artery (ACA), and posterior cerebral artery (PCA). If venous thrombosis is suspected, MRV can be useful. In both MRA and MRV, thrombosis is generally seen as an area of cutoff of signal loss within a vessel.

The typical pulse sequence for MRA is a 3D TOF sequence as opposed to MRV, discussed later. 3D TOF MRA is typically done in one or several "blocks" or "slabs" of excited tissue. These slabs of data undergo a second set of phase encoding steps at the end of the data acquisition in the slice-select direction. This second series of phase encoding steps reconstructs the slabs into discrete thin slice images. Zero-filling of *k*-space allows slices to be reconstructed with negative overlaps, just as with CT data. For example, a single 20cm slab of excited tissue can be reconstructed into twenty 2.0mm thin slice images every 1.0mm. In many instances, the reconstructed images can be submillimeter in thickness. When multiple slabs are prescribed, the slabs are typically overlapped to avoid interslab boundary artifact. Saturation pulses can also be used superiorly to "null" venous flow from the superior sagittal sinus. Used in conjunction with high-SNR phased array head coils, the result is high quality MRA of the intracranial arteries, including the Circle-of-Willis, internal carotid arteries, basilar artery, and anterior, middle, and posterior cerebral arteries.

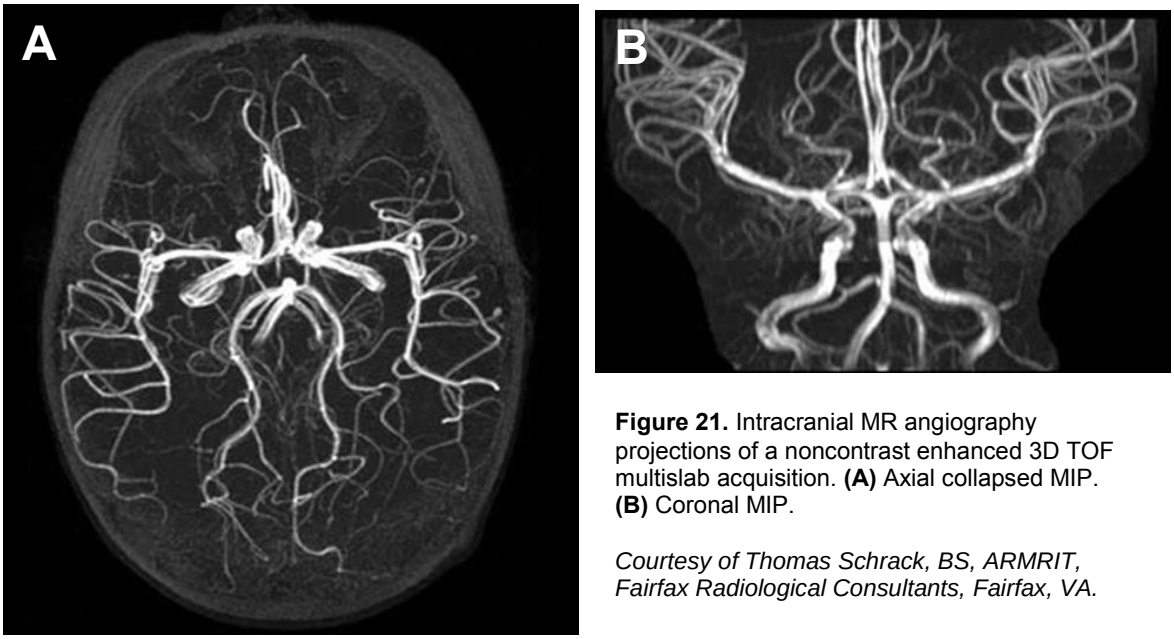



**Figure 21.** Intracranial MR angiography projections of a noncontrast enhanced 3D TOF multislab acquisition. **(A)** Axial collapsed MIP. **(B)** Coronal MIP.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

Unlike MRA of the neck, most radiologists believe that when imaging the arteries of the brain, noncontrast 3D TOF methods are optimal. When contrast is used, enhancement of venous structures and normal nonvascular structures affect visualization of the arterial vasculature. In essence, with IV contrast, MRA of the brain can become a “bowl of spaghetti,” making it very difficult to delineate individual vascular structures **(Figures 21 and 22)**. The exception is evaluation of the intracranial arteries following placement of an intracranial aneurysm clip.

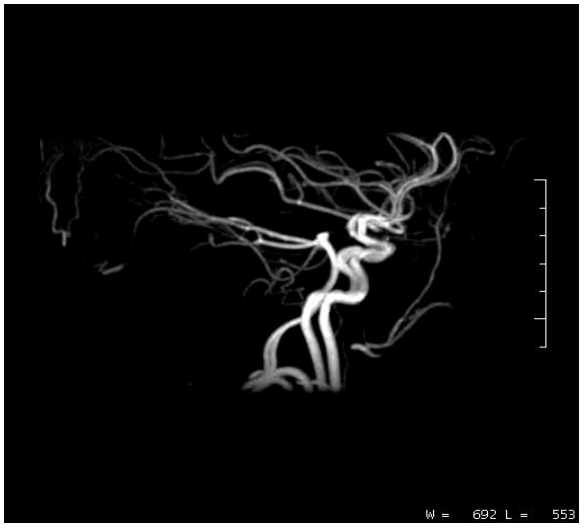



**Figure 22.** Movie of 3D TOF MRA of the brain.

Click here to view the movie on the ICPMEducation channel.

For many years, the existence of an implanted intracranial aneurysm clip was an absolute contraindication for MRI. Indeed, a patient death due to the torque by the magnetic field of the aneurysm clip has been documented (see FDA Safety Notification, November 1992).Today, it is rare to find a non-MRI safe intracranial aneurysm clip. With prudent and careful screening and verification, many patients with clip placement can undergo a safe and diagnostic MRI examination.

For patients with intracranial aneurysm clips, routine 3D TOF imaging may be inadequate because the titanium-based clip, while **non-ferrous**, creates a significant metal-related artifact that can completely obscure visualization of blood flow in the region of the clip. Fortunately, GBCA administration reduces this artifact signal drop-out.

## MRA of the Neck

MRA of the neck **(Figures 23-25)** is required to assess the patency of the following:

- origins of the three branches of the aortic arch (left subclavian artery, left common carotid artery, and the brachiocephalic, or innominate, artery that bifurcates into the right subclavian and the right common carotid arteries)
- right and left carotid artery bifurcation into the internal and external carotid arteries
- right and left vertebral arteries
- basilar artery

Typically MRA of the neck is performed using contrast-enhanced 3D fast gradient echo imaging. Timing data acquisition to the peak filling of vessels with contrast is achieved by various timing methods that range from manual bolus timing runs to automated bolus detection software, visual detection of the bolus, and extremely rapid imaging through several phases of bolus filling (**Figures 26 and 27).**

The primary advantage of contrast-enhanced MRA of the neck versus 2D and 3D TOF imaging is the known over-estimation of carotid bifurcation stenosis by TOF, a result of the loss of signal from vortex flow in the carotid bulb. The use of contrast alleviates this phenomenon. TOF images the *flow* of the blood, but in contrast-enhanced MRA, the blood *itself* is imaged. With contrast in the vessel, the direction of the flow and complex flow dynamics are irrelevant. However, timing of the bolus is critical since contrast in the jugular veins appears equally as bright as in the arteries.

**TOF images the *flow* of the blood, but in contrast-enhanced MRA, the blood *itself* is imaged.**

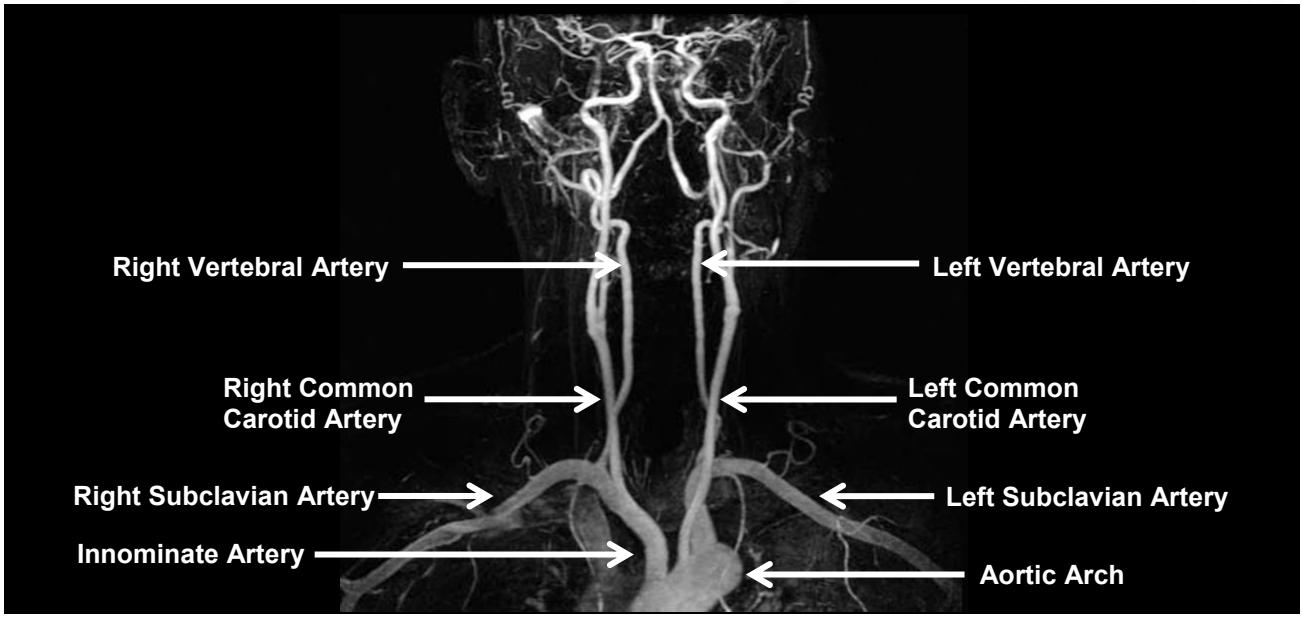



**Figure 23.** Normal vasculature of the neck.

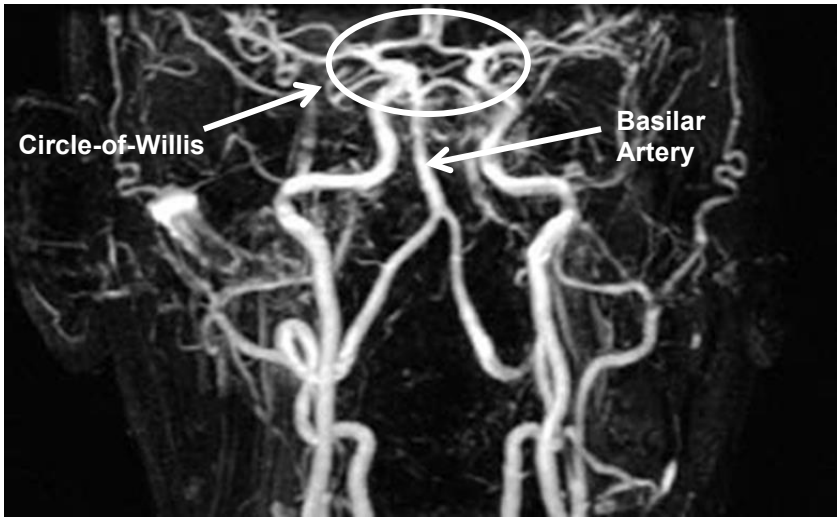



**Figure 24.** Intracranial vasculature.

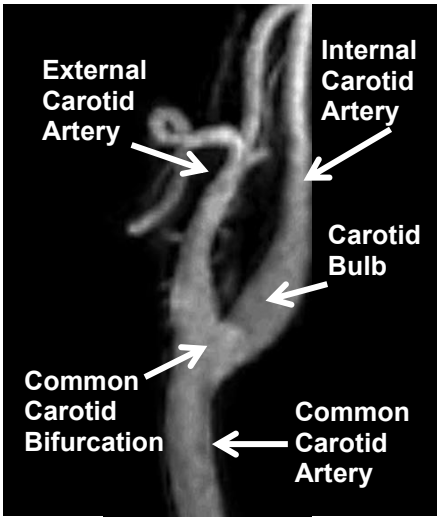



**Figure 25.** Normal carotid vessel.

**Figure 26.** Movie of MR angiogram. Cine MIP rotation of a contrast-enhanced 3D TOF of the neck. Aortic arch is demonstrated with three branches extending intracranially to the Circle-of-Willis. Contrast bolus injection was timed to maximize arterial enhancement while minimizing venous contamination. A significant stenosis is seen in the left internal carotid artery immediately distal to the carotid bifurcation. Click here to view the movie on the ICPMEducation channel.


**Figure 27.** Movie of MR angiogram. Targeted cine loop of the same 3D TOF series segmented to show only the bifurcation of the common carotid artery into the internal and external carotid arteries. These rotational views more precisely demonstrate a near 90% stenosis of the internal carotid artery. Click here to view the movie on the ICPMEducation channel.

*Movies courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

## MAGNETIC RESONANCE VENOGRAPHY (MRV)

Magnetic resonance venography can be performed by using one of several techniques, including 2D TOF, low-dose gadolinium-enhanced 3D MRV, and multiphase high-dose gadolinium-enhanced 3D MRA with image subtraction. In the latter technique, arterial phase MRA images, which contain only arteries, are subtracted from venous phase images, which contain both arteries and veins. Subtraction postprocessing to display only veins is performed as follows:

*Data set with arteries and veins* — *Data set with arteries only* = *Subtracted data set with veins only (MR venogram)*

Assessment of the veins of the brain is often indicated for symptoms arising from occlusion of the major cranial veins or venous thrombosis. MRV is used to assess the superficial (cortical) and deep cerebral veins, as well as the major dural sinuses, including the superior sagittal sinus, transverse sinus, sigmoid sinus, and jugular bulb **(Figure 28)**.

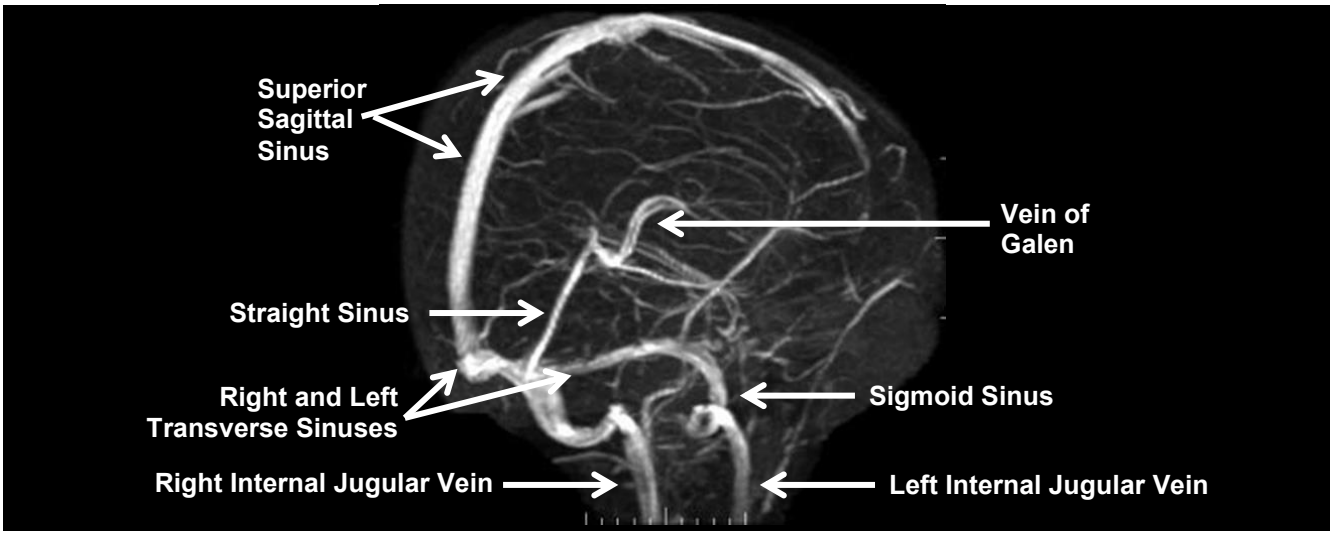



**Figure 28**. MRA of the brain.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

Venous angioma is a common, generally asymptomatic malformation. These cases represent anomalous venous drainage. Normally, venous malformations progress from the **ependymal** surface of the ventricle toward the periphery of the brain and are characterized by a ***caput medusae*** or tangle of abnormal medullary veins, converging into a prominent draining vein. Developmental venous anomalies (DVAs) are particularly visible after the administration of contrast. They tend not to bleed and lack **mass effect**. Not infrequently, cavernous malformations may be associated with venous angiomas and result in hemorrhage in the bed of the venous angioma **(Figure 29)**.

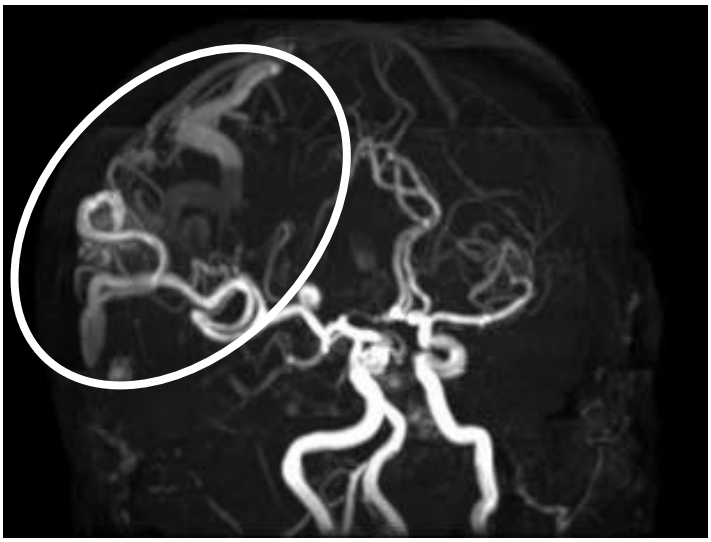


**Figure 29.** MRA/MRV MIP of large venous malformation draining from a posterior colloid cyst (circle).
*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

While techniques vary, TOF imaging is typically employed for MRV and in some cases contrast enhancement is used. Recall that TOF techniques suffer from artifacts that mimic thrombus when slow venous flow is in the same direction as the slice acquisition. For this reason, TOF techniques are often performed twice: once in the coronal direction (the y axis) to assess the left and right transverse sinuses and superior sagittal sinus in the AP direction and secondly in the axial (z axis) to assess the sagittal sinus in the superior-to-inferior direction.

Bolus timing is far less critical with contrast enhancement methods for MR venography. Since arterial enhancement is not desired, a long delay is programmed between the injection and data acquisition. Some arterial contamination is always present, but the lack of artifact from slow venous flow usually overrides this concern.

## Contrast-Enhanced Venography

Contrast-enhanced MR venography (CE MRV) provides information about the patency of venous structures. The identification of thrombus can be imperative to the health of a patient as thrombus has the potential to dislodge from its original location and form pulmonary emboli or cause stroke in the presence of abnormal arteriovenous communications. Several imaging techniques have proven capable of identifying thrombus and stenosis of veins in question, such as direct thrombus imaging and venous-enhanced subtracted peak arterial technique.

### Direct Thrombus Imaging

Direct thrombus imaging takes advantage of a predictable change in the T1 of blood as it undergoes clotting. When blood clots, T1 is substantially reduced and produces high signal intensity on T1-weighted images. Using a T1-weighted 3D technique that suppresses the signal from fat and nulls that from blood, direct clot images can be produced.

A 3D magnetization transfer T1-weighted sequence is used (TR 10.3, TE 4.0, flip angle 15, TI 20, FOV 350 x 300, matrix 256 x 160, 150 partitions, one acquisition, bandwidth 195). The high signal, short T1 material detected by MRI is likely to represent **methemoglobin**, an intermediate breakdown product of hemoglobin that occurs during clot maturation. False negative results may occur if imaging is carried out too soon, before T1 shortening has had time to take place, or too late, when further maturation of the clot results in hemosiderin formation and signal loss.

#### VENOUS-ENHANCED SUBTRACTED PEAK ARTERIAL TECHNIQUE

The venous-enhanced subtracted peak arterial technique uses multiphase contrast-enhanced 3D MRA data sets that allow the visualization of the arterial and venous vasculature. However, due to short arterial-to-venous bolus transit times, generation of pure venograms without arterial overlay is difficult. A 3D gradient echo sequence with (TE 2, TR 5) is used to acquire eight volumes. To suppress arterial signal in venograms, peak arterial phase data are subtracted from peak venous phase images.

## MRA OF THE BODY

### MRA of the Abdominal Aorta and Renal Arteries

Gadolinium contrast-enhanced 3D MRA is a safe and reliable technique for diagnostic evaluation of the abdominal aorta and major aortic branch arteries. The safety and accuracy of MRA make it an ideal choice for screening and diagnostic angiography of the abdominal aorta, renal, and visceral arteries; however, interventional procedures like angioplasty and stenting still require conventional digital subtraction angiography. CE MRA has largely replaced nonenhanced MR angiographic techniques such as TOF and phase contrast in the abdomen. Typical MR imaging protocols for the abdominal vasculature involve a combination of spin echo techniques and contrast-enhanced 3D gradient echo imaging. Total examination time averages 20 to 40 minutes. Both conventional CE MRA and ultrafast noncontrast cine angiography techniques are discussed in this section as they apply to abdominal aortic imaging **(Figure 30)**.

**Gadolinium contrast-enhanced 3D MRA is a safe and reliable technique for diagnostic evaluation of the abdominal aorta and major aortic branch arteries.**

In the early to mid-1990s, it was common to use phase contrast imaging in conjunction with TOF to determine whether or not a site of stenosis revealed on TOF was significant. Remember that phase contrast uses the velocity differences in flowing blood, resulting in the phase shifts in moving spins and providing image contrast in flowing vessels. Basically, if a flow void was seen on phase contrast imaging distal to the site of stenosis demonstrated by TOF imaging, the stenosis was considered hemodynamically significant. With the introduction of CE MRA techniques and movement to high spatial resolution matrices (512 x 512), TOF and phase contrast are not typically performed in this particular application because of their longer imaging times and reliance on flow-related enhancement.

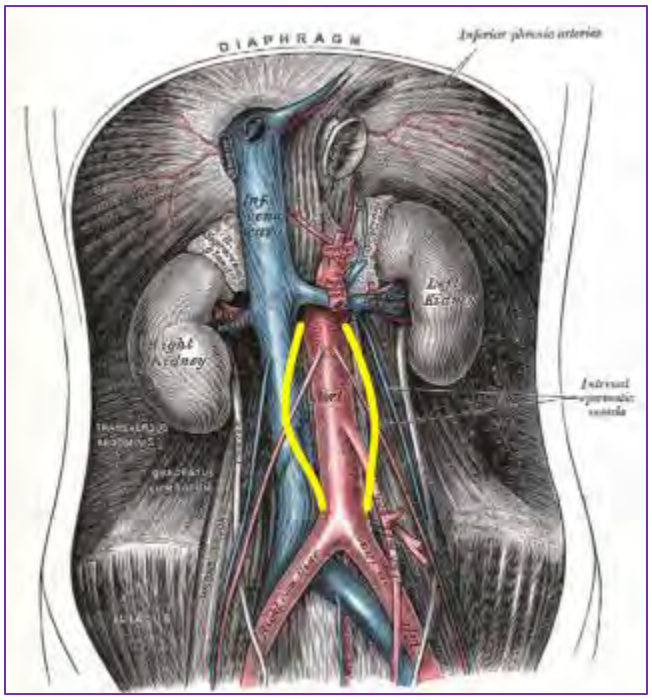



Figure 30. Abdominal aorta and renal arteries.

*Available at:* Wikimedia Commons.



## GENERAL ABDOMINAL EXAM

The general abdominal MRA examination begins with scout images of the abdomen in the three standard anatomic planes: axial, coronal, and sagittal. A rapid series of breath-held 2D images may also be obtained for a slightly more comprehensive overview of the abdomen or specific organ in question. These anatomical images are performed with single-shot fast spin echo (SSFSE) techniques (HASTE, Siemens) or steady-state sequences (FIESTA, GE Healthcare) in the axial or coronal plane. Using these reference images for localization, a suitable volume of tissue is selected for imaging that includes the arterial vasculature clinically in question. The typical imaging volume obtained is a slab in the coronal or slight coronal oblique orientation, utilizing a 256 or 512 matrix, depending on the capabilities of the MR unit. A rectangular field of view is applied to reduce the number of phase encoding steps, thereby reducing the overall acquisition time **(Figure 31)**.

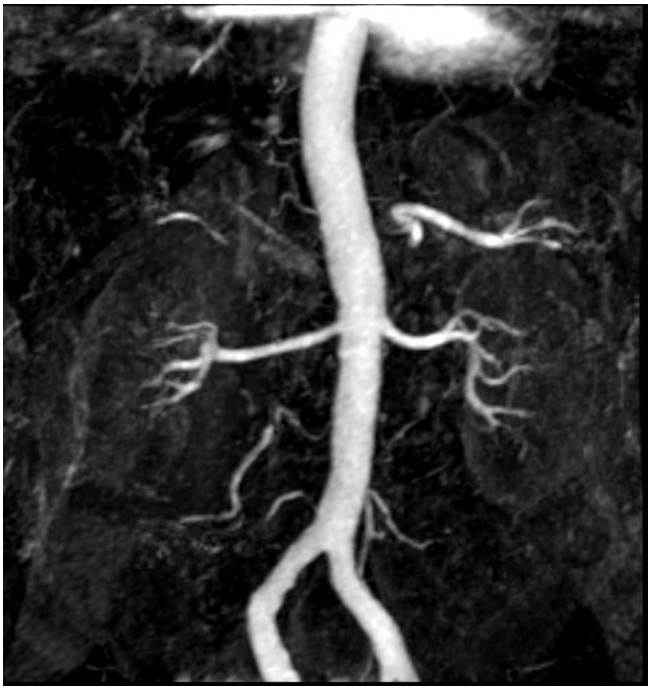


Figure 31. MRA of the abdominal aorta.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA.*

In abdominal MRA, there is one important overriding principle: the required spatial resolution is roughly proportional to the length of time necessary to image a given volume of tissue. However, directly opposed to this tenet is the fact that abdominal imaging must be obtained within a comfortable breath-hold, critical to obtaining quality CE MRA images as the primary cause of suboptimal abdominal MRA images is respiratory motion during the scan. To a lesser degree, patient movement, bowel peristalsis, and arterial pulsation also degrade image quality. Crucial tradeoffs exist between the length of scanning time and spatial resolution, and these must always be weighed when optimizing imaging parameters. TR and TE are set to a minimum, which is typically TR = 4 milliseconds and TE = 1.5 milliseconds. Flip angles are generally 25° to 40°. *k*-space sampling is either asymmetric ordering or centric ordering, based on the MR equipment vendor. Slice interpolation is always utilized to improve effective partition thinness and reduce partial volume averaging effects. Typical gadolinium contrast doses vary depending on contrast manufacturer and chelate concentration. Typical injection volumes range between single and double doses for abdominal MRA exams (0.1–0.2mmol/kg). Automated power injectors are preferable because they allow rapid injections while providing a more homogeneous bolus profile.

For most abdominal MRA, bolus timing to arrival of contrast in the abdominal aorta at the level of the artery in question is easily attained (refer to the section above on bolus timing techniques). A 3D gradient echo image is obtained in a breath-hold in the sagittal or coronal plane through the abdominal aorta; bolus timing can be applied in any plane. The timing of test bolus contrast arrival at the desired level of the aorta, ie, celiac axis, superior mesenteric artery, or renal arteries is used on the subsequent diagnostic scanning run as the time at which to begin scanning after the administration of contrast. Several formulas exist for determining the appropriate time at which to scan after the administration of contrast.

Ringing artifacts can result from acquiring the central lines of *k*-space too early while the concentration of contrast arriving in the scan volume arteries is rapidly increasing to its peak plateau. In reality, a bolus injection of 15-second duration spaces out approximately an additional 20% (3 seconds in this example) related to the fact that the contrast within the blood pool is diluting out to a volume greater than injected.

Fluoroscopically-triggered versions of intravascular contrast detection are increasing in popularity. "MR fluoroscopic" schemes allow direct visualization of contrast arrival in the desired vascular distribution with a real time 2D acquisition, which is typically updated every second. The CE MRA acquisition can then be triggered either manually or automatically with the visualization of contrast arrival.

Dissection and aneurysms are frequent clinical questions in the evaluation of the abdominal aorta. CE MRA only reveals details of the aortic lumen but very little information about the aortic wall or mural thrombus. To more comprehensively evaluate for aortic disease, including dissection, aneurysm rupture, and intramural hematoma, 2D fat-saturated gradient echo axial images are often obtained before and after the CE MRA acquisitions. These sequences are rapid breath-held sequences and therefore add no more than a minute or two to the total examination time. Alternatively, cine steady-state techniques can be used for imaging thoracic aortic disease. By adding these noncontrast imaging techniques, a short protocol of less than four minutes has been shown to be accurate in excluding or confirming the presence of dissection or aneurysm in the thorax.



### RENAL EXAM

Renal MR angiography is one of the most frequently used applications of abdominal MRA. Estimates of hypertension due to disease of the main renal artery range from 1-10% of all cases of hypertension. Understanding its etiology is crucial as hypertension caused by renal artery disease is one of the only curable causes of hypertension. Historically, Doppler ultrasound and nuclear medicine studies have been the screening modalities of choice for renal vascular hypertension. However, each of these techniques has significant limitations. Although Doppler ultrasound is noninvasive, relatively inexpensive, and widely available, the accuracy of this examination is highly operator-dependent and less sensitive than MRA. In addition, the patient's body habitus, ie, obese or high acoustic impedance, can be a limiting factor. Nuclear medicine studies are invasive, relatively expensive, and rely on nephrotoxic contrast agents.

**Understanding disease of the main renal artery is crucial as hypertension caused by renal artery disease is one of the only curable causes of hypertension.**

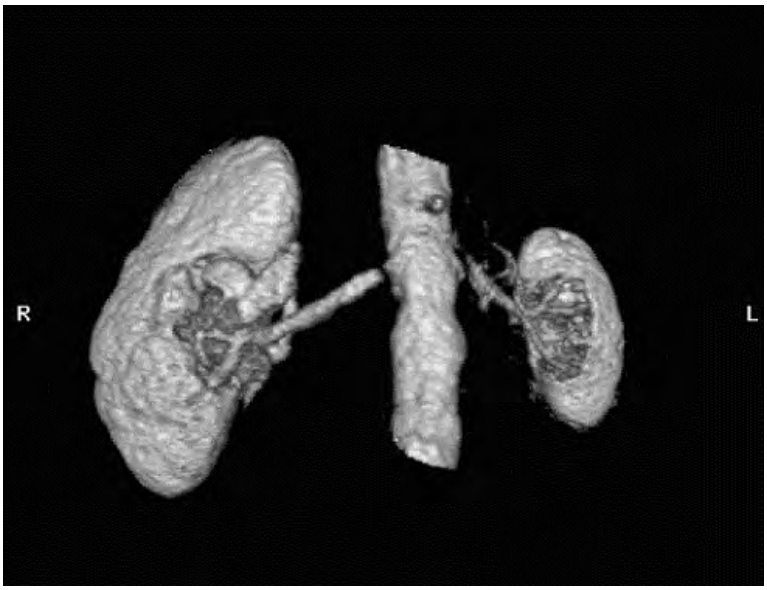



**Figure 32.** Volume rendered 3D MRA image illustrating bilateral proximal renal artery stenoses.

*Courtesy of F. Scott Pereles, MD, Northwestern Memorial Hospital.*

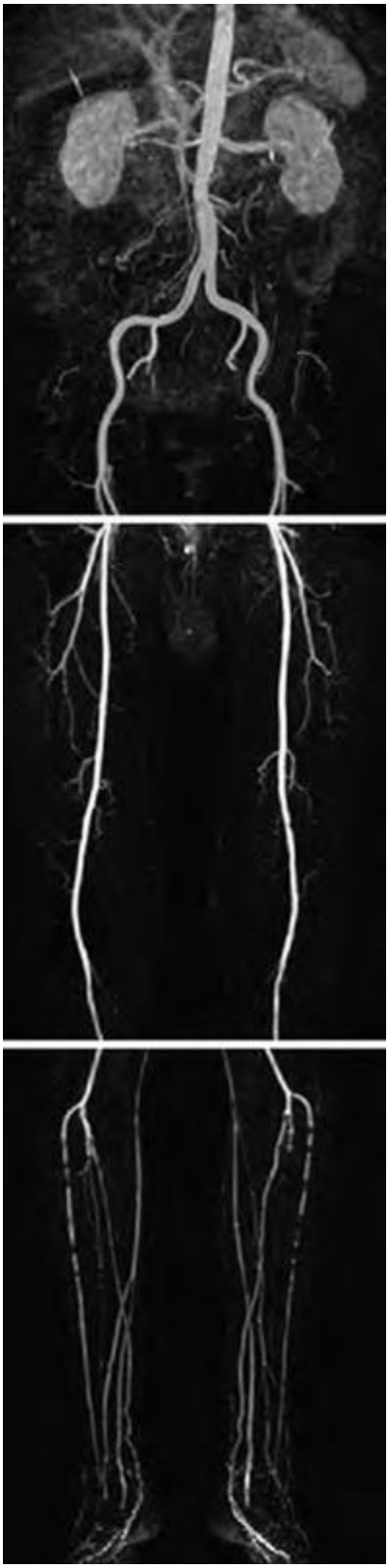
Contrast-enhanced renal MRA is relatively noninvasive, allows true 3D visualization, and uses a contrast material that has an exceptionally high safety profile as compared to other imaging modalities. Although there are some limitations, MRA is less operator-dependent and also less restricted by body habitus than ultrasound. Renal MRA provides significant spatial resolution and reveals true anatomical information of the renal pelvis as well as kidney parenchyma **(Figure 32)**.

Technical parameters for renal MRA are similar to those for other abdominal MRA exams; however, the imaging volume is placed more posterior within the abdomen to cover the retroperitoneum and expected course of the renal arteries from the aorta. The straight coronal or slight coronal oblique acquisition volume is placed with its anterior margin just anterior to the aorta as a reference structure. This ensures coverage of the left renal vein, which typically courses just anterior to the aorta and just posterior to the superior mesenteric artery. The posterior margin of the slab is then adjusted to include the posterior aspect of the kidneys. Typical slab thickness ranges from 60 to 100mm. The thinner the slab, the thinner effective partitions can be made, which increase through-plane spatial resolution for improved multiplanar reformatted 3D reconstructions.

## MRA of the Aortoiliac and Femoropopliteal Vessels

### STEPPING TABLES

In order to evaluate vasculature from the abdominal aorta through the lower extremities, the use of stepping tables is necessary to “chase the bolus” down the length of the body from the midsection to the feet.



Mobile MR tables, also called “stepping tables,” are available for all MR systems, and most high-field systems are equipped with an automated stepping table built into the MR hardware system. The primary application of a stepping table is to provide an automated method for doing the MR peripheral runoff exam. In this application, a bolus of contrast is injected and then, through careful timing, the patient is imaged in stations to essentially chase the bolus from the mid-abdominal aorta to the feet.

The automated stepping table is motorized and controlled remotely from the MR console without need for intervention in the scan room. The scan operator can reposition the table and perform multiple scans directly from the scan console without entering the scan room or repositioning the table or the patient, increasing patient safety and comfort.

### APPLICATION TO PERIPHERAL RUNOFF MRA

A complete peripheral MRA runoff can be acquired using a single bolus of IV contrast. The patient initially is positioned at the first anatomic station. Contrast is injected and the first set of images acquired. Next, the table is moved a specific distance, typically 30–45 cm, to center the patient towards the lower extremities, and the acquisition is repeated. The process continues until a complete angiographic set is acquired within the single contrast bolus. The entire process can be completed in as little as 15 minutes of imaging time and can cover 75–150 cm of anatomy **(Figure 33)**.

**Figure 33**. An example of a MR peripheral runoff exam. Note the coverage of the exam from superior to the renal arteries to the level of the feet. Also note the boundaries between “stations” indicating the three levels of scanning from the abdomen (upper station), lower pelvis and femoral areas (middle station), and lower legs (lower station).

*Courtesy of F. Scott Pereles, MD, Northwestern Memorial Hospital.*

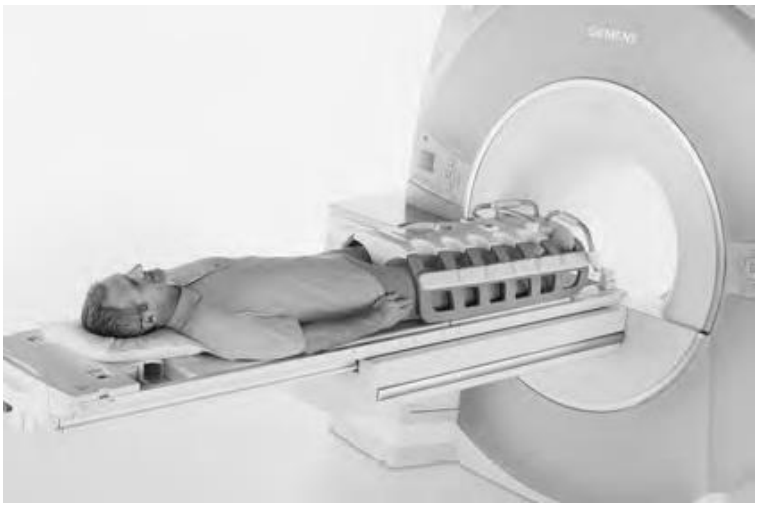


**Figure 34.** Example of placement of a run-off coil used for imaging blood vessels of the legs.

*Courtesy of Siemens.*

Acquisition of such a large field-of-view without repositioning the patient is most efficiently performed using an appropriate set of coils. Dedicated peripheral vascular coils are available from a variety of vendors **(Figure 34)**. Alternatively, multiple coils covering the anatomy of interest can be applied simultaneously by manually switching the coil used at each station. Some MR systems are capable of automatically switching to the coil set covering the current anatomic station.

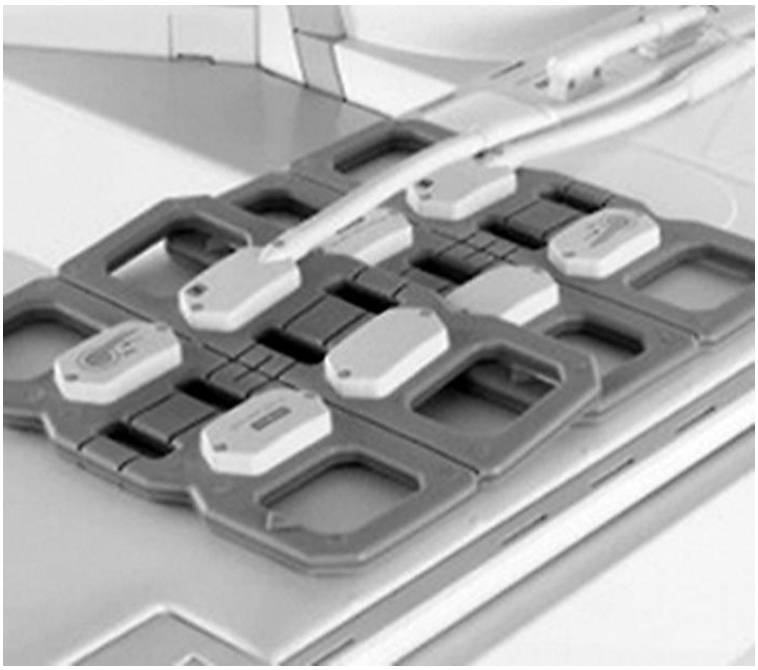


**Figure 35.** 16-channel phased array coil.

*Courtesy of GE Healthcare.*

Other examinations that take advantage of a stepping table for an extended field-of-view include abdominal and pelvic vascular imaging and whole body imaging for metastatic surveys.

### CONTINUOUS TABLE MOVEMENT

Advances in technology have made it possible to allow the table to continuously advance during the image acquisition. The advantage of a continually moving table is that the data acquisition is continuous throughout the entire runoff exam. In addition, the speed of the automatic table advance can be adjusted to track the movement of the contrast bolus, ensuring that the timing of the images at each location is correct so that the arterial phase is seen throughout, preventing **venous contamination**.

#### DUAL INJECTION

Timing of a single bolus arrival from renal arteries to the ankle region can be difficult even when using automated stepping tables. To obtain optimal timing for upper stations as well as middle and lower stations, many facilities employ a dual injection technique in both the pelvis and calves to avoid timing errors in the most distal station. In addition, acquisitions of the feet are obtained before imaging of the pelvis and thighs to minimize venous contamination and background signal. Often one bolus injection is done to obtain high resolution MRA of the calves into the feet.

A second injection is done to obtain high quality MRA of the abdomen/pelvis (upper station) and the thighs (middle station). This second injection employs the automated stepping table for the two stations.

#### PARALLEL IMAGING

Parallel imaging techniques use a reordering of *k*-space to drastically reduce scan time at the cost of signal-to-noise ratio. Examples of parallel imaging techniques are SENSE (Philips Medical), ASSET (GE Healthcare), and iPAT (Siemens Medical) and can be used to improve acquisition speed and reduce incidence of venous contamination.

### Contrast-enhanced MRA of the Aortic Arch and Thoracic Aorta

Evaluation of the aortic arch and thoracic aorta with MRA is a simple, minimally invasive, time-efficient examination.

A phased array body/torso coil is recommended for evaluation of these sections of the aorta **(Figure 35)**. As always, proper patient education is essential for all examinations. Having an informed patient can prevent movement, insufficient breath-holds, and the resultant misregistration on subtracted images. Total comprehensive examination time averages 30 minutes.

Although protocols will vary from one imaging facility to the next, general evaluation of the aortic arch and thoracic aorta begins with axial imaging from the top of the arch to the diaphragm, using both **bright-blood** (steady-state imaging) and **black-blood** (double inversion recovery-[IR]) prepped imaging techniques **(Figures 36)**. Cine steady-state techniques are also useful for evaluating blood flow through the aorta. If coarctation of the aorta is present, 2D phase contrast imaging can be done to obtain quantitative flow gradient information across the coarctation. All of these techniques require cardiac gating.

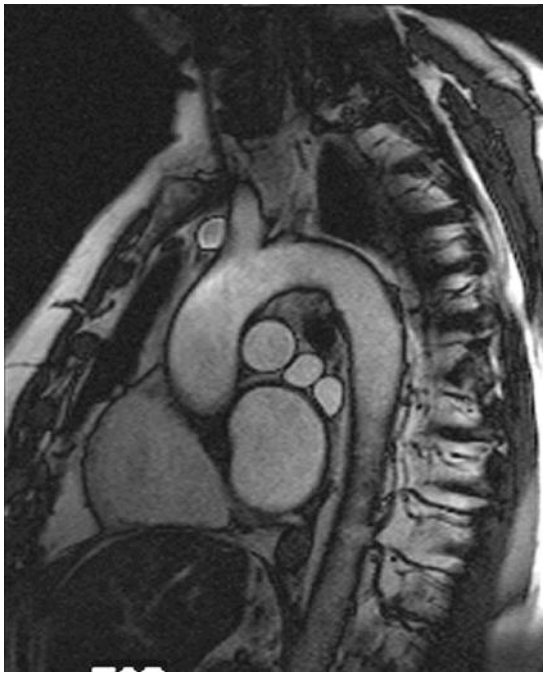


**Figure 36.** Normal aorta, left anterior oblique single slice true fast imaging with steady-state precession.

*Courtesy of F. Scott Pereles, MD, Northwestern Memorial Hospital.*

Conventional contrast-enhanced MRA also requires matching of data acquisition and bolus arrival using either real-time or prior information, such as manual timing runs (range of 12 to 17 runs).

The contrast injection protocol for contrast-enhanced MR angiography involves the use of an automatic injector. The amount of gadolinium-based contrast agent and the rate of injection are dependent on the contrast agent type and manufacturer's recommendation for volume and rate of injection. Individual facility preferences also play a role in injector parameters. A pre-injection "mask" acquisition is typically obtained just before the contrast injection run. Subtraction of the first data set from all subsequent data sets is performed on-line as on-axis MIP reconstruction. Therefore, the subtracted images, the unsubtracted images, and MIP images of each phase are available for viewing within two minutes of injection. The MIP images are time-stamped and used in place of a timing run for any subsequent high spatial resolution MRA.

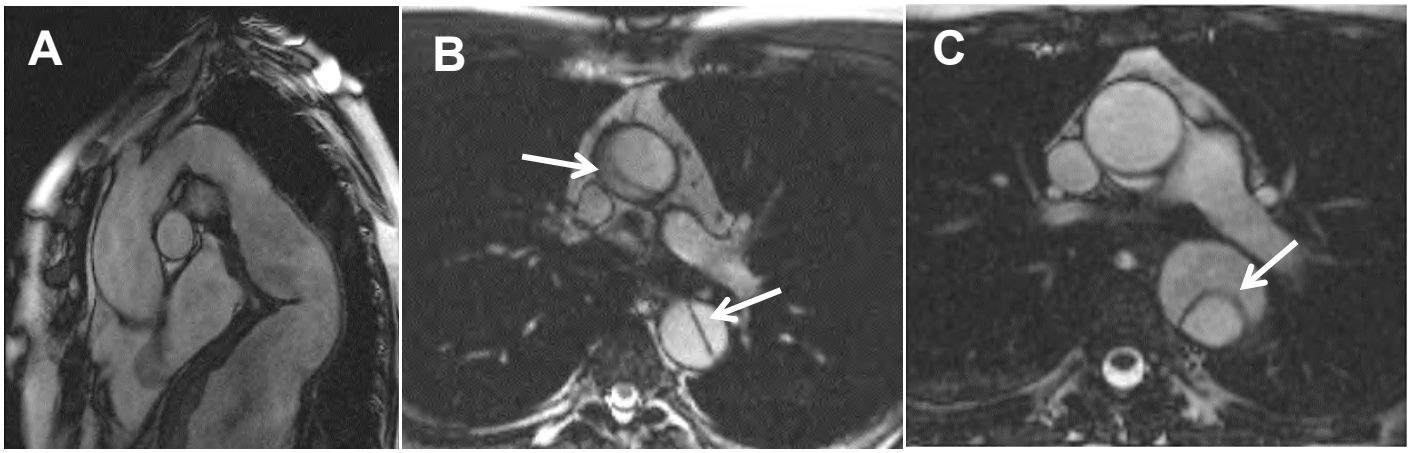



**Figure 37A-C. (A)** Multiple sites of aortic aneurysm, sagittal oblique single slice steady-state precession. **(B) Stanford type** A aortic dissection. **(C)** Stanford type B aortic dissection.

*Courtesy of F. Scott Pereles, MD, Northwestern Memorial Hospital.*

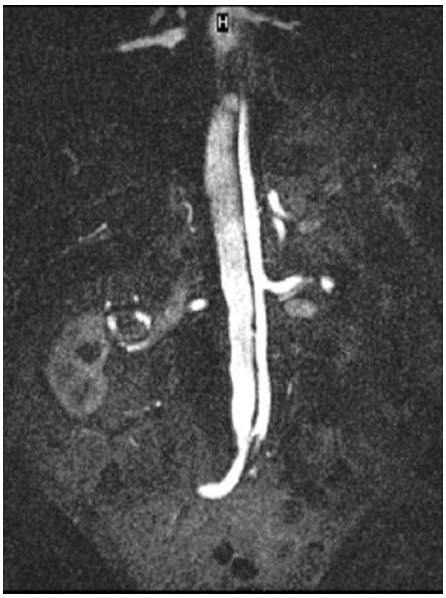


**Figure 38.** Source image from high spatial resolution CE MRA demonstrates dissection flap in thoracoabdominal portion of a Stanford type B aortic dissection.

*Courtesy of F. Scott Pereles, MD, Northwestern Memorial Hospital.*

Contrast-enhanced MRA requires the use of a bolus-timing technique. The particular technique used is up to the individual facility and the capabilities of the MRI system. 3D MRA allows resolution of distinct right- and left-heart enhancement phases. In patients with aortic aneurysms, 3D MRA clearly shows the temporal filling patterns and can demonstrate differential flow within true and false lumens of dissections. A disadvantage of the dynamic, subsecond data acquisition is the requirement for rapid bolus injection into a vein. Slower infusion rates tend to offset the advantage of high temporal resolution acquisition. Breath-hold times tend to be greater than 20 seconds **(Figures 37 and 38)**.

Remember that 3D MRA is truly a luminogram and lacks any revealing information about the aortic wall or surrounding anatomy. The pulmonary arterial, pulmonary venous, and systemic arterial phases of vascular enhancement can all be well defined by using time-resolved techniques to guide the timing of higher spatial resolution 3D acquisitions. Pathology identified with these techniques includes patent ductus arteriosus, atrial septal defect, and coarctation of the aorta. Another aspect of rapid MR angiographic imaging is the potential to measure circulation times.

## Contrast-enhanced Pulmonary MRA

Contrast-enhanced pulmonary MR angiography is an alternative to conventional angiography and computed tomographic angiography (CTA) for the analysis and evaluation of pulmonary circulation and morphology. Because of its less invasive technique and non-nephrotoxic, low-allergenic contrast media, MR angiography of the pulmonary vessels is commonly used for diagnosis and evaluation of pulmonary vascular disease.

Pathological conditions of the pulmonary vasculature include stenosis of the pulmonary arteries caused by thromboembolism or external compression (neoplastic disease), congenital cardiovascular anomalies, arteriovenous malformations (AVM), and pulmonary hypertension. Given its life-threatening potential, evaluation of pulmonary embolism is the most critical indication for pulmonary angiography.

**A major difference between evaluation of the aorta and the pulmonary arteries is that where the 3D contrast-enhanced series is usually a sagittal acquisition of the aorta, it is a coronal acquisition for the pulmonary arteries.**

Pulmonary thromboembolism is characterized by the transport of a fragment of thrombus from the systemic veins to the pulmonary circulation and impaction in the pulmonary arteries. The majority of cases of pulmonary emboli arise from the deep veins of the legs, pelvic veins, and inferior vena cava (IVC). The pulmonary arteries originate at the pulmonary valve via the right atrium and divide within the pericardium into the right and left branches. Pulmonary arteries take their course along the bronchial tree. Pulmonary veins run separately from the arteries, extend toward the left atrium, and can be distinguished by their lack of accompanying bronchi.

The techniques used in pulmonary angiography require high performance gradients with gradient amplitudes of 30 mT/m or higher and peak slew rates of 100 mT/m/msec or faster. Patient preparation includes informing the patient that breath-holding is required during the test. A phased array body/torso coil is recommended and should be placed over the thorax. Cardiac gating is employed for 2D morphological imaging, just as with MR evaluation of the aorta.

Typical imaging protocols closely approximate those used for evaluating the ascending aorta in that 2D gated bright-blood imaging is obtained prior to the 3D contrast series. The bright-blood sequences, typically a steady-state technique, are done in short breath-hold times and often include cine steady techniques. As with evaluation of the aorta, a bolus-timing technique is used in accordance with facility preferences and system capabilities. A major difference between evaluation of the aorta and the pulmonary arteries is that where the 3D contrast-enhanced series is usually a sagittal acquisition of the aorta, it is a coronal acquisition for the pulmonary arteries.

In pulmonary MRA, as in evaluation of the aorta, the first image set is a precontrast acquisition and used as a mask for subtraction from the postcontrast acquisition. A MIP is then created from the subtraction of the first and second high spatial resolution measurements **(Figures 39 and 40)**. The subtractions contain opacified pulmonary arteries and veins. The partition data provide detailed angiographic information of the segmental and subsegmental vessels.

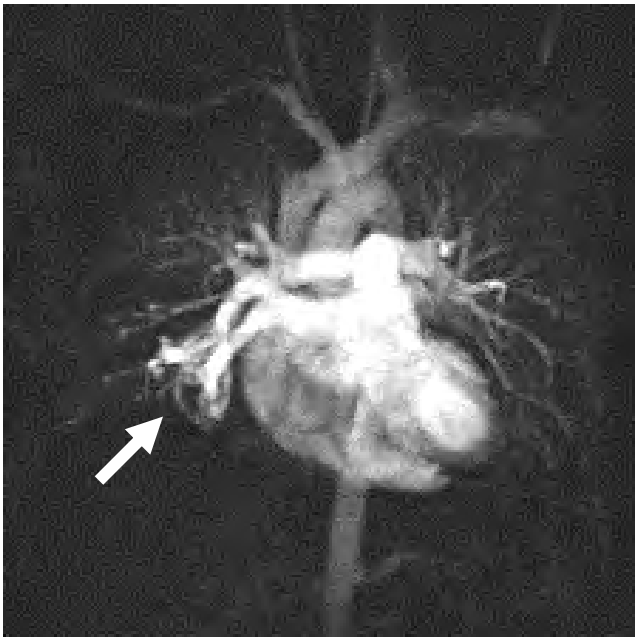


**Figure 39.** Single subtracted MIP image from subsecond MR angiography showing a pulmonary AVM in the right lower lobe (arrow).

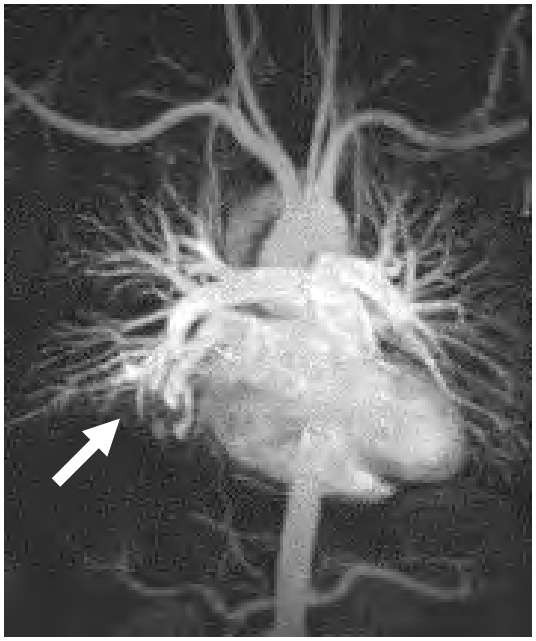


**Figure 40.** MIP image from high spatial resolution CE MRA showing a pulmonary AVM in the right lower lobe (arrow).

*Courtesy of F. Scott Pereles, MD, Northwestern Memorial Hospital.*

## Basic Coronary Artery MRA

Accurate imaging of the coronary arteries is crucial to the diagnosis and treatment of patients with coronary artery disease (CAD). X-ray angiography with contrast has long been the gold standard for this indication; however, this type of angiography is highly invasive, exposes the patient and physician to radiation, and carries a small but significant risk of complications. In addition to these limitations, coronary angiography delivers only morphological information and is incapable of providing flow data, which is valuable to any cardiac study.

Coronary CT angiography has surpassed x-ray angiography as the method-of-choice for evaluation of the coronary arteries **(Figure 41)**. Coronary CTA has the advantage of being extremely fast (often a single breath-hold for a complete exam) and yields images of high spatial resolution. However, CTA has the disadvantage of exposing the patient to ionizing radiation, and patients with compromised kidney function may be contraindicated for iodine-based contrast agents.

Advances in technology and pulses sequences have made MRA an increasingly appealing alternative to conventional coronary angiography, particularly in the evaluation of anomalous coronary arteries.

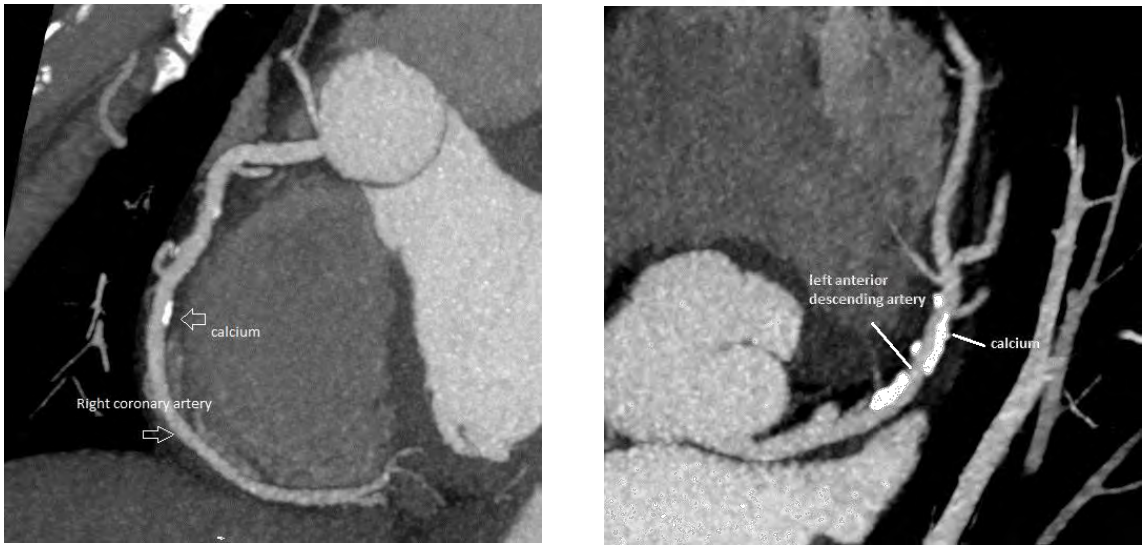



**Figure 41.** Coronary artery CT angiography.

*Courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA*.

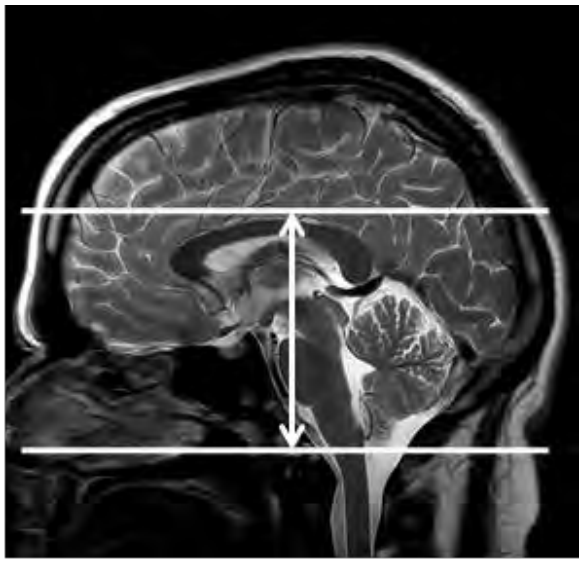
A number of fast imaging techniques allow for good visualization of the epicardial coronary arteries without the aliasing artifacts associated with respiratory and cardiac motion. The most commonly used method is multiphase gradient echo with fat suppression, which acquires images during 16-beat cardiac cycles and a single 15-20 second breath-hold. As compared to CTA, however, cardiac MRA offers lower spatial resolution, preventing optimal imaging of the coronary artery wall. Thus a combination of black-blood and bright-blood images is used to complete the picture.

The ability of MRA to provide 3D images is a distinct advantage in visualizing small coronary vessels and differentiating them from adjacent tissues, particularly in identifying potential anomalies. Both black-blood (IR-prep-based techniques) and bright-blood (steady-state techniques) sequences have demonstrated utility in assessing vessel patency after bypass grafting procedures, and other methods such as flow-mapping and 3D contrast-enhanced MRA have also shown promise. Likewise, MR coronary artery imaging is useful in the evaluation of blood flow in patients who have undergone other types of cardiac surgery, including transplantation. These applications are not used widely in clinical imaging. As technological developments continue, coronary MRA promises to become an extremely versatile and accurate tool for CAD detection and treatment.

## SUMMARY

MR angiography remains a robust application in the daily clinical practice of most MRI facilities. Ultrafast gradients, specialized coils, faster reconstruction processes, and power injectors provide highly diagnostic images of the vasculature, rendering the information provided by MRA an essential component of the patient's examination and treatment.

## PROTOCOLS

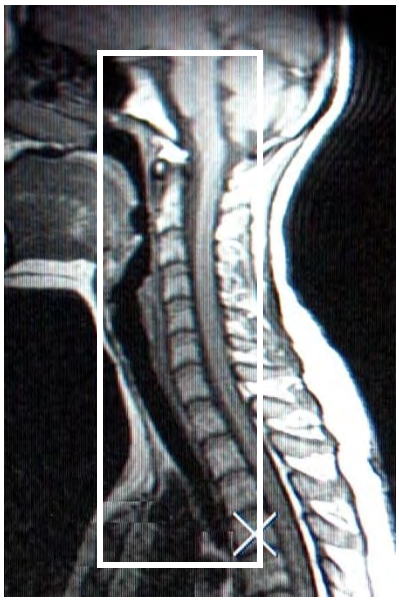


### Intracranial MR Angiography Protocol

**Axial 3D TOF multi-slab**

Coverage:
From foramen magnum to the top of the corpus callosum

Slice Thickness: ≤ 1.5mm



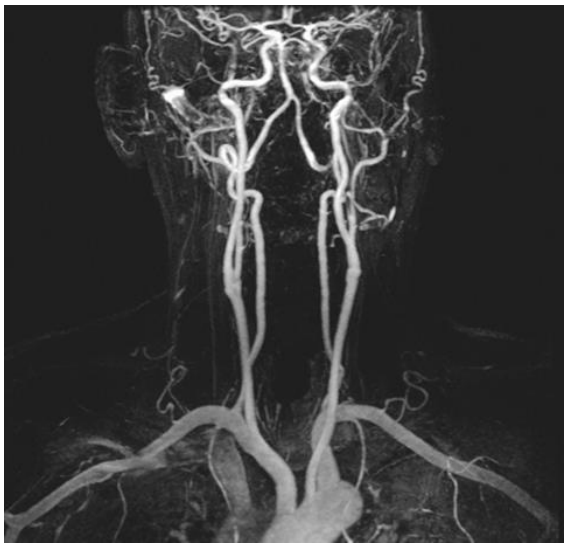
### MR Angiography of the Neck Protocol

**Coronal 3D contrast-enhanced**

Coverage:
From aortic arch to the Circle-of-Willis. Include basilar and vertebral arteries through carotid siphon

Slice Thickness: ≤ 1.5mm

In this exam, some form of bolus timing technique is performed.



*Protocols courtesy of Thomas Schrack, BS, ARMRIT, Fairfax Radiological Consultants, Fairfax, VA*

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## GLOSSARY OF ACRONYMS

| | |
|---|---|
| **2D** | two-dimensional |
| **3D** | three-dimensional |
| **ACA** | anterior cerebral artery |
| **ACR** | American College of Radiology |
| **AE** | adverse event |
| **AERS** | Adverse Event Reporting System |
| **AVM** | arteriovenous malformations |
| **$ß_0$** | strength of the local magnetic field |
| **CAD** | coronary artery disease |
| **CE MRA/MRV** | contrast-enhanced magnetic resonance angiography/venography |
| **CNS** | central nervous system |
| **CTA** | computed tomographic angiography |
| **FDA** | Food and Drug Administration |
| **FOV** | field of view |
| **GBCA** | gadolinium-based contrast agent |
| **GRE** | gradient echo (also gradient recalled echo) |
| **IR** | inversion recovery |
| **IV** | intravenous |
| **IVC** | inferior vena cava |
| **kg** | kilogram |
| **m** | meter |
| **MCA** | middle cerebral artery |
| **mg** | milligram |
| **MinIP** | minimum intensity pixel projection |
| **MIP** | maximum intensity pixel projection |
| **mL** | milliliter |
| **mm** | millimeter |
| **mmol** | millimole |
| **MRA** | magnetic resonance angiography |
| **MRI** | magnetic resonance imaging |
| **MRV** | magnetic resonance venography |
| **msec** | millisecond |
| **mT** | milliTesla |
| **NSF** | nephrogenic systemic fibrosis |
| **PACS** | picture archiving and communication system |
| **PC** | phase contrast |
| **PCA** | posterior cerebral artery |

| | |
|---|---|
| **RF** | radiofrequency |
| **ROI** | region of interest |
| **sec** | second |
| **SNR** | signal-to-noise ratio |
| **SSFSE** | single-shot fast spin echo |
| **SWI** | susceptibility-weighted imaging |
| **T** | Tesla |
| **TE** | echo time |
| **TI** | inversion time |
| **TOF** | time-of-flight |
| **TR** | time to recovery |
| **VENC** | velocity encoding value |
| **Ω** | Larmor frequency |
| **ɣ** | gyromagnetic ratio |

## GLOSSARY OF TERMS

**algorithm**
a step-by-step process for solving a problem or achieving a goal

**aliasing**
a common artifact caused when the field-of-view selected is smaller than the area of tissue excited; also known as “wrap-around”

**aneurysm**
ballooning of a segment of a vein or artery resulting from disease or weakness of the vessel wall

**angiography**
an imaging technique used to visualize the inside of blood vessels or organs, especially the arteries, veins, and heart chambers

**arteriogram**
imaging of the lumen of arteries using a contrast agent

**bipolar gradients**
application of gradient pulses applied in equal but opposite magnitudes

**black-blood MRI**
sequences designed to null the signal of flowing blood so that vessels can be assessed without interference from a bright-blood signal; usually inversion recovery techniques

**bolus**
in CE MRA, a single full dose of a gadolinium-based contrast agent given in order to deliver the agent to an area of interest in a predictable amount of time

**bright-blood MRI**
sequences designed to show blood as hyperintense as compared to other tissues; usually steady-state imaging techniques

**caput medusae**
appearance of distended or engorged veins

**cine**
in MRI, the recording of images in such a rapid fashion that the images can be displayed in a movie loop to demonstrate real-time movement or function as with cardiac imaging or rapid contrast uptake imaging

**dephasing**
the loss of phase coherence of spins in the transverse plane (x, y)

**echo time (TE)**
echo delay time; time interval between the initial RF pulse and the first echo of a pulse sequence

**ependymal**
pertaining to the membranes lining the ventricles of the brain and the central canal of the spinal cord

**flip angle**
angle by which the net magnetization vector rotates after an RF excitation pulse; the amount of the tip measured in terms of the angle between the original $B_0$ axis and the angle of the precession

**hemosiderin**
an insoluble form of intracellular storage iron and by-product of hemorrhagic stroke

**infarct/infarction**
a necrotic area of tissue caused by loss of blood flow

**inhomogeneity**
imperfections in the main magnetic field ($B_0$) that may occur as one area of the field deviates from the average magnetic field strength

**in-plane flow**
flowing blood that runs parallel to slice orientation

**ischemia**
restriction in the blood supply

**_k_-space**
the domain in which the information from the phase-encoding step is placed during a pulse sequence. Each line of *k*-space corresponds to each phase-encoding step; once the required amount of *k*-space is filled, image reconstruction with a Fourier transform can begin.

**Larmor frequency**
The frequency at which magnetic resonance is produced in a sample of hydrogen nuclei or other types of nuclei used in MRI; the frequency at which the hydrogen nuclei precess when disturbed from their alignment in the $B_0$ magnetic field. Named for Irish physicist and mathematician, Joseph Larmor (1857-1942).

**lumen**
the inside of an artery or vein; does not pertain to the vessel wall itself

**mass effect**
usually described in the brain, it is the visualization of brain tissue being displaced by some invading disease process such as a malignant tumor

**methemoglobin**
a compound formed from hemoglobin by oxidation. A small amount is found in the blood normally, but injury or toxic agents convert a larger proportion of hemoglobin into methemoglobin, which does not function as an oxygen carrier.

**nephrogenic systemic fibrosis (NSF)**
a rare and serious condition that has been associated with the use of gadolinium-based contrast agents in patients with end-stage kidney disease

**non-ferrous**
not related to or containing iron

**osseous tissue**
bone tissue, which is the major structural and supportive connective tissue of the body

**paramagnetic**
an element that is slightly attracted to a magnetic field, eg, gadolinium. A paramagnetic substance may significantly reduce T1 and T2 relaxation times and/or amplify the external magnetic field produced by the MRI system.

**phase coherence**
state in which rotating objects move in phase or unison

**phase contrast imaging (PC)**
an imaging technique that applies extra gradient pulses that are sensitive to moving tissues or flowing blood. Compared to time-of-flight imaging, phase contrast imaging typically has lower resolution but can measure the direction and velocity of blood flow.

**pixel**
the smallest discrete part of a digital image display; from “picture element”

**radiofrequency (RF) excitation pulse**
the radiofrequency pulse that causes magnetic resonance

**saturation band**
the application of a specific pre-saturation RF pulse at the beginning of a pulse sequence to suppress unwanted tissue signal. Specific to MRA, saturation bands are used to eliminate unwanted blood flow, eg, saturating jugular flow when imaging the carotid arteries.

**spatial misregistration**
in MRI, an artifact caused by chemical shift, which occurs when the resonant frequency properties of fat and water cause a pixel shift in frequency in the image

**Stanford Type dissection**
a means for classifying aortic dissection. Stanford type A involves the ascending aorta and/or aortic arch and possibly the descending aorta and is usually treated surgically. Type B involves the descending aorta or the arch without involvement of the ascending aorta and is usually treated medically.

**stenosis**
abnormal narrowing of a vessel

**thrombosis/thrombus**
the formation of a blood clot

**through-plane flow**
blood flow that is perpendicular to the slice orientation

**time-of-flight imaging (TOF)**
a pulse sequence specifically designed to make stationary materials appear dark, while moving tissues such as blood appear bright. The resulting image shows only flowing blood, which in turn provides an outline of the blood vessels.

**time to inversion (TI)**
in an inversion recovery pulse sequence, the time allowed from the initial 180° excitation pulse until the 90° pulse; TI determines the amount of T1 recovery time for a given tissue

**time to recovery; repetition time (TR)**
time interval from the beginning of one pulse sequence to the beginning of the next. Used to control the amount of T1 image contrast desired in the resultant image acquisition.

**tinnitus**
a sensation of ringing or roaring caused by disturbance of the auditory nerve

**tracker**
in an automated bolus detection MRA pulse sequence, a small-volume area of interest prescribed by the technologist that monitors an area of interest for the arrival of a contrast bolus. Once detected, the imaging sequence begins automatically.

**tri-phasic flow**
naturally occurring property of flowing blood where arterial flow moves in three distinct phases: fast forward, short reverse, then fast forward again

**venogram**
imaging of the lumen of veins using a contrast agent

**venous contamination**
in an MRA image, unwanted signal of veins typically due to mistiming the arrival of the contrast bolus

**voxel**
a pixel that also displays depth as a 3rd dimension; from “volume element”