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Each practice guideline and technical standard, representing a policy statement by the College, has undergone a thorough consensus process in which it has been subjected to extensive review, requiring the approval of the Commission on Quality and Safety as well as the ACR Board of Chancellors, the ACR Council Steering Committee, and the ACR Council. The practice guidelines and technical standards recognize that the safe and effective use of diagnostic and therapeutic radiology requires specific training, skills, and techniques, as described in each document. Reproduction or modification of the published practice guideline and technical standard by those entities not providing these services is not authorized.

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ACR PRACTICE GUIDELINE FOR THE PERFORMANCE OF PEDIATRIC AND ADULT BODY MAGNETIC RESONANCE ANGIOGRAPHY (MRA)

PREAMBLE

These guidelines are an educational tool designed to assist practitioners in providing appropriate radiologic care for patients. They are not inflexible rules or requirements of practice and are not intended, nor should they be used, to establish a legal standard of care. For these reasons and those set forth below, the American College of Radiology cautions against the use of these guidelines in litigation in which the clinical decisions of a practitioner are called into question.

The ultimate judgment regarding the propriety of any specific procedure or course of action must be made by the physician or medical physicist in light of all the circumstances presented. Thus, an approach that differs from the guidelines, standing alone, does not necessarily imply that the approach was below the standard of care. To the contrary, a conscientious practitioner may responsibly adopt a course of action different from that set forth in the guidelines when, in the reasonable judgment of the practitioner, such course of action is indicated by the condition of the patient, limitations on available resources, or advances in knowledge or technology subsequent to publication of the guidelines. However, a practitioner who employs an approach substantially different from these guidelines is advised to document in the patient record information sufficient to explain the approach taken.

The practice of medicine involves not only the science, but also the art of dealing with the prevention, diagnosis, alleviation, and treatment of disease. The variety and complexity of human conditions make it impossible to always reach the most appropriate diagnosis or to predict with certainty a particular response to treatment.

Therefore, it should be recognized that adherence to these guidelines will not assure an accurate diagnosis or a successful outcome. All that should be expected is that the practitioner will follow a reasonable course of action based on current knowledge, available resources, and the needs of the patient to deliver effective and safe medical care. The sole purpose of these guidelines is to assist practitioners in achieving this objective.

I. INTRODUCTION

Magnetic resonance angiography (MRA) is a proven and useful tool for the evaluation, assessment of severity, and followup of diseases of the vascular system. MRA is a rapidly evolving technology. Consequently, only general recommendations can be made regarding imaging techniques. Detailed imaging protocols have been omitted to avoid promoting obsolete methodology. This document pertains to the assessment of vessels below the thoracic inlet, referred to as body MRA. For information on assessment of vessels of the head and neck, see the [Practice Guideline for the Performance of Pediatric and Adult Cerebrovascular Magnetic Resonance Angiography \(MRA\)](#).

Body MRA should be performed only for a valid medical reason. Additional or specialized pulse sequences are frequently required to optimize the examination. While it is not possible to detect all abnormalities by using MRA, adherence to the following guideline will enhance the probability of their detection.

MRA has important attributes that make it valuable in the assessment of vascular disease. Compared to radiographic

catheter-based invasive angiography, it is noninvasive with no risk of arterial injury or adverse effects from iodinated contrast media. Compared to vascular ultrasound, it is less operator dependent, yields images of the vascular system in a format familiar to referring physicians, is less limited by body habitus, and has greater three-dimensional capability.

MRA is also useful in diagnosis of vascular disease in children. Pediatric MRA may require specialized imaging approaches to accommodate the different spectrum of disease as compared to that seen in adults.

Application of this guideline should be in accordance with the [ACR Practice Guideline for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#), the [ACR Practice Guideline for Pediatric Sedation/Analgesia](#), and the [ACR Practice Guideline for Adult Sedation/Analgesia](#).

(For pediatric considerations, see Sections III. B. 4, and V.C.)

II. QUALIFICATIONS AND RESPONSIBILITIES OF PERSONNEL

See the [ACR Practice Guideline for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#).

The physician responsible for performing body MRA must fully appreciate the benefits, alternatives, and risks of the procedure. He/she must have a thorough understanding of thoracic, abdominal, and extremity anatomy (including congenital and developmental variants and common collateral pathways).

III. INDICATIONS

A. General Considerations

Adult indications for body MRA include, but are not limited to, the definition and evaluation of the following:

1. Presence and extent of atherosclerotic occlusive disease and thromboembolic phenomena.
2. Etiology of visceral, thoracic, abdominal, or pelvic hemorrhage.
3. Relevant vascular anatomy for determining the effect of therapeutic measures, including post-treatment evaluation of endovascular treatment of aneurysm, stenosis, and arteriovenous malformation (AVM) ablation.
4. Presence, location, and anatomy of aneurysms and vascular malformations.
5. Presence, nature, and extent of injury to vessels, including dissection.
6. Vascular supply to tumors.
7. Presence of venous disease.

8. Nature and extent of other congenital or acquired vascular abnormality.

B. Specific Considerations

1. Thoracic vasculature

MRA is useful for assessing the aorta and its branch vessels and can be used to assess the pulmonary vasculature. Indications for thoracic MRA include, but are not limited to, the definition and evaluation of the following:

- a. Thoracic aorta
 - i. Aneurysm of the thoracic aorta and branch vessels
 - ii. Post-traumatic pseudoaneurysm
 - iii. Acute aortic syndrome evaluation
 - a) Dissection
 - b) Intramural hematoma
 - c) Penetrating atherosclerotic ulcer
 - iv. Atheroembolic disease – identification of aortic thrombi
 - v. Vasculitis
 - vi. Neoplasia, both primary and secondary
 - vii. Postoperative evaluations
 - a) Perianastomotic leaks
 - b) Infection
 - c) Pseudoaneurysm
 - viii. Stent-graft, including endoleaks
 - ix. Congenital disorders in adults, such as arch anomalies, aortic coarctation, and pulmonary vein anomalies
 - b. Coronary artery assessments
 - i. Aberrant arterial anatomy
 - ii. Atherosclerotic narrowing
 - iii. Vasculitis
 - iv. Aneurysmal disease
 - c. Pulmonary venous evaluations
 - i. Venous mapping prior to and following radiofrequency ablation for atrial fibrillation
 - d. Pulmonary arterial evaluations
 - i. Thromboembolism
 - ii. Pulmonary artery hypertension
 - iii. Stenosis
 - iv. Vascular malformations
 - a) Pulmonary sequestration
 - b) Pulmonary arteriovenous malformations
 - v. Neoplastic disease
 - e. Internal mammary and intercostal vessel evaluations
 - f. Bronchial arteries
- #### 2. Extremity evaluations
- a. Arterial evaluations
 - i. Atherosclerotic occlusive disease

- a) Intermittent claudication
 - b) Acute and chronic critical ischemia
 - c) Patients with previous interventions (post-op)
 - i. Stents / stent grafts
 - ii. Bypass grafts
 - d) Atheroembolism
 - ii. Congenital anomalies
 - iii. Vasculitides
 - iv. Arterial fibrodysplasias
 - v. Postinterventional intimal hyperplasia
 - vi. Arterial entrapment syndromes
 - vii. Adventitial cystic disease
 - viii. Vascular malformations and fistulae
 - ix. Aneurysmal disease
 - x. Assessment of complications of arterial bypass grafts
 - xi. Assessment of surgically created dialysis fistulas
 - xii. Preoperative mapping of vascular anatomy for plastic surgery graft procedures
- b. Assessment for vascular involvement with musculoskeletal tumors
- c. Venous evaluations
- i. Thrombus
 - a) Central
 - b) Peripheral
 - c) Effort thrombosis of the upper extremity
 - d) Venous compression
 - ii. Venous malformations
 - iii. Varicose veins
 - iv. Venous incompetence
 - v. Assessment for vascular involvement with musculoskeletal tumors
 - vi. Assessment of causes of peripheral edema
 - a) Thrombus
 - b) Venous compression
 - c) Assessment of strictures from indwelling catheters
 - vii. Assessment of patent vessels for venous access
 - viii. Assessment of vein suitability as bypass conduits
3. Abdominal and pelvic MRA
- a. Diagnosis and/or assessment of the following vascular abnormalities:
 - i. Aneurysm of the aorta or branch vessels
 - ii. Stenosis or occlusion of the aorta and major branch vessels resulting from atherosclerotic disease, thromboembolic disease, or large vessel vasculitis
 - iii. Dissection of the aorta
 - iv. Arteriovenous fistula or malformation
 - v. Portal, mesenteric, or splenic vein thrombosis
 - vi. Inferior vena cava (IVC), renal vein, or hepatic vein thrombosis
 - b. Vascular evaluation in one of the following clinical scenarios:
 - i. Lower extremity claudication
 - ii. Suspected renovascular hypertension
 - iii. Suspected chronic mesenteric ischemia
 - iv. Hemorrhagic hereditary telangiectasia
 - v. Suspected Budd-Chiari syndrome
 - vi. Portal hypertension
 - vii. Suspected gonadal vein reflux
 - c. Preprocedure assessment for the following:
 - i. Vascular mapping prior to living organ donation
 - a) Hepatic
 - b) Renal
 - c) Pancreatic
 - ii. Assessment of renal vein and IVC patency in setting of renal cell carcinoma
 - iii. Vascular mapping prior to portosystemic shunt surgery or TIPS placement
 - iv. Vascular mapping prior to resection of abdominal and pelvic neoplasms
 - v. Vascular mapping prior to uterine fibroid embolization
 - vi. Vascular mapping prior to hepatic chemo-embolization procedures
 - d. Postprocedure assessment for the following:
 - i. Evaluation of organ transplant vascular anastomoses
 - ii. Detection of suspected leak following aortic aneurysm surgery or MR-compatible aortic stent graft placement
 - iii. Evaluation of ovarian artery collateral flow following uterine fibroid embolization
4. Pediatric indications for body MRA
- MRA is particularly applicable in children due to the risk (albeit low) related to angiographic procedures. Various studies of children with strokes that compared MRA to conventional angiography found MRA to be 1) accurate in the delineation of stenosis and/or occlusion, and 2) able to demonstrate collateral vascular anatomy. Indications for body MRA for children include, but are not limited to, the definition and evaluation of the following:
- a. Arterial dissection
 - b. Congenital anomalies of the aorta and associated branch vessels

- c. Vascular malformations of the trunk and extremity
 - d. Vasculities
 - e. Aneurysmal disease
 - f. Vascular abnormalities associated with sickle cell anemia
 - g. Blood supply to vascular neoplasms for operative planning
 - h. Vascular anastomoses and complications of organ transplants
 - i. Presence of visceral venous occlusive disease
 - j. Postoperative anatomy following vascular surgery
5. Evaluation of the aortic arch and subclavian arteries in adults and children may require separate techniques and sequences. Indications include, but are not limited to, the following:
- a. Dissection of the aorta and/or its branches
 - b. Aneurysm of the aorta and/or its branches, and subclavian steal
 - c. Differentiation of aneurysms and masses
 - d. Definition of the relationship of masses to nearby vascular structures
 - e. Identification of congenital abnormalities of the aorta, such as coarctation, double arch, and aberrant subclavian artery
 - f. Evaluation of superior vena cava syndrome or unilateral upper extremity edema

IV. SAFETY GUIDELINES AND POSSIBLE CONTRAINDICATIONS

See the [ACR Practice Guideline for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) and the ACR White Paper on Magnetic Resonance Safety¹.

Peer-reviewed literature pertaining to MR safety should be reviewed on a regular basis [86,87].

V. SPECIFICATIONS OF THE EXAMINATION

The supervising physician must have complete understanding of the indications, risks, and benefits of the examination, as well as alternative imaging procedures. The physician must be familiar with potential hazards associated with MRI, including potential adverse reactions to contrast media. The physician should be familiar with relevant ancillary studies that the patient may have undergone. The physician performing MRI interpretation must have a clear understanding and

knowledge of the anatomy and pathophysiology relevant to the MRI examination.

The written or electronic request for body MRA should provide sufficient information to demonstrate the medical necessity of the examination and allow for its proper performance and interpretation.

Documentation that satisfies medical necessity includes 1) signs and symptoms and/or 2) relevant history (including known diagnoses). Additional information regarding the specific reason for the examination or a provisional diagnosis would be helpful and may at times be needed to allow for the proper performance and interpretation of the examination.

The request for the examination must be originated by a physician or other appropriately licensed health care provider. The accompanying clinical information should be provided by a physician or other appropriately licensed health care provider familiar with the patient's clinical problem or question and consistent with the state scope of practice requirements. (2006 - ACR Resolution 35)

The supervising physician must also understand the pulse sequences to be employed and their effect on the appearance of the images, including the potential generation of image artifacts. Standard imaging protocols may be established and varied on a case-by-case basis when necessary. These protocols should be reviewed and updated periodically.

A. Patient Selection

The physician responsible for the examination shall supervise patient selection and preparation, and be available in person or by phone for consultation. Patients shall be screened and interviewed prior to the examination to exclude individuals who may be at risk by exposure to the MR environment.

Certain indications require administration of intravenous (IV) contrast media. IV contrast enhancement should be performed using appropriate injection protocols and in accordance with the institution's policy on IV contrast utilization. (See the [ACR Practice Guideline for the Use of Intravascular Contrast Media](#).)

Patients suffering from anxiety or claustrophobia may require sedation or additional assistance. Administration of moderate or "conscious" sedation may be needed to achieve a successful examination. If moderate sedation is necessary, refer to the [ACR Practice Guideline for Adult Sedation/Analgesia](#) or the [ACR Practice Guideline for Pediatric Sedation/Analgesia](#).

¹In 2007 the following updated version was published: ACR Guidance Document for Safe MR Practices. AJR 2007; 188:1-27.

B. Facility Requirements

Appropriate emergency equipment and medications must be immediately available to treat adverse reactions associated with administered medications. The equipment and medications should be monitored for inventory and drug expiration dates on a regular basis.

C. Examination Technique

Magnetic resonance angiography is a general term that refers to a diverse group of MR pulse sequences. Four different mechanisms can be used to generate signal from flowing blood. The most common method, called time of flight (TOF), relies on inflow enhancement to generate images of blood flow. Flow images and quantitative measurements of flow velocity can be obtained using phase contrast (PC) MRA methods in which the image contrast is generated by velocity induced phase shifts. A third method relies on enhancement of the blood signal by paramagnetic contrast agents and employs rapid, three-dimensional (3D) T1-weighted gradient echo acquisitions. A fourth method relies on a steady state free precession (SSFP) sequence that captures the intrinsic T1 and T2 features of blood as bright signal. The SSFP renders bright signal in patent arteries and veins; however, it cannot selectively depict either system. Individuals using MRA shall understand the artifacts and limitations of 2D TOF, 3D TOF, 2D or 3D PC, and contrast-enhanced 3D imaging techniques.

The most commonly used inflow techniques are 2D TOF and 3D TOF. In 2D TOF acquisitions, multiple contiguous thin slices are obtained and combined to form a three-dimensional data set. The 3D techniques inherently acquire a volume of data. With either approach the vascular structures are delineated and emphasized by selecting pixels with maximum intensity and projecting these onto a plane (MIP) or by using volume-rendering techniques.

The MRA data sets appear as two dimensional source images. The supervising physician should review the source images to reduce possible confusion of high signal material (e.g., fat or thrombus) with flow signal. Review of the source images also aids diagnosis by eliminating overlapping structures and determining if artifacts are the cause of spurious signal or signal loss.

MRA data are routinely postprocessed using a maximum intensity projection (MIP) reconstruction algorithm or volume rendering techniques. Rotating displays of three-dimensional data sets allow separation of vessels that are superimposed on routine projections. Additionally, multiple views are needed to fully depict altered vascular anatomy. Targeted MIP renderings should be made to clarify areas of tortuosity and vessel overlap. The

supervising physician shall be familiar with MIP, surface display, volume display, and multiplanar reformatting techniques and with the limitations and strengths of each method. The type and frequency of artifacts will vary with the display technique; thus, the supervising physician must understand the potential errors with each display method.

Contrast-enhanced 3D MRA combines a fast T1-weighted gradient echo acquisition with an intravenously administered paramagnetic contrast agent. Such agents reduce T1 relaxation time of blood and nearly eliminate the loss of signal related to saturation effects, thus leading to a more accurate assessment of stenoses. MRA with contrast enhancement has documented efficacy in the assessment of the arterial and venous systems in the thorax, abdomen/pelvis, and extremities. MRA with contrast does not require cardiac gating and is, therefore, more widely applicable in patients with irregular cardiac rhythms. Furthermore, breath holding eliminates respiratory artifacts, and artifacts due to flow related enhancement are not encountered. These advantages make MRA with contrast extremely useful for imaging of the vasculature in the thorax, abdomen, pelvis, and extremities.

PC MRA can be obtained as either a two-dimensional or three-dimensional dataset. Intravenous contrast enhancement may also be employed to increase the signal obtained from blood. PC techniques are based on the physical properties of moving spins. As protons move through a magnetic field, they acquire a phase shift directly proportional to their velocity. The magnitude of the phase shift can be measured, and an image of the flowing blood can be generated. Display of the vessels is similar to that of the TOF technique, although direction of flow can also be indicated. PC MRA can be obtained without or with ECG triggering. The application of ECG triggering will typically lengthen the acquisition time.

It is essential to trigger the PC acquisition to the cardiac cycle to measure flow velocity or flow volume. Therefore, peripheral or cardiac gating should be available.

In infancy and childhood, MRA can provide valuable information about the vascular system, particularly for the assessment of vascular malformations. However, technical and safety issues are more complex in pediatric patients. The smaller size of the pediatric patient increases the demand for higher resolution. In addition, sedation is frequently required to successfully complete the examination. Special attention to the appropriate dose of contrast media and to methods of administration of contrast and fluid flush are needed in the infant population.

VI. DOCUMENTATION

Reporting should be in accordance with the [ACR Practice Guideline for Communication of Diagnostic Imaging Findings](#). In addition to examining the vascular structures of interest, the MR source images should be examined for extravascular abnormalities that may have clinical relevance. These abnormalities should be described in the formal report of the examination.

VII. EQUIPMENT SPECIFICATIONS

The MRI equipment specifications and performance shall meet all state and federal requirements. The requirements include, but are not limited to, specifications of maximum static magnetic strength, maximum rate of change of the magnetic field strength (dB/dt), maximum radiofrequency power deposition (specific absorption rate), and maximum acoustic noise levels.

VIII. QUALITY CONTROL AND IMPROVEMENT, SAFETY, INFECTION CONTROL, AND PATIENT EDUCATION CONCERNS

Policies and procedures related to quality, patient education, infection control, and safety should be developed and implemented in accordance with the ACR Policy on Quality Control and Improvement, Safety, Infection Control, and Patient Education Concerns appearing elsewhere in the ACR Practice Guidelines and Technical Standards book.

Specific policies and procedures related to MRI safety should be in place with documentation that is updated annually and compiled under the supervision and direction of the supervising MRI physician. Guidelines should be provided that deal with potential hazards associated with the MRI examination of the patient as well as to others in the immediate area [82,84,86,87]. Screening forms must also be provided to detect those patients who may be at risk for adverse events associated with the MRI examination [82,84,86,87].

Equipment monitoring should be in accordance with the [ACR Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance Imaging \(MRI\) Equipment](#).

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REFERENCES

1. Adamis MK, Goldszer RC, Pulde MF, et al. Renal vasculature in potential renal transplant donors: comparison of MR imaging and digital subtraction angiography. *Radiology* 1995;197:467-472.
2. Alley MT, Shifrin RY, Pelc NJ, et al. Ultrafast contrast-enhanced three-dimensional MR angiography: state of the art. *Radiographics* 1998;18:273-285.
3. Anzai Y, Prince MR, Chenevert TL, et al. MR angiography with an ultra-small superparamagnetic iron oxide blood pool agent. *J Magn Reson Imaging* 1997;7:209-214.
4. Arpasi PJ, Bis KG, Shetty AN, et al. MR angiography of the thoracic aorta with an electrocardiographically triggered breath-hold contrast-enhanced sequence. *Radiographics* 2000;20:107-120.
5. Arrazola L, Sutherland DE, Sozen H, et al. May-Thurner syndrome in renal transplantation. *Transplantation* 2001;71:698-702.
6. Baum RA, Rutter CM, Sunshine JH, et al. Multicenter trial to evaluate vascular magnetic resonance angiography of the lower extremity. American College of Radiology Rapid Technology Assessment Group. *JAMA* 1995;274:875-880.

7. Bongers V, Bakker J, Beutler JJ, et al. Assessment of renal artery stenosis: comparison of captopril renography and gadolinium-enhanced breath-hold MR angiography. *Clin Radiol* 2000;55:346-353.
8. Boos M, Scheffler K, Haselhorst R, et al. Arterial first pass gadolinium-CM dynamics as a function of several intravenous saline flush and Gd volumes. *J Magn Reson Imaging* 2001;13:568-576.
9. Calhoun PS, Kuszyk BS, Heath DG, et al. Three-dimensional volume rendering of spiral CT data: theory and method. *Radiographics* 1999;19:745-764.
10. Carpenter JP, Golden MA, Barker CF, et al. The fate of bypass grafts to angiographically occult runoff vessels detected by magnetic resonance angiography. *J Vasc Surg* 1996;23:483-489.
11. Carr JC, Laub G, Zheng J, et al. Time-resolved three-dimensional pulmonary MR angiography and perfusion imaging with ultrashort repetition time. *Acad Radiol* 2002;9:1407-1418.
12. Carr JC, Nemcek AA Jr, Abecassis M, et al. Preoperative evaluation of the entire hepatic vasculature in living liver donors with use of contrast-enhanced MR angiography and true fast imaging with steady-state precession. *J Vasc Interv Radiol* 2003;14:441-449.
13. Carroll TJ, Korosec FR, Swan JS, et al. The effect of injection rate on time-resolved contrast-enhanced peripheral MRA. *J Magn Reson Imaging* 2001;14:401-410.
14. Cesare ED, Giordano AV, Cerone G, et al. Comparative evaluation of TEE, conventional MRI and contrast-enhanced 3D breath-hold MRA in the post-operative follow-up of dissecting aneurysms. *Int J Card Imaging* 2000;16:135-147.
15. Chapuis L, Gudinchet F. Meso-atrial shunt for Budd-Chiari syndrome: evaluation of patency by magnetic resonance angiography, with color Doppler ultrasound and angiographic correlation. *Pediatr Radiol* 1993;23:198-199.
16. Choe YH, Kim DK, Koh EM, et al. Takayasu arteritis: diagnosis with MR imaging and MR angiography in acute and chronic active stages. *J Magn Reson Imaging* 1999;10:751-757.
17. Colletti PM. Magnetic resonance procedures and pregnancy. In: Shellock FG, ed. *Magnetic Resonance Procedures: Health Effects and Safety*. Boca Raton Fla: CRC Press; 2001:149-182.
18. Connell DA, Koulouris G, Thorn DA, et al. Contrast-enhanced MR angiography of the hand. *Radiographics* 2002;22:583-599.
19. Cortell ED, Kaufman JA, Geller SC, et al. MR angiography of tibial runoff vessels: imaging with the head coil compared with conventional arteriography. *AJR* 1996;167:147-151.
20. Dalman RL, Li KC, Moon WK, et al. Diminished postprandial hyperemia in patients with aortic and mesenteric arterial occlusive disease: quantification by magnetic resonance flow imaging. *Circulation* 1996;94:II206-210.
21. De Cobelli F, Venturini M, Vanzulli A, et al. Renal arterial stenosis: prospective comparison of color Doppler US and breath-hold, three-dimensional, dynamic, gadolinium-enhanced MR angiography. *Radiology* 2000;214:373-380.
22. Douek PC, Revel D, Chazel S, et al. Fast MR angiography of the aortoiliac arteries and arteries of the lower extremity: value of bolus-enhanced, whole-volume subtraction technique. *AJR* 1995;165:431-437.
23. Drutman J, Gyorke A, Davis WL, et al. Evaluation of subclavian steal with two-dimensional phase-contrast and two-dimensional time-of-flight MR angiography. *AJNR* 1994;15:1642-1645.
24. Du YP, Parker DL, Davis WL. Vessel enhancement filtering in three-dimensional MR angiography. *J Magn Reson Imaging* 1995;5:353-359.
25. Earls JP, DeSena S, Bluemke DA. Gadolinium-enhanced three-dimensional MR angiography of the entire aorta and iliac arteries with dynamic manual table translation. *Radiology* 1998;209:844-849.
26. Fain SB, King BF, Breen JF, et al. High-spatial-resolution contrast-enhanced MR angiography of the renal arteries: a prospective comparison with digital subtraction angiography. *Radiology* 2001;218:481-490.
27. Finn JP, Baskaran V, Carr JC, et al. Thorax low-dose contrast-enhanced three-dimensional MR angiography with subsecond temporal resolution: initial results. *Radiology* 2002;224:896-904.
28. Finelli DA, Rezai AR, Ruggieri PM, et al. MR imaging-related heating of deep brain stimulation electrodes: in vitro study. *AJNR* 2002;23:1795-1802.
29. Foo TK, Saranathan M, Prince MR, et al. Automated detection of bolus arrival and initiation of data acquisition in fast, three-dimensional, gadolinium-enhanced MR angiography. *Radiology* 1997;203:275-280.
30. Foo TK, Ho VB, Hood MN, et al. High-spatial-resolution multistation MR imaging of lower-extremity peripheral vasculature with segmented volume acquisition: feasibility study. *Radiology* 2001;219:835-841.
31. Gallix BP, Achard-Lichere C, Dauzat M, et al. Flow-independent magnetic resonance venography of the calf. *J Magn Reson Imaging* 2003;17:421-426.
32. Giessing M, Kroencke TJ, Taupitz M, et al. Gadolinium-enhanced three-dimensional magnetic resonance angiography versus conventional digital subtraction angiography: which modality is superior in evaluating living kidney donors? *Transplantation* 2003;76:1000-1002.
33. Gilfeather M, Yoon HC, Siegelman ES, et al. Renal artery stenosis: evaluation with conventional

- angiography versus gadolinium-enhanced MR angiography. *Radiology* 1999;210:367-372.
34. Goldberg MA, Yucel EK, Saini S, et al. MR angiography of the portal and hepatic venous systems: preliminary experience with echoplanar imaging. *AJR* 1993;160:35-40.
 35. Goyen M, Lauenstein TC, Herborn CU, et al. 0.5 M Gd chelate (Magnevist) versus 1.0 M Gd chelate (Gadovist): dose-independent effect on image quality of pelvic three-dimensional MR angiography. *J Magn Reson Imaging* 2001;14:602-607.
 36. Grist TM, Korosec FR, Peters DC, et al. Steady-state and dynamic MR angiography with MS-325: initial experience in humans. *Radiology* 1998;207:539-544.
 37. Hahn U, Miller S, Nagele T, et al. Renal MR angiography at 1.0 T: three-dimensional (3D) phase-contrast techniques versus gadolinium-enhanced 3D fast low-angle shot breath-hold imaging. *AJR* 1999;172:1501-1508.
 38. Hany TF, Carroll TJ, Omary RA, et al. Aorta and runoff vessels: single-injection MR angiography with automated table movement compared with multi-injection time-resolved MR angiography: initial results. *Radiology* 2001;221:266-272.
 39. Haustein J, Niendorf HP, Krestin G, et al. Renal tolerance of gadolinium-DTPA/dimeglumine in patients with chronic renal failure. *Invest Radiol* 1992;27:153-156.
 40. Ho KY, de Haan MW, Kessels AG, et al. Peripheral vascular tree stenoses: detection with subtracted and nonsubtracted MR angiography. *Radiology* 1998;206:673-681.
 41. Ho VB, Corse WR, Hood MN, et al. MRA of the thoracic vessels. *Semin Ultrasound CT MR* 2003;24:192-216.
 42. International Commission on Non-Ionizing Radiation Protection (ICNIRP) statement. Medical magnetic resonance procedures: protection of patients. *Health Physics* 2004;87:197-216.
 43. Johnson DB, Lerner CA, Prince MR, et al. Gadolinium-enhanced magnetic resonance angiography of renal transplants. *Magn Reson Imaging* 1997;15:13-20.
 44. Kandaswamy R, Stillman AE, Granger DK, et al. MRI is superior to angiography for evaluation of living related simultaneous pancreas and kidney donors. *Transplant Proc* 1999;31:604-605.
 45. Kaufman JA, McCarter D, Geller SC, et al. Two-dimensional time-of-flight MR angiography of the lower extremities: artifacts and pitfalls. *AJR* 1998;171:129-135.
 46. Kaufman JA, Geller SC, Bazari H, et al. Gadolinium-based contrast agents as an alternative at vena cavography in patients with renal insufficiency: early experience. *Radiology* 1999;212:280-284.
 47. Kim BS, Kim TK, Jung DJ, et al. Vascular complications after living related liver transplantation: evaluation with gadolinium-enhanced three-dimensional MR angiography. *AJR* 2003;181:467-474.
 48. Knopp MV, Giesel FL, von Tengg-Kobligk H, et al. Contrast-enhanced MR angiography of the run-off vasculature: intraindividual comparison of gadobenate dimeglumine with gadopentetate dimeglumine. *J Magn Reson Imaging* 2003;17:694-702.
 49. Koelemay MJ, Lijmer JG, Stoker J, et al. Magnetic resonance angiography for the evaluation of lower extremity arterial disease: a meta-analysis. *JAMA* 2001;285:1338-1345.
 50. Korosec FR, Frayne R, Grist TM, et al. Time-resolved contrast-enhanced 3D MR angiography. *Magn Reson Med* 1996;36:345-351.
 51. Krinsky GA, Rofsky NM, DeCorato DR, et al. Thoracic aorta: comparison of gadolinium-enhanced three-dimensional MR angiography with conventional MR imaging. *Radiology* 1997;202:183-193.
 52. Krinsky G, Jacobowitz G, Rofsky N. Gadolinium-enhanced MR angiography of extraanatomic arterial bypass grafts. *AJR* 1998;170:735-741.
 53. Lambert AW, Wilkins DC. Popliteal artery entrapment syndrome. *Br J Surg* 1999;86:1365-1370.
 54. Lance NJ, Levinson DJ. Aortitis and periaortic fibrosis. *J Rheumatol* 1991;18:1095-1099.
 55. Lee VS, Martin DJ, Krinsky GA, et al. Gadolinium-enhanced MR angiography: artifacts and pitfalls. *AJR* 2000;175:197-205.
 56. Leiner T, de Weert TT, Nijenhuis RJ, et al. Need for background suppression in contrast-enhanced peripheral magnetic resonance angiography. *J Magn Reson Imaging* 2001;14:724-733.
 57. Leiner T, Tordoir JH, Kessels AG, et al. Comparison of treatment plans for peripheral arterial disease made with multi-station contrast medium-enhanced magnetic resonance angiography and duplex ultrasound scanning. *J Vasc Surg* 2003;37:1255-1262.
 58. Leyendecker JR, Johnson SP, Diffin DC, et al. Time-of-flight MR arteriography of below-knee arteries with maximum-intensity-projection reconstruction: is interpretation of the axial source images helpful? *AJR* 1997;169:1145-1149.
 59. Leyendecker JR, Rivera E Jr, Washburn WK, et al. MR angiography of the portal venous system: techniques, interpretation, and clinical applications. *Radiographics* 1997;17:1425-1443.
 60. Li KC. Mesenteric occlusive disease. *Magn Reson Imaging Clin N Am* 1998;6:331-350.
 61. Maki JH, Prince MR, Londy FJ, et al. The effects of time varying intravascular signal intensity and k-space acquisition order on three-dimensional MR angiography image quality. *J Magn Reson Imaging* 1996;6:642-651.
 62. Maki JH, Wilson GJ, Eubank WB, et al. Utilizing SENSE to achieve lower station sub-millimeter

- isotropic resolution and minimal venous enhancement in peripheral MR angiography. *J Magn Reson Imaging* 2002;15:484-491.
63. Meaney JF, Weg JG, Chenevert TL, et al. Diagnosis of pulmonary embolism with magnetic resonance angiography. *N Engl J Med* 1997;336:1422-1427.
 64. Meaney JF, Ridgway JP, Chakraverty S, et al. Stepping-table gadolinium-enhanced digital subtraction MR angiography of the aorta and lower extremity arteries: preliminary experience. *Radiology* 1999;211:59-67.
 65. Merkle EM, Klein S, Wisianowsky C, et al. Magnetic resonance imaging versus multislice computed tomography of thoracic aortic endografts. *J Endovasc Ther* 2002;2:II2-13.
 66. Miyazaki M, Sugiura S, Tateishi F, et al. Non-contrast-enhanced MR angiography using 3D ECG-synchronized half-Fourier fast spin echo. *J Magn Reson Imaging* 2000;12:776-783.
 67. Morrin MM, Pedrosa I, Rofsky NM. Magnetic resonance imaging for disorders of liver vasculature. *Top Magn Reson Imaging* 2002;13:177-190.
 68. Muller MF, Siewert B, Stokes KR, et al. MR angiographic guidance for transjugular intrahepatic portosystemic shunt procedures. *J Magn Reson Imaging* 1994;4:145-150.
 69. Nelemans PJ, Leiner T, de Vet HC, et al. Peripheral arterial disease: meta-analysis of the diagnostic performance of MR angiography. *Radiology* 2000;217:105-114.
 70. Pandharipande PV, Lee VS, Morgan GR, et al. Vascular and extravascular complications of liver transplantation: comprehensive evaluation with three-dimensional contrast-enhanced volumetric MR imaging and MR cholangio-pancreatography. *AJR* 2001;177:1101-1107.
 71. Pereles FS, McCarthy RM, Baskaran V, et al. Thoracic aortic dissection and aneurysm: evaluation with nonenhanced true FISP MR angiography in less than 4 minutes. *Radiology* 2002;223:270-274.
 72. Peters DC, Korosec FR, Grist TM, et al. Undersampled projection reconstruction applied to MR angiography. *Magn Reson Med* 2000;43:91-101.
 73. Prince MR. Body MR angiography with gadolinium contrast agents. *MR Clin N Am* 1996;4:11-24.
 74. Prince MR, Arnoldus C, Frisoli JK. Nephrotoxicity of high-dose gadolinium compared with iodinated contrast. *J Magn Reson Imaging* 1996;6:162-166.
 75. Rezaei AR, Phillips M, Baker KB, et al. Neurostimulation system used for deep brain stimulation (DBS): MR safety issues and implications of failing to follow safety recommendations. *Invest Radiol* 2004;39:300-303.
 76. Rezaei AR, Finelli D, Nyenhuis JA, et al. Neurostimulation systems for deep brain stimulation: in vitro evaluation of magnetic resonance imaging-related heating at 1.5 Tesla. *J Magn Reson Imaging* 2002;15:241-250.
 77. Rispoli P, Moniaci D, Zan S, et al. Cystic adventitial disease of the popliteal artery: report of one case and review of the literature. *J Cardiovasc Surg (Torino)* 2003;44:255-258.
 78. Rofsky NM, Weinreb JC, Bosniak MA, et al. Renal lesion characterization with gadolinium-enhanced MR imaging: efficacy and safety in patients with renal insufficiency. *Radiology* 1991;180:85-89.
 79. Rofsky NM, Johnson G, Adelman MA, et al. Peripheral vascular disease evaluated with reduced-dose gadolinium-enhanced MR angiography. *Radiology* 1997;205:163-169.
 80. Rofsky NM, Adelman MA. MR angiography in the evaluation of atherosclerotic peripheral vascular disease. *Radiology* 2000;214:325-338.
 81. Ruehm SG, Weishaupt D, Debatin JF. Contrast-enhanced MR angiography in patients with aortic occlusion (Leriche syndrome). *J Magn Reson Imaging* 2000;11:401-410.
 82. Sawyer-Glover AM, Shellock FG. Pre-MRI procedure screening: recommendations and safety considerations for biomedical implants and devices. *J Magn Reson Imaging* 2000;12:92-106.
 83. Schoenberg SO, Bock M, Kallinowski F, et al. Correlation of hemodynamic impact and morphologic degree of renal artery stenosis in a canine model. *J Am Soc Nephrol* 2000;11:2190-2198.
 84. Shellock FG, Crues JV. MR procedures: biologic effects, safety, and patient care. *Radiology* 2004;232:635-652.
 85. Shellock FG. Biomedical implants and devices: assessment of magnetic field interactions with a 3.0 Tesla MR system. *J Magn Reson Imaging* 2002;16:721-732.
 86. Shellock FG. *Reference Manual for Magnetic Resonance Safety, Implants, and Devices*. 2005 edition. Los Angeles, Calif: Biomedical Research Publishing Group; 2005.
 87. Shellock FG. *Magnetic Resonance Procedures: Health Effects and Safety*. Boca Ration, Fla: CRC Press; 2001.
 88. Shellock FG, Tkach JA, Ruggieri PM, et al. Aneurysm clips: evaluation of magnetic field interactions and translational attraction by use of "long-bore" and "short-bore" 3.0 T MR imaging systems. *AJNR* 2003;24:463-471.
 89. Shinde TS, Lee VS, Rofsky NM, et al. Three-dimensional gadolinium-enhanced MR venographic evaluation of patency of central veins in the thorax: initial experience. *Radiology* 1999;213:555-560.
 90. Shirkhoda A, Konez O, Shetty AN, et al. Mesenteric circulation: three-dimensional MR angiography with a gadolinium-enhanced multiecho gradient-echo technique. *Radiology* 1997;202:257-261.

91. Siegelman ES, Charafeddine R, Stolpen AH, et al. Suppression of intravascular signal on fat-saturated contrast-enhanced thoracic MR arteriograms. *Radiology* 2000;217:115-118.
92. Sodickson DK, McKenzie CA, Li W, et al. Contrast-enhanced 3D MR angiography with simultaneous acquisition of spatial harmonics: a pilot study. *Radiology* 2000;217:284-289.
93. Sugano S, Yamamoto K, Sasao K, et al. Portal venous blood flow while breath-holding after inspiration or expiration and during normal respiration in controls and cirrhotics. *J Gastroenterol* 1999;34:613-618.
94. Van Hoe L, De Jaegere T, Bosmans H, et al. Breath-hold contrast-enhanced three-dimensional MR angiography of the abdomen: time-resolved imaging versus single-phase imaging. *Radiology* 2000;214:149-156.
95. Wolpert LM, Rahmani O, Stein B, et al. Magnetic resonance venography in the diagnosis and management of May-Thurner syndrome. *Vasc Endovascular Surg* 2002;36:51-57.
96. Yamada N, Okita Y, Minatoya K, et al. Preoperative demonstration of the Adamkiewicz artery by magnetic resonance angiography in patients with descending or thoracoabdominal aortic aneurysms. *Eur J Cardiothorac Surg* 2000;18:104-111.
97. Yucel EK, Anderson CM, Edelman RR, et al. AHA scientific statement. Magnetic resonance angiography: update on applications for extracranial arteries. *Circulation* 1999;100:2284-2301.