ACR–NASCI–SPR PRACTICE PARAMETER FOR THE PERFORMANCE OF BODY MAGNETIC RESONANCE ANGIOGRAPHY (MRA)

The American College of Radiology, with more than 40,000 members, is the principal organization of radiologists, radiation oncologists, and clinical medical physicists in the United States. The College is a nonprofit professional society whose primary purposes are to advance the science of radiology, improve radiologic services to the patient, study the socioeconomic aspects of the practice of radiology, and encourage continuing education for radiologists, radiation oncologists, medical physicists, and persons practicing in allied professional fields.

The American College of Radiology will periodically define new practice parameters and technical standards for radiologic practice to help advance the science of radiology and to improve the quality of service to patients throughout the United States. Existing practice parameters and technical standards will be reviewed for revision or renewal, as appropriate, on their fifth anniversary or sooner, if indicated.

Each practice parameter 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 and approval. The practice parameters 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 parameter and technical standard by those entities not providing these services is not authorized.

PREAMBLE

This document is an educational tool designed to assist practitioners in providing appropriate radiologic care for patients. Practice Parameters and Technical Standards are not inflexible rules or requirements of practice and are not intended, nor should they be used, to establish a legal standard of care[1]. For these reasons and those set forth below, the American College of Radiology and our collaborating medical specialty societies caution against the use of these documents 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 practitioner considering all the circumstances presented. Thus, an approach that differs from the guidance in this document, 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 this document when, in the reasonable judgment of the practitioner, such course of action is indicated by variables such as the condition of the patient, limitations of available resources, or advances in knowledge or technology after publication of this document. However, a practitioner who employs an approach substantially different from the guidance in this document may consider documenting in the patient record information sufficient to explain the approach taken.

The practice of medicine involves the science, and 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 the guidance in this document 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 purpose of this document is to assist practitioners in achieving this objective.

---

1 *Iowa Medical Society and Iowa Society of Anesthesiologists v. Iowa Board of Nursing, 831 N.W.2d 826 (Iowa 2013) Iowa Supreme Court refuses to find that the "ACR Technical Standard for Management of the Use of Radiation in Fluoroscopic Procedures (Revised 2008)" sets a national standard for who may perform fluoroscopic procedures in light of the standard's stated purpose that ACR standards are educational tools and not intended to establish a legal standard of care. See also, Stanley v. McCarver, 63 P.3d 1076 (Ariz. App. 2003) where in a concurring opinion the Court stated that "published standards or guidelines of specialty medical organizations are useful in determining the duty owed or the standard of care applicable in a given situation" even though ACR standards themselves do*

not establish the standard of care.

I. INTRODUCTION

This practice parameter was revised collaboratively by the American College of Radiology (ACR), the North American Society for Cardiovascular Imaging (NASCI), and the Society for Pediatric Radiology (SPR).

Magnetic resonance angiography (MRA) is a proven and useful tool for the initial diagnosis, assessment of severity, and follow-up of diseases of the vascular system. MRA techniques can be categorized as noncontrast and contrast enhanced. Contrast-enhanced MRA (CE-MRA) has been shown to be equivalent to conventional angiography for evaluating various vascular system diseases and pretreatment planning [1-5]. When compared with conventional angiography, MRA is less expensive, less invasive, and lacks ionizing radiation exposure. Despite its proven efficacy, MRA remains an evolving amalgam of different techniques. Consequently, only general recommendations can be made regarding imaging protocols. Detailed protocols have been deliberately omitted to prevent the endorsement of methods that may become outdated. This document pertains to the assessment of vessels below the thoracic inlet, which are referred to as body MRA. For information on assessment of vessels of the head and neck or assessment of the heart, see the ACR–ASNR–SNIS–SPR Practice Parameter for the Performance of Magnetic Resonance Angiography (MRA) of the Head and Neck [6] and the ACR–NASCI–SPR Practice Parameter for the Performance and Interpretation of Cardiac Magnetic Resonance Imaging (MRI) [7].

Body MRA should be performed only for a valid medical reason. Most MRI systems have available specialized sequences that have been optimized for performing MRA. Although it is not possible to detect all vascular abnormalities by using MRA, adherence to the following practice parameters will enhance the probability of their detection.

MRA has important attributes that make it valuable in assessing vascular disease. Compared with catheter-based invasive angiography, it is noninvasive with no significant risk of vascular injury. Although MRA techniques are free of adverse effects from iodinated contrast media, some gadolinium-based contrast agents have been linked to the development of nephrogenic systemic fibrosis (NSF) in patients with severe renal insufficiency and associated with gadolinium deposition in the brain tissue in patients without renal disease (see the ACR Manual on Contrast Media) [8-12]. The newer cyclic gadolinium agents are not affected by this More recently Ferumoxytol has been reported as a suitable alternative to gadolinium-based contrast agents and as capable of yielding high-quality CE-MRA. It is an iron replacement product that may be used as an ultra-small superparamagnetic iron oxide (USPIO) contrast agent through off-label use, as opposed to gadolinium-based contrast agents [13-18]. Noncontrast MRA techniques are also available for those who cannot receive gadolinium-based contrast agents [19-22]. Compared with vascular ultrasound, MRA is less dependent on the operator, is less affected by body habitus and overlying bowel gas, and offers superior 3-D imaging capabilities. Contrast-enhanced CT angiography (CTA) can also provide excellent vascular illustration and calcific burden but is associated with increased patient concerns related to exposure to ionizing radiation and the use of iodinated contrast media—concerns not borne by utilization of MRA. MRA not only offers time-resolved vascular imaging without the concerns of additional ionizing radiation exposure associated with multiphase CTA, but it also provides capabilities not available with CTA. For instance, phase contrast MRA (PC-MRA) can deliver quantitative information about blood flow, and susceptibility-weighted MRA can assess oxygen saturation—features that CTA lacks. MRA has also shown promising results for atherosclerotic plaque characterization, notably for the detection of high-risk features (eg, intraplaque hemorrhage, plaque ulceration, lipid-rich necrotic core, or fibrous cap thinning/rupture) of carotid atherosclerotic plaque [23-25].

Given the lack of radiation exposure and ability to include time-resolved techniques, MRA is particularly useful if diagnosing vascular disease in children. Pediatric MRA may require specialized imaging approaches to accommodate the different spectrum of disease, physiology, smaller vessel caliber, typically faster blood flow, higher potential for motion artifact, and varying body size as compared with adults and may require sedation or general anesthesia.

Application of this practice parameter should be in accordance with the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [26] and the ACR–SIR Practice Parameter for Minimal and/or Moderate Sedation/Analgesia [27].

(For pediatric considerations, see sections II.B.4 and IV.C.)

II. 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 vascular stenosis or occlusion due to atherosclerosis, vasculitis, or thromboembolic phenomena
2. Etiology of thoracic, abdominal, or pelvic hemorrhage
3. Mapping vascular anatomy for preprocedural planning and postprocedural surveillance of treatment
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, or involvement by, tumors
7. Presence and extent of venous disease, including occlusion, thrombosis, and tumor invasion
8. Venous anatomy, including congenital abnormalities, extrinsic compression, or causes of intrinsic stenosis or obstruction
9. Presurgical assessment of vascularity that may be involved by or affected by disorders in proximity
10. Nature and extent of other congenital or acquired vascular abnormality
11. Quantitative measurements of blood flow

II. INDICATIONS

B. Specific Considerations

1. Thoracic vasculature

1. MRA is useful for assessing the aorta, its branch vessels, and 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 and/or atherosclerosisof the thoracic aorta and branch vessels
        ii. Posttraumatic pseudoaneurysm
        iii. Acute aortic syndrome evaluation

- Dissection
- Intramural hematoma
- Penetrating atherosclerotic ulcer

iv. Atheroembolic disease—identification of aortic thrombi
v. Vasculitis
vi. Neoplasia, both primary and secondary
vii. Postoperative evaluations
- Perianastomotic leaks
- Infection
- Pseudoaneurysm

viii. Endovascular stent graft, including endoleaks
ix. Congenital disorders, including vascular malformations, arch anomalies, and aortic coarctation
x. Connective tissue disease

b. Coronary arteries
i. Coronary artery anomaly
ii. Atherosclerosis
iii. Vasculitis
iv. Aneurysmal disease (including Kawasaki disease)
v. Coronary artery bypass graft

c. Pulmonary veins
i. Venous mapping before and following radiofrequency (RF) ablation for atrial fibrillation
ii. Pulmonary vein anomalies, including anomalous return and stenosis

d. Pulmonary arteries
i. Thromboembolism
ii. Pulmonary artery hypertension
iii. Stenosis
iv. Vascular malformations
- Pulmonary sequestration
- Pulmonary arteriovenous malformations

v. Neoplastic disease
vi. Preoperative and postoperative assessment of lung transplantation

e. Internal mammary and intercostal vessel evaluations
f. Bronchial arteries and aortopulmonary collateral vessels
g. Congenital or acquired thoracic venous disorders
h. Assessment of preoperative and postoperative status, including known or suspected complications following repair or palliation of congenital cardiovascular disorders in adults and children

II.
INDICATIONS

B.
Specific Considerations

2.
Extremity Evaluations

a. Arteries
i. Atherosclerotic occlusive disease
- Intermittent claudication
- Acute and chronic critical limb ischemia
- Patients with previous interventions (postoperative)
  - Stent grafts
  - Bypass grafts

- Atheroembolism

ii. Congenital anomalies, including vascular malformations
iii. Vasculitides
iv. Arterial fibrodysplasia
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 and grafts with unenhanced MRA
xii. Preoperative mapping of vascular anatomy for plastic surgery graft procedures

b. Assessment for vascular involvement with musculoskeletal tumors
c. Venous evaluations

i. Thrombus
- Central
- Peripheral
- Effort thrombosis of the upper extremity
- Venous compression

ii. Venous malformations
iii. Varicose veins/venous mapping
iv. Assessment for vascular involvement with musculoskeletal tumors
v. Assessment of causes of peripheral edema
- Thrombus
- Venous compression
- Assessment of strictures from indwelling catheters

vi. Assessment of patent vessels for venous access and mapping for surgical creation of native dialysis fistulas and grafts with unenhanced MRA
vii. Assessment of vein suitability as bypass conduits

II.
INDICATIONS

B.
Specific Considerations

3.
Abdominal and pelvic vasculature

a. Diagnosis and/or assessment of the following vascular abnormalities:

i. Aneurysm of the aorta and major 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. Vascular malformation and arteriovenous fistula
v. Portal, mesenteric, or splenic vein thrombosis
vi. Inferior vena cava (IVC), pelvic vein, gonadal vein, renal vein, or hepatic vein thrombosis

b. Vascular evaluation in one of the following clinical scenarios:

i. Lower-extremity claudication
ii. Known or suspected renovascular hypertension
iii. Known or suspected chronic mesenteric ischemia
iv. Hemorrhagic hereditary telangiectasia
v. Known or suspected Budd-Chiari syndrome

vi. Portal hypertension
vii. Known or suspected gonadal vein reflux

c. Preprocedure assessment for the following:
   i. Vascular mapping prior to living organ donation
      - Liver
      - Kidney
      - Pancreas
      - Combined organ transplant
   ii. Assessment of renal vein and IVC patency in the setting of renal malignancy or neoplasm
   iii. Vascular mapping before placement of or surgery on a transjugular intrahepatic portosystemic shunt
   iv. Vascular mapping before resection of abdominal and pelvic neoplasms
   v. Vascular mapping before uterine fibroid embolization
   vi. Vascular mapping before to hepatic bland embolization, chemoembolization, and radioembolization procedures
   vii. Vascular mapping before tissue grafting

d. Postprocedure assessment for the following:
   i. Evaluation of organ transplant vascular anastomoses after organ transplant (hepatic, renal, and pancreatic)
   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

II. INDICATIONS

B. Specific Considerations

4. Pediatric indications for body MRA

MRA is particularly applicable in children because of the risk (albeit low) related to catheter-based angiographic procedures, including risks related to exposure to ionizing radiation [28]. The need and potential risks associated with sedation should be considered. Several studies of children have shown MRA to be useful for assessing vascular abnormalities of the chest, abdomen, and extremities [1, 29-31].
Indications for body MRA for children include, but are not limited to::

a. Congenital anomalies of the aorta, coronary arteries, pulmonary vasculature, and associated branch vessels
b. Aortic, pulmonary arterial, and branch vessel vasculopathies in the setting of a known or suspected syndrome (eg, Marfan syndrome and other connective tissue disorders, midaortic syndrome, neurofibromatosis type 1, and Williams syndrome)
c. Vasculitis
d. Arterial dissection
e. Aneurysmal disease
f. Renovascular hypertension
g. Vascular malformations of the trunk and extremities
h. Central and peripheral venous occlusive disease
i. Congenital venous/portovenous anomalies
j. Presence of thrombosis, including caval, portal, mesenteric, or splenic vein
k. Blood supply to vascular neoplasms for operative planning
l. Vascular anastomoses and complications of organ transplants
m. Postoperative anatomy following vascular surgery
n. Evaluation of surgically created dialysis fistulas and grafts

o. Evaluation of extremity peripheral vasculature in congenital anomalies (eg, Klippel-Trenaunay syndrome)
p. Portal hypertension
q. Arterial and venous thoracic outlet syndrome
r. Assessment of preoperative anatomy

Detailed discussion for additional imaging of the coronary arteries can be found in the ACR–NASCI–SPR Practice Parameter for the Performance and Interpretation of Cardiac Magnetic Resonance Imaging (MRI) [7].

III. QUALIFICATIONS AND RESPONSIBILITIES OF PERSONNEL

See the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [26].

The physician responsible for performing body MRA should be knowledgeable on the benefits, alternatives, and risks of the procedure. The physician must have a thorough understanding of thoracic, abdominal, and extremity anatomy (including congenital or developmental variants and common collateral pathways) as well as the indications, pertinent vascular considerations, and complications associated with common vascular procedures and surgeries.

IV. SPECIFICATIONS OF THE EXAMINATION

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

Documentation that satisfies medical necessity includes 1) signs and symptoms and/or 2) relevant history (including known diagnoses). The provision of 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. (ACR Resolution 35 adopted in 2006 – revised in 2016, Resolution 12-b)

The supervising physician must have adequate understanding of the indications, risks, and benefits of the examination as well as the 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 already undergone. The physician performing MRI interpretation must have a clear understanding and knowledge of the anatomy and pathophysiology relevant to the MRI examination.

The supervising physician should have an understanding of both the clinical indications for body MRA as well as the pulse sequences to be used 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.

IV. SPECIFICATIONS OF THE EXAMINATION

A. Patient Selection and Preparation

The physician responsible for the examination should supervise patient selection and preparation, protocol the examination, and be available in person or by phone for consultation. Patients should be screened and interviewed prior to the examination to exclude individuals who may be at risk by exposure to the MR environment or, in the case of CE-MRA, by exposure to gadolinium-based contrast media (see the ACR–SPR Practice Parameter for the Use of Intravascular Contrast Media [32]) and ACR Manual on MR safety [33].

When intravenous (IV) gadolinium-based contrast media are required for successful performance of MRA, 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–SPR Practice Parameter for the Use of Intravascular Contrast Media [32]).

Patients suffering from anxiety or claustrophobia may require sedation or additional assistance. Administration of moderate sedation may be needed to achieve a successful examination. General anesthesia may be required for certain patients, particularly young children. If moderate sedation is necessary, refer to the ACR–SIR Practice Parameter for Minimal and/or Moderate Sedation/Analgesia [27]. Although in some age groups (generally less than 6 years) some form of sedation may be needed, the need for sedation may be mitigated with the use of an alternative [34, 35], such as use of an audiovisual system during MRI [36] or the "feed-and-sleep" technique in neonates and infants [37].

IV. SPECIFICATIONS OF THE EXAMINATION

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. The equipment, medications, and other emergency support must also be appropriate for the range of ages and sizes in the patient population. Patients with cardiovascular conditions may have additional considerations, and these can be found in the ACCF/ACR/AHA/NASCI/SCMR 2010 Expert Consensus Document on Cardiovascular Magnetic Resonance: A Report of the American College of Cardiology Foundation Task Force on Expert Consensus Documents [38].

IV. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

MRA is a general term that refers to a diverse group of MR pulse sequences. Different mechanisms can be used to generate signal from flowing blood with and without contrast [19-22, 39-41]. The use of contrast media for CE-MRA has the benefit of speed of acquisition and reliable vascular signal for detection of intraluminal defects, such as an intimal tear, as well as the ability to provide time-resolved MRA (TR-MRA). CE-MRA relies on enhancement of the blood signal by intravascular paramagnetic contrast agents, typically gadolinium-based, and uses a rapid, 3-D T1-weighted gradient-echo acquisition [42-44]. Individuals using MRA must understand these concerns as well as those related to the artifacts and limitations of the various MRA techniques available at their sites. Benefits and

technical concerns for MRA vary based on the field strength of the MR scanner [45-47]. MRA performed on a high-field MR scanner (eg, 3T), for instance, offers the advantages of speed and higher vascular signal-to-noise relative to that performed on a low-field 0.5T MR scanner [45]. However, MRA performed on a high-field MR scanner presents concerns related to higher specific absorption rate and artifacts related to metallic susceptibility.

IV. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

1. Noncontrast MRA

The steady-state free-precession (SSFP) sequence aptures the intrinsic T1 and T2 characteristics of blood as a bright signal [48-50]. Two-dimensional and 3-D SSFP MRA techniques employ an unspoiled gradient-echo sequence with balanced gradients, generating a composite signal from free-induction decay and stimulated echoes. The typical balanced SSFP (bSSFP) sequence does not depend on flow and, therefore, does not distinguish flow direction or velocity. Flow-related artifacts are also dramatically reduced with this type of sequence, but the bSSFP is sensitive to artifacts from static magnetic field inhomogeneity (off-resonance artifacts). Because of bSSFP reliance on the T2/T1 signal, intraluminal thrombus may be masked in bSSFP MRA. However, PC-MRA, a flow-based technique, can confirm luminal patency in these cases. Additionally, an asymmetrically applied inversion prepulse can selectively image the abdominal aorta and visceral (eg, renal) arterial branches by effectively nulling the signal from venous blood [19].

a. Nonsubtractive, inflow dependent MRA
   i. Time-of-flight (TOF) sequence remains a fundamental technique for visualizing blood flow without contrast, although its utility is limited by saturation effects in larger fields of view. TOF relies on inflow enhancement to generate images of blood flow [19].
   ii. The most common inflow techniques are 2-D TOF and 3-D TOF. In 2-D TOF, multiple contiguous thin slices are combined to create a 3-D data set from a substantial volume of data. For imaging the aorta and lower extremity arteries with 2-D TOF, cardiac or peripheral gating can reduce vascular pulsation artifacts and improve image quality, although this significantly lengthens the examination [51, 52]. Saturation bands can selectively image blood flow in a particular direction, and in 2-D TOF, these bands can move with the imaging slice to undesirable signals along the vessels of interest [51, 52]. The coverage of 3-D TOF is limited by radiofrequency saturation within the acquisition volume.
   iii. Quiescent inflow slice-selective MRA
   Quiescent inflow slice-selective (QISS) MRA is a variant of TOF that relies on radiofrequency saturation of stationary in-plane spins followed by a delay time to allow inflow enhancement [53-56]. Its primary clinical use is evaluating peripheral arteries, particularly for detecting stenosis. QISS MRA has advantages over other MRA techniques, including a shorter acquisition time that depicts slow flow and is less susceptible to flow-related artifacts. Disadvantages include limited spatial resolution potentially impacting the detection of smaller vessels and dependence on cardiac gating [56].
   iv. Inflow-dependent inversion recovery
   Inflow-dependent inversion recovery is a respiratory-gated 3-D SSFP pulse sequence. It is highly accurate for renal artery imaging [57] but may suffer from image degradation in patients with irregular breathing and incomplete vessel visualization due to slow flow in patients with medical renal disease or severe stenosis [58].

b. Subtractive 3-D MRA
   i. Cardiac-gated subtractive 3-D fast spin-echo
   Cardiac-Gated 3-D Fast Spin-Echo relies on the natural contrast between flowing blood and stationary tissue. It exploits the differences in signal intensity between the systolic and diastolic phases of the cardiac cycle to enhance the visualization of vascular structures. It is particularly

beneficial for detecting vessel wall lesions, such as plaques and dissection, and other abnormalities that may not be apparent on traditional MRA [59, 60]. It is also successfully used in imaging of the renal arteries. The strength of this technique lies in its ability to prevent off-resonance artifacts seen in bSSFP. However, it depends on electrocardiogram gating and is susceptible to misregistration artifacts caused by patient motion [58].

ii. Flow-sensitive dephasing

Flow-sensitive dephasing is comparable to cardiac-gated 3D Fast Spin-Echo; however, it employs an SSFP readout instead of an FSE readout. The application of this method was described in the lower extremities and hands[61-63].

iii. Arterial spin labeling

Arterial spin labeling is a time-resolved imaging technique for assessing blood flow. It involves acquiring two images: a control image providing a background anatomy signal and a labeled image in which an RF pulse alters spin magnetization upstream. Subtraction of these images removes stationary background signal and enhances arterial signal, akin to x-ray digital subtraction angiography. This sequence is effective for rapid flow but misregistration artifacts may arise from patient motion.

c. Velocity-selective 3-D MRA

Velocity-selective 3-D MRA sequences employ radiofrequency (RF) pulses with velocity-dependent gradients to selectively dephase or saturate spins in blood flowing at specific velocities. Different velocity ranges can be targeted by adjusting parameters such as gradient strength and RF pulse duration, enabling the suppression of signal from blood with velocities outside the desired range. As such, appropriately adjusted velocity sensitivity may allow the depiction of the entire vessel. The method's limitations include sensitivity to magnetic field inhomogeneities (B0 and B1) leading to artifacts or signal loss and difficulty suppressing signal from tissues with short T1 relaxation times, such as subacute hemorrhage [58].

d. PC

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. The display of the vessels is similar to that of the TOF technique, although the direction of flow can also be indicated without the need for saturation bands. As with TOF, PC-MRA can be obtained as a 2-D or 3-D data set (ie, 4-D flow MRI).

The PC technique offers the advantage of quantifying blood flow velocity and rate. However, it has limitations, such as aliasing artifacts due to high velocity encoding sensitivity and the long scan times, especially in 4-D flow.

IV. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

2. CE-MRA

3-D CE-MRA combines a fast T1-weighted gradient-echo acquisition with an intravenously administered paramagnetic contrast agent. There are now a variety of contrast agents available for performance of CE-MRA that may differ in terms of relaxivity, gadolinium concentration, biodistribution, elimination, and various safety concerns (see the ACR Manual on Contrast Media) [12, 41, 64-68]. For example, higher-relaxivity gadolinium-chelate extracellular contrast agents can provide improved vascular signal-to-noise and contrast-to-noise ratios for an equimolar dose of a lower-relaxivity gadolinium-chelate extracellular contrast agent. Such agents reduce T1 relaxation time of blood and nearly eliminate the loss of signal related to saturation effects and flow-related artifacts due to intravoxel dephasing, thus leading to a more accurate assessment of stenosis [69]. CE-MRA has

documented efficacy in assessing the arterial and venous systems in the thorax, abdomen, pelvis, and extremities [2, 5, 69-82]. In most cases, CE-MRA does not require cardiac gating and is, therefore, easily applicable in patients with irregular cardiac rhythms. The coronary arteries and aortic root, however, move quite significantly during each cardiac cycle, and CE-MRA of these vessels typically benefits from proper cardiac gating [83, 84]. Using breath-holding during MRA often minimizes imaging artifacts related to respiratory motion. Respiratory-gated MRA using navigator echoes that synchronize image acquisition with the respiratory cycle in real time can often achieve higher-resolution 3-D MRA, notably in patients with limited breath-holding ability. These advantages make CE-MRA extremely useful for imaging of the vasculature in the thorax, abdomen, pelvis, and extremities. CE-MRA techniques can be combined with a moving table to allow large areas of coverage [85-87]. Contemporary k-space filling and parallel imaging techniques allow for high-temporal-resolution (time-resolved) imaging of vascular territories [41, 45, 88-91], potentially eliminating the need for precise acquisition timing. Alternatively, accurate timing of acquisition can be enhanced through the use of a timing bolus, "fluoroscopic triggering," or automatic bolus detection techniques [92-94]. It is important for non–TR-MRA that the contrast bolus duration matches the image acquisition duration to avoid either edge enhancement or blurring secondary to the changing contrast concentration in the vessels of interest throughout the scan. This can be done by adjusting the injection rate. CE-MRA is typically performed during the first pass of the bolus but often includes equilibrium phase acquisitions, which provide time-resolved vascular information. Postcontrast imaging using SSFP MRA [95] and PC-MRA [93] can often provide supplemental vascular information to CE-MRA even when performed well after the first pass of the bolus.

More recently, Ferumoxytol, a nongadolinium-based USPIO contrast agent, has been reported to successfully yield high-quality CE-MRA [13-18]; This is an off-label use, as Ferumoxytol was initially approved by the Food and Drug Administration as an iron replacement therapy for patients with anemia due to chronic renal failure [96]. Ferumoxytol does not pose a risk of NSF because it is not a gadolinium-based contrast agent. Although recent studies suggest an excellent safety profile, careful consideration to relative risk and benefit is nonetheless required, given that the agent has a "black box" warning from the FDA and anaphylactic reactions resulting in death have been reported. Ferumoxytol has a long intravascular half-life on the order of 14-15 hours, much longer than that of traditional extracellular gadolinium-based contrast agents.[96]. Ferumoxytol must be diluted and administered via slow IV infusion under supervision over a minimum of 15 minutes. The typical dose of Ferumoxytol is 3 mg of Ferumoxytol per kg of body weight, with a dosing range of 1-5 mg Fe/kg [97].

IV. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

3. Special Considerations

a. MR venography

Venous illustration can be achieved using both noncontrast and CE-MRA methods. Indications for MRV are listed above. Contrast-enhanced MR venography (CE-MRV) is implemented in much the same way as CE-MRA, whereby an IV gadolinium-based contrast agent injection is combined with the acquisition of a 3-D T1-weighted spoiled gradient-echo data set [98]. Digital subtraction of a precontrast mask from a postcontrast acquisition may improve depiction of venous structures, but this is not considered essential. Exact timing of the contrast bolus is less critical for venous imaging. Selection of an empiric delay time of 40–60 seconds following the contrast injection, which allows time for the contrast agent to fully equilibrate in the venous system, is usually adequate. The use of a blood pool contrast agent is particularly advantageous when imaging venous structures because it remains within the circulation for several hours after the initial injection [99]. Blood pool contrast agents ensure prolonged increase in vascular signal for high spatial resolution steady state CE-MRV. Respiratory gating can be used for equilibrium phase imaging

in the thorax to allow free-breathing image acquisition. Ferumoxytol, which has a prolonged vascular half-life and does not have the same patient safety concerns (eg, NSF) as gadolinium-based contrast agents, may be particularly appropriate for MRV.

Noncontrast MRV is another option for MRV in patients with renal dysfunction, pregnancy, gadolinium-based contrast agent allergy, and in children [12, 100]. Noncontrast MRV is best achieved with SSFP or turbo spin-echo [101] imaging approaches. Electrocardiogram or respiratory gating can be employed in the chest to offset motion artifact, and inversion recovery may be used to improve contrast and background suppression. TOF imaging, which depends on the generation of signal from flowing blood, may also be used for imaging the venous system and is best suited to the portal and intracranial circulations.

There are some specific clinical disorders of the venous system in which additional maneuvers or techniques may be helpful for further disease characterization. Venous imaging using TR-MRA, which allows direct visualization of the physiologic blood flow dynamics, is helpful for the diagnosis of pelvic congestion syndrome because of its ability to determine temporal filling and whether anterograde or retrograde flow is present in the ovarian vein [102]. Provocative positioning of the patient may be required in some instances for final diagnosis. In Paget-Schroetter syndrome (ie, effort-induced thrombosis), for example, MRV, either during first pass or steady state, may need to be performed during both arm adduction and arm abduction to demonstrate dynamic compression of the subclavian vein between clavicle and rib.

b. Pediatric Patients

In infancy and childhood, MRA can provide valuable information about the vascular system, particularly for assessing various types of vascular malformations and syndromes, congenital lesions, such as coarctation of the aorta, or anomalous pulmonary venous return. However, technical and safety issues are more complex in pediatric patients. The smaller size of vasculature increases the demand for higher spatial resolution, and more rapid circulation time requires higher temporal resolution. In addition, sedation and/or general anesthesia may be necessary to successfully complete the examination, depending on the age of the child or possibly the complexity of the clinical questions being answered. Many of these concerns have been discussed earlier in this document by suggesting noncontrast, free-breathing high-resolution MRA imaging or using the "feed-and-bundle" method without need for sedation. Regarding the safety of using gadolinium-based contrast agents in neonates, readers are referred to the ACR–SPR Practice Parameter for the Use of Intravascular Contrast Media [32]. Given the small body size of some pediatric patients, certain clinical applications of CE-MRA may necessitate dilution of contrast media to increase the volume of the administered contrast.

c. MRA Interpretation

The supervising physician should review all MRA 2-D source images to reduce possible confusion of high-signal material (eg, fat or thrombus) with flow signal. Review of the source images also aids diagnosis by eliminating overlapping structures and determining whether artifacts are the cause of spurious signal or signal loss.

MRA data are routinely postprocessed using multiplanar reformation (MPR), maximum intensity projection (MIP) reconstruction, and volume-rendering techniques. Rotating displays of 3-D data sets allow separation of vessels that are superimposed on a single projection. Additionally, multiple views are needed to fully depict altered vascular anatomy. Targeted MIP renderings can be made to clarify areas of tortuosity and vessel overlap. However, if there is any uncertainty in rendered images, source images should be relied on because they provide original, unaltered anatomy. The supervising physician must be familiar with MPR, MIP, and volume-rendering 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 associated with each display method [103-109]. Optimized pulse sequences and quantitative postprocessing tools for evaluating blood vessel caliber, flow velocity, volume, and direction should be used when indicated clinically.

V. DOCUMENTATION

Reporting should be in accordance with the ACR Practice Parameter for Communication of Diagnostic Imaging Findings [110].

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.

In addition, if contrast agents are used for MRA, the dose, method of injection, and type of contrast agent administered must be documented.

Specific policies and procedures related to MRI safety should be in place with documentation that is updated annually and compiled under the supervision of the MR director. Guidelines that deal with potential hazards associated with the MRI examination of the patient as well as to others in the immediate area should be provided [33]. Screening forms must also be provided to detect those patients who may be at risk for adverse events associated with the MRI examination.

Peer-reviewed literature pertaining to MR safety should be reviewed on a regular basis [33].

For additional safety considerations, see the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [26], the ACR Manual on MR Safety [33], and the ACR Manual on Contrast Media [12].

VI. EQUIPMENT SPECIFICATIONS

The MRI equipment specifications and performance must 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 RF power deposition (specific absorption rate), and maximum acoustic noise levels.

Equipment monitoring should be in accordance with the ACR–AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance (MR) Imaging Equipment [111].

VII. QUALITY CONTROL AND IMPROVEMENT, SAFETY, INFECTION CONTROL, AND PATIENT EDUCATION

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 appearing under the heading *ACR Position Statement on Quality Control and Improvement, Safety, Infection Control and Patient Education* on the ACR website (https://www.acr.org/Advocacy-and-Economics/ACR-Position-Statements/Quality-Control-and-Improvement).

ACKNOWLEDGEMENTS

This practice parameter was revised according to the process described under the heading *The Process for Developing ACR Practice Parameters and Technical Standards* on the ACR website (https://www.acr.org/Clinical-Resources/Practice-Parameters-and-Technical-Standards) by the Committee on Body Imaging (Cardiovascular) of the Commission on Body Imaging and by the Committee on Practice Parameters – Pediatric Imaging of the Commission on Pediatric Radiology, in collaboration with the NASCI and the SPR.

Writing Committee – members represent their societies in the initial and final revision of this practice parameter

ACR
Casaburi, Larissa Braga MD, MPH, PhD, Chair
Battey, Thomas W K MD
Collard, Michael MD
Hagspiel, Klaus MD
Lee, Yoo Jin MD
Rivard, Andrew L. MD

NASCI
Allen, Bradley D MD
Bergmann, Liisa MD
Karur, Gauri Rani MD
Young, Phillip M MD

SPR
Griffin, Lindsay M MD
Otero, Hansel J MD
Priya, Sarv MD
Smalley, Robert MD

Committee on Cardiovascular Imaging – Body Imaging
(ACR Committee responsible for sponsoring the draft through the process)

Hagspiel, Klaus MD, Chair
Casaburi, Larissa Braga MD, MPH, PhD
Prosper, Ashley MD
Blasco, Lucia Flors MD, PhD
Lee, Yoo Jin MD
Rivard, Andrew L. MD

Committee on Practice Parameters and Technical Standards
(ACR Committee responsible for sponsoring the draft through the process)

Caplin, Drew M MD, Chair

Committee on Practice Parameters – Pediatric Imaging
(ACR Committee responsible for sponsoring the draft through the process)

Amodio, John B MD, Chair
Betz, Bradford W MD
Collard, Michael MD
Lai, Hollie A MD
Lasiecka, Zofia M MD, PhD
Levin, Terry L MD
Maloney, John A MD
Shah, Summit MD
Vatsky, Seth DO
Alizai, Hamza MD
Blumfield, Einat MD
Goldman-Yassen, Adam MD
Lala, Shailee V MD
Laufer, Adina MD
Li, Arleen MD
Noda, Sakura MD
Trout, Andrew T MD

Bulas, Dorothy I MD, Chair, Commission on Pediatric Radiology
Larson, David B MBA, MD, Chair, Commission on Quality and Safety
Rosenkrantz, Andrew MD, Chair, Commission on Body Imaging

Comments Reconciliation Committee

Optican, Robert MD - CSC, Co-Chair
Allen, Bradley D MD
Battey, Thomas W K MD
Bulas, Dorothy I MD
Collard, Michael MD
Griffin, Lindsay M MD
Karur, Gauri Rani MD
Lee, Yoo Jin MD
Priya, Sarv MD
Rosenkrantz, Andrew MD
Young, Phillip M MD

Schoppe, Kurt MD - CSC, Chair
Amodio, John B MD
Bergmann, Liisa MD
Casaburi, Larissa Braga MD, MPH, PhD
Crummy, Timothy MD, MHA - CSC
Hagspiel, Klaus MD
Larson, David B MBA, MD
Otero, Hansel J MD
Rivard, Andrew L. MD
Smalley, Robert MD

REFERENCES

1. [18380760] Cantinotti M, Hegde S, Bell A, Razavi R. Diagnostic role of magnetic resonance imaging in identifying aortic arch anomalies. Congenit Heart Dis. 2008;3(2):117-23.
2. [18492924] Ersoy H, Rybicki FJ. MR angiography of the lower extremities. AJR. 2008;190(6):1675-1684.
3. [15760761] Koss SA, Yucel EK. Role of MR angiography in vascular interventional planning. Magn Reson Imaging Clin N Am. 2005 Feb;13(1):153-60, vi.
4. [18287451] Lohan DG, Tomasian A, Krishnam M, Jonnala P, Blackwell KE, Finn JP. MR angiography of lower extremities at 3 T: presurgical planning of fibular free flap transfer for facial reconstruction. AJR Am J Roentgenol. 190(3):770-6, 2008 Mar.
5. [19098189] Poschenrieder F, Hamer OW, Herold T, et al. Diagnostic accuracy of intraarterial and i.v. MR angiography for the detection of stenoses of the infrainguinal arteries. AJR Am J Roentgenol. 2009 Jan;192(1):117-21.
6. [-3102215] American College of Radiology. ACR–ASNR–SNIS–SPR Practice Parameter for the Performance of Cervicocerebral Magnetic Resonance Angiography (MRA). Available at: https://gravitas.acr.org/PPTS/GetDocumentView?docId=73+&releaseId=2
7. [-3197717] American College of Radiology. ACR-NASCI-SPR Practice Parameter for the Performance and Interpretation of Cardiac Magnetic Resonance Imaging (MRI). Available at https://gravitas.acr.org/PPTS/GetDocumentView?docId=179+&releaseId=2
8. [16431890] Grobner T. Gadolinium--a specific trigger for the development of nephrogenic fibrosing dermopathy and nephrogenic systemic fibrosis? Nephrol Dial Transplant. 2006; 21(4):1104-1108.
9. [19019996] Juluru K, Vogel-Claussen J, Macura KJ, Kamel IR, Steever A, Bluemke DA. MR imaging in patients at risk for developing nephrogenic systemic fibrosis: protocols, practices, and imaging techniques to maximize patient safety. Radiographics. 2009;29(1):9-22.
10. [17213364] Kuo PH, Kanal E, Abu-Alfa AK, Cowper SE. Gadolinium-based MR contrast agents and nephrogenic systemic fibrosis. Radiology. 2007 Mar;242(3):647-9.
11. [16885403] Marckmann P, Skov L, Rossen K, et al. Nephrogenic systemic fibrosis: suspected causative role of gadodiamide used for contrast-enhanced magnetic resonance imaging. J Am Soc Nephrol. 2006 Sep;17(9):2359-62.
12. [-3188535] American College of Radiology. ACR Committee on Drugs and Contrast Media. Manual on Contrast Media. Available at: https://www.acr.org/Clinical-Resources/Clinical-Tools-and-Reference/Contrast-Manual.
13. [26102308] Hope MD, Hope TA, Zhu C, et al. Vascular Imaging With Ferumoxytol as a Contrast Agent. AJR 2015;205:W366-73.
14. [27504713] Fananapazir G, Bashir MR, Corwin MT, Lamba R, Vu CT, Troppmann C. Comparison of ferumoxytol-enhanced MRA with conventional angiography for assessment of severity of transplant renal artery stenosis. J Magn Reson Imaging. 45(3):779-785, 2017 03.
15. [27678106] Lai LM, Cheng JY, Alley MT, Zhang T, Lustig M, Vasanawala SS. Feasibility of ferumoxytol-enhanced neonatal and young infant cardiac MRI without general anesthesia. J Magn Reson Imaging. 45(5):1407-1418, 2017 05.
16. [29731126] Lehrman ED, Plotnik AN, Hope T, Saloner D. Ferumoxytol-enhanced MRI in the peripheral

vasculature. Clin Radiol. 2019 Jan;74(1):S0009-9260(18)30126-0.
17. [31228293] Knobloch G, Colgan T, Schiebler ML, et al. Comparison of gadolinium-enhanced and ferumoxytol-enhanced conventional and UTE-MRA for the depiction of the pulmonary vasculature. Magn Reson Med. 2019 Nov;82(5):1660-1670.
18. [27862577] Schubert T, Motosugi U, Kinner S, et al. Crossover comparison of ferumoxytol and gadobenate dimeglumine for abdominal MR-angiography at 3.0 tesla: Effects of contrast bolus length and flip angle. J Magn Reson Imaging. 2017 Jun;45(6):1617-1626.
19. [18566168] Miyazaki M, Lee VS. Nonenhanced MR angiography. Radiology. 2008; 248(1):20-43.
20. [22173999] Miyazaki M, Akahane M. Non-contrast enhanced MR angiography: Established techniques. J Magn Reson Imaging. 2012;35(1):1-19.
21. [21415179] Morita S, Masukawa A, Suzuki K, Hirata M, Kojima S, Ueno E. Unenhanced MR angiography: techniques and clinical applications in patients with chronic kidney disease. Radiographics. 2011;31(2):E13-33.
22. [22807222] Wheaton AJ, Miyazaki M. Non-contrast enhanced MR angiography: physical principles. J Magn Reson Imaging. 2012 Aug;36(2):286-304.
23. [23988640] Gupta A, Baradaran H, Schweitzer AD, et al. Carotid plaque MRI and stroke risk: a systematic review and meta-analysis. Stroke 2013;44:3071-7.
24. [31202755] Schindler A, Schinner R, Altaf N, et al. Prediction of Stroke Risk by Detection of Hemorrhage in Carotid Plaques: Meta-Analysis of Individual Patient Data. JACC Cardiovasc Imaging. 13(2 Pt 1):395-406, 2020 02.
25. [20404256] Hellings WE, Peeters W, Moll FL, et al. Composition of carotid atherosclerotic plaque is associated with cardiovascular outcome: a prognostic study. Circulation. 2010 May 04;121(17):1941-50.
26. [-3098654] American College of Radiology. ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI). Available at: https://gravitas.acr.org/PPTS/GetDocumentView?docId=146+&releaseId=2
27. [-3197619] American College of Radiology. ACR–SIR Practice Parameter For Minimal and/or Moderate Sedation/Analgesia. Available at https://gravitas.acr.org/PPTS/GetDocumentView?docId=95+&releaseId=2
28. [6729111] Geard CR, Osmak RS, Hall EJ, Simon HE, Maudsley AA, Hilal SK. Magnetic resonance and ionizing radiation: a comparative evaluation in vitro of oncogenic and genotoxic potential. Radiology. 1984 Jul;152(1):199-202.
29. [15221239] Chung T. Magnetic resonance angiography of the body in pediatric patients: experience with a contrast-enhanced time-resolved technique. Pediatr Radiol. 2005 Jan;35(1):3-10.
30. [15565341] Grist TM, Thornton FJ. Magnetic resonance angiography in children: technique, indications, and imaging findings. Pediatr Radiol. 2005 Jan;35(1):26-39.
31. [17597422] Uçar T, Fitoz S, Tutar E, Atalay S, Uysalel A. Diagnostic tools in the preoperative evaluation of children with anomalous pulmonary venous connections. Int J Cardiovasc Imaging. 2008 Feb;24(2):229-35.
32. [-3197748] American College of Radiology. ACR–SPR Practice Parameter for the use of Intravascular Contrast Media. Available at https://gravitas.acr.org/PPTS/GetDocumentView?docId=142+&releaseId=2
33. [-3188538] American College of Radiology. ACR Committee on MR Safety. 2024 ACR Manual on MR Safety. Available at: https://edge.sitecorecloud.io/americancoldf5f-acrorgf92a-productioncb02-3650/media/ACR/Files/Clinical/Radiology-Safety/Manual-on-MR-Safety.pdf.
34. [27601689] McGuirt D. Alternatives to Sedation and General Anesthesia in Pediatric Magnetic Resonance Imaging: A Literature Review. Radiol Technol. 2016 Sep;88(1):18-26.
35. [21678113] Edwards AD, Arthurs OJ. Paediatric MRI under sedation: is it necessary? What is the evidence for the alternatives?. Pediatr Radiol. 2011 Nov;41(11):1353-64.
36. [19630083] Lemaire C, Moran GR, Swan H. Impact of audio/visual systems on pediatric sedation in magnetic resonance imaging. J Magn Reson Imaging. 2009 Sep;30(3):649-55.
37. [21861089] Windram J, Grosse-Wortmann L, Shariat M, Greer ML, Crawford MW, Yoo SJ. Cardiovascular MRI without sedation or general anesthesia using a feed-and-sleep technique in neonates and infants. Pediatr Radiol. 2012 Feb;42(2):183-7.
38. [20513610] American College of Cardiology Foundation Task Force on Expert Consensus Documents, Hundley WG, Bluemke DA, et al. ACCF/ACR/AHA/NASCI/SCMR 2010 expert consensus document on cardiovascular magnetic resonance: a report of the American College of Cardiology Foundation Task Force on Expert Consensus Documents. [Review] [426 refs]. J Am Coll Cardiol. 55(23):2614-62, 2010 Jun 08.
39. [-3197760] Lohan DG, Saleh R, Nael K, Krishnam M, Finn JP. Contrast-enhacend MRA versus nonenhanced MRA: pros and cons. Appl Radiol 2007;36 (suppl):3-15.
40. [19364602] Kramer H, Nikolaou K, Sommer W, Reiser MF, Herrmann KA. Peripheral MR angiography. Magn Reson Imaging Clin N Am. 2009 Feb;17(1):91-100.

41. [23712843] Morelli JN, Gerdes CM, Schmitt P, et al. Technical considerations in MR angiography: an image-based guide. J Magn Reson Imaging. 2013 Jun;37(6):1326-41.
42. [17893051] Michaely HJ, Attenberger UI, Kramer H, Nael K, Reiser MF, Schoenberg SO. Abdominal and pelvic MR angiography. Magn Reson Imaging Clin N Am. 2007 Aug;15(3):301-14, v-vi.
43. [8134563] Prince MR. Gadolinium-enhanced MR aortography. Radiology. 1994 Apr;191(1):155-64.
44. [8673710] Prince MR. Body MR angiography with gadolinium contrast agents. Magn Reson Imaging Clin N Am. 1996 Feb;4(1):11-24.
45. [21388544] Hartung MP, Grist TM, Francois CJ. Magnetic resonance angiography: current status and future directions. J Cardiovasc Magn Reson 2011;13:19.
46. [23064714] Umutlu L, Maderwald S, Kinner S, et al. First-pass contrast-enhanced renal MRA at 7 Tesla: initial results. Eur Radiol. 2013 Apr;23(4):1059-66.
47. [23143021] van den Bosch HC, Westenberg JJ, Caris R, et al. Peripheral arterial occlusive disease: 3.0-T versus 1.5-T MR angiography compared with digital subtraction angiography. Radiology. 2013 Jan;266(1):337-46.
48. [14990821] Coenegrachts KL, Hoogeveen RM, Vaninbroukx JA, et al. High-spatial-resolution 3D balanced turbo field-echo technique for MR angiography of the renal arteries: initial experience. Radiology. 2004 Apr;231(1):237-42.
49. [15327427] Katoh M, Buecker A, Stuber M, Günther RW, Spuentrup E. Free-breathing renal MR angiography with steady-state free-precession (SSFP) and slab-selective spin inversion: initial results. Kidney Int. 2004 Sep;66(3):1272-8.
50. [19365850] Cukur T, Lee JH, Bangerter NK, Hargreaves BA, Nishimura DG. Non-contrast-enhanced flow-independent peripheral MR angiography with balanced SSFP. Magn Reson Med. 2009 Jun;61(6):1533-9.
51. [10050798] Steffens JC, Link J, Schwarzenberg H, Mueller-Huelsbeck S, Brinkmann G, Heller M. Lower extremity occlusive disease: diagnostic imaging with a combination of cardiac-gated 2D phase-contrast and cardiac-gated 2D time-of-flight MRA. J Comput Assist Tomogr. 1999;23(1):7-12.
52. [8686623] Glickerman DJ, Obregon RG, Schmiedl UP, et al. Cardiac-gated MR angiography of the entire lower extremity: a prospective comparison with conventional angiography. AJR Am J Roentgenol. 1996 Aug;167(2):445-51.
53. [24338813] Hansmann J, Morelli JN, Michaely HJ, et al. Nonenhanced ECG-gated quiescent-interval single shot MRA: image quality and stenosis assessment at 3 tesla compared with contrast-enhanced MRA and digital subtraction angiography. J Magn Reson Imaging. 2014;39(6):1486-1493.
54. [25697720] Wagner M, Knobloch G, Gielen M, et al. Nonenhanced peripheral MR-angiography (MRA) at 3 Tesla: evaluation of quiescent-interval single-shot MRA in patients undergoing digital subtraction angiography. Int J Cardiovasc Imaging. 31(4):841-50, 2015 Apr.
55. [28109932] Varga-Szemes A, Wichmann JL, Schoepf UJ, et al. Accuracy of Noncontrast Quiescent-Interval Single-Shot Lower Extremity MR Angiography Versus CT Angiography for Diagnosis of Peripheral Artery Disease: Comparison With Digital Subtraction Angiography. JACC Cardiovasc Imaging. 10(10 Pt A):1116-1124, 2017 10.
56. [29336780] Edelman RR, Carr M, Koktzoglou I. Advances in non-contrast quiescent-interval slice-selective (QISS) magnetic resonance angiography. Clin Radiol. 2019 Jan;74(1):S0009-9260(17)30567-6.
57. [27536710] Sebastia C, Sotomayor AD, Pano B, et al. Accuracy of unenhanced magnetic resonance angiography for the assessment of renal artery stenosis. Eur J Radiol Open. 3:200-6, 2016.
58. [30566270] Edelman RR, Koktzoglou I. Noncontrast MR angiography: An update. J Magn Reson Imaging 2019;49:355-73.
59. [21098208] Hoey ET, Ganeshan A, Puni R, Henderson J, Crowe PM. Fresh blood imaging of the peripheral vasculature: an emerging unenhanced MR technique. AJR Am J Roentgenol. 2010; 195(6):1444-1448.
60. [21330081] Miyazaki M, Isoda H. Non-contrast-enhanced MR angiography of the abdomen. Eur J Radiol. 2011 Oct;80(1):9-23.
61. [19877278] Fan Z, Sheehan J, Bi X, Liu X, Carr J, Li D. 3D noncontrast MR angiography of the distal lower extremities using flow-sensitive dephasing (FSD)-prepared balanced SSFP. Magn Reson Med. 2009 Dec;62(6):1523-32.
62. [21330560] Sheehan JJ, Fan Z, Davarpanah AH, et al. Nonenhanced MR angiography of the hand with flow-sensitive dephasing-prepared balanced SSFP sequence: initial experience with systemic sclerosis. Radiology. 2011 Apr;259(1):248-56.
63. [23440691] Priest AN, Joubert I, Winterbottom AP, See TC, Graves MJ, Lomas DJ. Initial clinical evaluation of a non-contrast-enhanced MR angiography method in the distal lower extremities. Magn Reson Med. 2013 Dec;70(6):1644-52.
64. [21458187] Nael K, Moriarty JM, Finn JP. Low dose CE-MRA. Eur J Radiol. 2011;80(1):2-8.

65. [23680931] Bashir MR, Jaffe TA, Brennan TV, Patel UD, Ellis MJ. Renal transplant imaging using magnetic resonance angiography with a nonnephrotoxic contrast agent. Transplantation. 96(1):91-6, 2013 Jul 15.
66. [23701079] Sabach AS, Bruno M, Kim D, et al. Gadofosveset trisodium: abdominal and peripheral vascular applications. AJR Am J Roentgenol. 2013 Jun;200(6):1378-86.
67. [27613998] Kanda T, Nakai Y, Oba H, Toyoda K, Kitajima K, Furui S. Gadolinium deposition in the brain. Magn Reson Imaging. 2016 Dec;34(10):S0730-725X(16)30139-4.
68. [30032482] Layne KA, Dargan PI, Archer JRH, Wood DM. Gadolinium deposition and the potential for toxicological sequelae - A literature review of issues surrounding gadolinium-based contrast agents. Br J Clin Pharmacol. 2018 Nov;84(11):2522-2534.
69. [17259830] Hahn WY, Hecht EM, Friedman B, Babb JS, Jacobowitz GR, Lee VS. Distal lower extremity imaging: prospective comparison of 2-dimensional time of flight, 3-dimensional time-resolved contrast-enhanced magnetic resonance angiography, and 3-dimensional bolus chase contrast-enhanced magnetic resonance angiography. J Comput Assist Tomogr. 2007; 31(1):29-36.
70. [12630683] Vogt FM, Goyen M, Debatin JF. MR angiography of the chest. Radiol Clin North Am. 2003 Jan;41(1):29-41.
71. [12933470] Herborn CU, Goyen M, Lauenstein TC, Debatin JF, Ruehm SG, Kröger K. Comprehensive time-resolved MRI of peripheral vascular malformations. AJR Am J Roentgenol. 2003 Sep;181(3):729-35.
72. [16958067] Du J, Thornton FJ, Mistretta CA, Grist TM. Dynamic MR venography: an intrinsic benefit of time-resolved MR angiography. J Magn Reson Imaging. 2006 Oct;24(4):922-7.
73. [16985163] Mohrs OK, Petersen SE, Voigtlaender T, et al. Time-resolved contrast-enhanced MR angiography of the thorax in adults with congenital heart disease. AJR Am J Roentgenol. 2006;187(4):1107-1114.
74. [17142706] Cantwell CP, Cradock A, Bruzzi J, Fitzpatrick P, Eustace S, Murray JG. MR venography with true fast imaging with steady-state precession for suspected lower-limb deep vein thrombosis. J Vasc Interv Radiol. 2006;17(11 Pt 1):1763-1769.
75. [17489082] Koizumi J, Horie T, Muro I, et al. Magnetic resonance venography of the lower limb. Int Angiol. 2007 Jun;26(2):171-82.
76. [18349313] Kim CY, Mirza RA, Bryant JA, et al. Central veins of the chest: evaluation with time-resolved MR angiography. Radiology. 2008;247(2):558-566.
77. [20846985] Dick EA, Burnett C, Anstee A, Hamady M, Black D, Gedroyc WM. Time-resolved imaging of contrast kinetics three-dimensional (3D) magnetic resonance venography in patients with pelvic congestion syndrome. Br J Radiol. 2010;83(994):882-887.
78. [21085962] Kirby JM, Burrows D, Haider E, Maizlin Z, Midia M. Utility of MRI before and after uterine fibroid embolization: why to do it and what to look for. [Review]. Cardiovasc Intervent Radiol. 34(4):705-16, 2011 Aug.
79. [22031489] Zou Z, Kate Lee H, Levine JL, et al. Gadofosveset trisodium-enhanced abdominal perforator MRA. J Magn Reson Imaging. 2012 Mar;35(3):711-6.
80. [22843836] Nielsen YW, Thomsen HS. Contrast-enhanced peripheral MRA: technique and contrast agents. Acta Radiol. 2012 Sep 01;53(7):769-77.
81. [23088949] Kramer JH, Grist TM. Peripheral MR Angiography. Magn Reson Imaging Clin N Am. 2012 Nov;20(4):S1064-9689(12)00094-3.
82. [23545949] Fink C, Henzler T, Shirinova A, Apfaltrer P, Wasser K. Thoracic magnetic resonance imaging: pulmonary thromboembolism. [Review]. Journal of Thoracic Imaging. 28(3):171-7, 2013 May.
83. [21786125] Vasanawala SS, Chan FP, Newman B, Alley MT. Combined respiratory and cardiac triggering improves blood pool contrast-enhanced pediatric cardiovascular MRI. Pediatr Radiol. 2011 Dec;41(12):1536-44.
84. [23617479] Young PM, McGee KP, Pieper MS, et al. Tips and tricks for MR angiography of pediatric and adult congenital cardiovascular diseases. AJR Am J Roentgenol. 2013 May;200(5):980-8.
85. [10189454] 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(1):59-67.
86. [11536410] Kita M, Mitani Y, Tanihata H, et al. Moving-table reduced-dose gadolinium-enhanced three-dimensional magnetic resonance angiography: velocity-dependent method with three-phase gadolinium infusion. J Magn Reson Imaging. 2001 Sep;14(3):319-28.
87. [9494486] Ho KY, Leiner T, de Haan MW, Kessels AG, Kitslaar PJ, van Engelshoven JM. Peripheral vascular tree stenoses: evaluation with moving-bed infusion-tracking MR angiography. Radiology. 1998 Mar;206(3):683-92.
88. [11012458] Sodickson DK, McKenzie CA, Li W, Wolff S, Manning WJ, Edelman RR. Contrast-enhanced 3D MR angiography with simultaneous acquisition of spatial harmonics: A pilot study. Radiology. 217(1):284-9, 2000 Oct.
89. [17179394] Andreisek G, Pfammatter T, Goepfert K, et al. Peripheral arteries in diabetic patients: standard

bolus-chase and time-resolved MR angiography. Radiology. 2007;242(2):610-620.
90. [17717331] Sutter R, Nanz D, Lutz AM, et al. Assessment of aortoiliac and renal arteries: MR angiography with parallel acquisition versus conventional MR angiography and digital subtraction angiography. Radiology. 245(1):276-84, 2007 Oct.
91. [8875403] Korosec FR, Frayne R, Grist TM, Mistretta CA. Time-resolved contrast-enhanced 3D MR angiography. Magn Reson Med. 1996 Sep;36(3):345-51.
92. [8939219] Earls JP, Rofsky NM, DeCorato DR, Krinsky GA, Weinreb JC. Breath-hold single-dose gadolinium-enhanced three-dimensional MR aortography: usefulness of a timing examination and MR power injector. Radiology. 1996 Dec;201(3):705-10.
93. [9314974] Prince MR, Schoenberg SO, Ward JS, Londy FJ, Wakefield TW, Stanley JC. Hemodynamically significant atherosclerotic renal artery stenosis: MR angiographic features. Radiology. 1997; 205(1):128-136.
94. [9314975] Wilman AH, Riederer SJ, King BF, Debbins JP, Rossman PJ, Ehman RL. Fluoroscopically triggered contrast-enhanced three-dimensional MR angiography with elliptical centric view order: application to the renal arteries. Radiology. 1997 Oct;205(1):137-46.
95. [12353288] Foo TK, Ho VB, Marcos HB, Hood MN, Choyke PL. MR angiography using steady-state free precession. Magn Reson Med. 2002 Oct;48(4):699-706.
96. [24974785] Bashir MR, Bhatti L, Marin D, Nelson RC. Emerging applications for ferumoxytol as a contrast agent in MRI. J Magn Reson Imaging. 2015 Apr;41(4):884-98.
97. [36197052] Adams LC, Jayapal P, Ramasamy SK, et al. Ferumoxytol-Enhanced MRI in Children and Young Adults: State of the Art. AJR Am J Roentgenol. 2023 Apr;220(4):590-603.
98. [10511166] Thornton MJ, Ryan R, Varghese JC, Farrell MA, Lucey B, Lee MJ. A three-dimensional gadolinium-enhanced MR venography technique for imaging central veins. AJR Am J Roentgenol. 1999 Oct;173(4):999-1003.
99. [17639407] Bremerich J, Bilecen D, Reimer P. MR angiography with blood pool contrast agents. Eur Radiol. 2007 Dec;17(12):3017-24.
100. [30406414] Dillman JR, Trout AT, Merrow AC, et al. Non-contrast three-dimensional gradient recalled echo Dixon-based magnetic resonance angiography/venography in children. Pediatr Radiol. 2019 Mar;49(3):407-414.
101. [18647930] Ito K, Koike S, Shimizu A, et al. Portal venous system: evaluation with unenhanced MR angiography with a single-breath-hold ECG-synchronized 3D half-Fourier fast spin-echo sequence. AJR Am J Roentgenol. 2008 Aug;191(2):550-4.
102. [20815070] Pandey T, Shaikh R, Viswamitra S, Jambhekar K. Use of time resolved magnetic resonance imaging in the diagnosis of pelvic congestion syndrome. J Magn Reson Imaging. 2010 Sep;32(3):700-4.
103. [11997561] Mallouhi A, Schocke M, Judmaier W, et al. 3D MR angiography of renal arteries: comparison of volume rendering and maximum intensity projection algorithms. Radiology. 2002; 223(2):509-516.
104. [12664119] Fink C, Hallscheidt PJ, Hosch WP, et al. Preoperative evaluation of living renal donors: value of contrast-enhanced 3D magnetic resonance angiography and comparison of three rendering algorithms. Eur Radiol. 13(4):794-801, 2003 Apr.
105. [15323400] Persson A, Dahlstrom N, Engellau L, Larsson EM, Brismar TB, Smedby O. Volume rendering compared with maximum intensity projection for magnetic resonance angiography measurements of the abdominal aorta. Acta Radiol. 45(4):453-9, 2004 Jul.
106. [15383846] Wehrschuetz M, Aschauer M, Portugaller H, et al. Review of source images is necessary for the evaluation of gadolinium-enhanced MR angiography for renal artery stenosis. Cardiovasc Intervent Radiol. 2004;27(5):441-6.
107. [15760755] Glockner JF. MR angiography interpretation: techniques and pitfalls. Magn Reson Imaging Clin N Am. 2005 Feb;13(1):23-40, v.
108. [18635618] Runck F, Steiner RP, Bautz WA, Lell MM. MR imaging: influence of imaging technique and postprocessing on measurement of internal carotid artery stenosis. AJNR Am J Neuroradiol. 2008 Oct;29(9):1736-42.
109. [9648776] Kaufman JA, McCarter D, Geller SC, Waltman AC. Two-dimensional time-of-flight MR angiography of the lower extremities: artifacts and pitfalls. AJR Am J Roentgenol. 1998 Jul;171(1):129-35.
110. [-3194115] American College of Radiology. ACR practice guideline for communication: diagnostic radiology. In: Practice guidelines and technical standards, 2004. Reston, VA: American College of Radiology 2004; 5–7
111. [-3197639] American College of Radiology. ACR–AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance (MR) Imaging Equipment. Available at https://gravitas.acr.org/PPTS/GetDocumentView?docId=57+&releaseId=2

Revised 2025 (Resolution 4)

Practice parameters and technical standards are published annually with an effective date of October 1 in the year in which amended, revised or approved by the ACR Council. For practice parameters and technical standards published before 1999, the effective date was January 1 following the year in which the practice parameter or technical standard was amended, revised, or approved by the ACR Council.

Development Chronology for this Practice Parameter

2005 (Resolution 6)

Amended 2006 (Resolution 35)

Revised 2010 (Resolution 22)

Amended 2012 (Resolution 8 – title)

Amended 2014 (Resolution 39)

Revised 2015 (Resolution 8)

Revised 2020 (Resolution 29)

Amended 2023 (Resolution 2c)
Revised 2025 (Resolution 4)