Revised 2020 (Resolution 29) *

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

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 evaluation, assessment of severity, and follow-up of diseases of the vascular system. Contrast-enhanced MRA (CE-MRA) has been shown to be equivalent to conventional angiography in the evaluation of diseases of many portions of the vascular system and for pretreatment planning [1-5]. In addition, as 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 omitted to avoid promoting obsolete methodology. 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 Cervicocerebral Magnetic Resonance Angiography (MRA) [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 radiographic catheter-based invasive angiography, it is considerably less invasive 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 (see the ACR Manual on Contrast Media) [8-12]. More recently, Ferumoxytol, an ultra-small superparamagnetic iron oxide (USPIO) contrast agent and not a gadolinium-based contrast agent, has been reported as a suitable alternative to gadolinium-based contrast agents and as capable of yielding high-quality CE-MRA [13-18]; however, this is an off-label indication. Noncontrast MRA techniques are also available for assessing the vasculature in patients who cannot or should not receive gadolinium-based contrast agents [19-22]. Compared with vascular ultrasound, MRA is less operator dependent, yields images of the vascular system in a format familiar to most referring physicians, is less limited by body habitus and overlying bowel gas, and has greater 3-D capability. Contrast-enhanced CT angiography (CTA) can also provide excellent vascular illustration 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 has the ability also to provide time-resolved vascular imaging without the additional ionizing radiation exposure concerns related to multiphase CTA. In addition, CTA does not provide quantitative information about blood flow, which is possible with phase contrast MRA (PC-MRA), and CTA does not assess oxygen saturation, which is possible with susceptibility-weighted MRA. MRA has also shown promising results for atherosclerotic plaque characterization, notably for detection of high-risk features (eg, intraplaque hemorrhage, lipid-rich necrotic core, or fibrous cap thinning/rupture) of carotid atherosclerotic plaque [23-25].

MRA is also useful in diagnosing vascular disease in children and is more advantageous for this patient population given the lack of radiation exposure and ability to include time-resolved scans. Pediatric MRA may require specialized imaging approaches to accommodate the different spectrum of disease, physiology, smaller vessel caliber, typically faster blood flow, larger motion concerns, 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 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

B. Specific Considerations

1. Thoracic vasculature
   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 atherosclerosis of the thoracic aorta and branch vessels
      ii. Posttraumatic pseudoaneurysm
      iii. Acute aortic syndrome evaluation
         1) Dissection
         2) Intramural hematoma
         3) 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. Endovascular stent graft, including endoleaks
      ix. Congenital disorders, including vascular malformations, arch anomalies, and aortic coarctation
   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 prior to and following radiofrequency 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
    a) Pulmonary sequestration
    b) 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

2. Extremity evaluations
    a. Arteries
        i. Atherosclerotic occlusive disease
            a) Intermittent claudication
            b) Acute and chronic critical limb ischemia
            c) Patients with previous interventions (postoperative)
                i. Stent grafts
                ii. Bypass grafts
            d) Atheroembolism
        ii. Congenital anomalies, including vascular malformations
        iii. Vasculitide
        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
            a) Central
            b) Peripheral
            c) Effort thrombosis of the upper extremity
            d) 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
            a) Thrombus
            b) Venous compression
            c) 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

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
a) Liver
b) Kidney
c) Pancreas
d) Combined organ transplant
ii. Assessment of renal vein and IVC patency in the setting of renal malignancy or neoplasm
iii. Vascular mapping prior to placement of or surgery on a transjugular intrahepatic portosystemic shunt (TIPS).
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 bland embolization, chemoembolization, and radioembolization procedures
vii. Vascular mapping prior to tissue grafting

d. Postprocedure assessment for the following:
i. Evaluation of organ transplant vascular anastomoses (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

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 the small potential risk of exposure to ionizing radiation [28]. The need and potential risk of sedation should be considered. Various 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, the definition and evaluation of the following:

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 William 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 with unenhanced MRA
o. Evaluation of extremity peripheral vasculature in congenital anomalies (eg, Klippel-Trenaunay syndrome)
p. Portal hypertension
q. Arterial and venous thoracic outlet syndrome

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 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 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 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.

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]).

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 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 [33,34], such as use of an audiovisual systems during MRI [35] or the "feed-and-sleep" technique in neonates and infants [36].

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 [37].

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 without gadolinium [19-22,38-40]. 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 an intravascular paramagnetic contrast agents, typically gadolinium-based, and uses a rapid, 3-D T1-weighted gradient-echo acquisition [41-43]. 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. There are also benefits and technical concerns for MRA based on the field strength of the MR scanner. 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 [44-46]. However, MRA performed on a high-field MR scanner presents concerns related to higher absorption rate (specific absorption rate [SAR]) and artifacts related to metallic susceptibility.

1. Noncontrast MRA

   Time-of-flight (TOF) technique relies on inflow enhancement to generate images of blood flow [10]**.** The most commonly used inflow techniques are 2-D TOF and 3-D TOF. In 2-D TOF acquisitions, multiple contiguous thin slices are obtained and combined to form a 3-D data set. The 3-D technique inherently acquires a volume of data. The region of coverage of a 3-D TOF sequence is limited by radiofrequency saturation within the acquisition volume. When using a 2-D TOF technique to image the aorta and arteries of the lower extremities, cardiac or peripheral gating can minimize artifacts related to vascular pulsation and improve image quality at the expense of a greatly lengthened examination [47,48]. Blood flow in a particular direction can be selectively imaged through the use of saturation bands. With a 2-D acquisition, these saturation bands can be prescribed to travel with the imaging slice, ensuring adequate elimination of undesirable signal along the entire course of the vessels of interest.

   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 for inflow enhancement [49-52]. Initial

experience with this technique for the noncontrast evaluation of the lower-extremity peripheral arteries shows promising results.

Flow images and quantitative measurements of flow velocity can be obtained using PC-MRA methods in which the image contrast is generated by velocity-induced phase shifts [53,54]. As with TOF, PC-MRA can be obtained as either a 2-D or 3-D data set (ie, 4-D flow MRI). IV contrast enhancement may also be used to increase the signal obtained from the 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 without the need for saturation bands. PC-MRA can be obtained without or with electrocardiogram (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 if measurements of flow velocity or flow volume are desired. Therefore, peripheral or cardiac gating should be available.

A third method relies on a steady state free-precession (SSFP) sequence that captures the intrinsic T1 and T2 features of blood as bright signal [55-57]. Because of balanced SSFP's (bSSFP) reliance on T2/T1 signal, intraluminal thrombus may be masked on bSSFP MRA (Nota bene, use of PC-MRA, a flow-based technique, is often helpful to confirm luminal patency in these cases). Two-dimensional and 3-D SSFP MRA techniques use a type of unspoiled gradient-echo sequence in which the gradients are balanced and the signal is a composite signal from free-induction decay and stimulated echoes. The typical 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 it is sensitive to artifacts from static magnetic field inhomogeneity (off-resonance artifacts). The abdominal aorta and visceral (eg, renal) arterial branches can be selectively imaged, however, through the use of an asymmetrically applied inversion prepulse that can effectively null the signal from venous blood [19].

A fourth technique requires some form of cardiac gating and exploits the different signal intensities of blood using a T2-weighted echo train spin-echo sequence between systole, at which time flow void predominates, and diastole, at which time the relatively static blood has high signal intensity. During systole, intravascular signal is reduced because of the flow-related signal void using a T2-weighted echo train spin-echo or bSSFP sequence. During diastole, the blood behaves as a relatively immobile fluid and demonstrates relatively high signal intensity. By timing the acquisition of data sets to the cardiac cycle, systolic and diastolic data sets can be acquired and subtracted, eliminating background signal. The remaining intravascular signal can be displayed in a similar manner to other MRA techniques. This technique is best suited for imaging vessels that exhibit pulsatile flow and therefore may be limited in evaluation of distal extremity circulation when severe inflow disease diminishes distal pulsatility [58,59].

A fifth technique is the two-point Dixon water-fat separation technique noncontrast MRA of the whole heart and vasculature that has shown promising results on 1.5T and 3T scanners compared with spectral presaturation inversion recovery (SPIR) fat-suppressed balanced fast field echo (BFFE) coronary MRA in coronary imaging and vascular studies [60,61]. A novel 3-D respiratory-triggered gradient-recalled echo Dixon-based MRA/MR venography (MRV) technique that provides high-resolution anatomical imaging of the vasculature of the neck, body, and extremities without the need for IV contrast material or breath-holding has also recently been described [62].

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) [12,38,63-67]. 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 [68,69]. CE-MRA has documented efficacy in assessing the arterial and venous systems in the thorax, abdomen, pelvis, and extremities [2,5,39,41,68,70-82]. 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, [38,46,88-91], 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 in order 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, an USPIO contrast agent, has been reported to successfully yield high-quality CE-MRA [13-18]; however, this is an off-label indication. Ferumoxytol is not a gadolinium-based contrast agent, and unlike gadolinium-based contrast agents, it does not pose a risk of NSF. 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 prolonged intravascular half-life of several hours, which is much longer than that of traditional extracellular gadolinium-based contrast agents, which provides a prolonged window of opportunity for MRA.

3. Special Considerations
   a. MRV

      Venous illustration can be achieved using both noncontrast and CE-MRA methods. Indications for MRV are listed above. Contrast-enhanced MRV (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 [96]. 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 [97]. 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 [62]. Noncontrast MRV is best achieved with SSFP or turbo spin-echo [98] imaging approaches. ECG or respiratory gating can be employed in the chest to offset motion artifact, and inversion recovery may be utilized 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 where 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 [99]. 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-sleep" 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. 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 [69,100-105]. 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 [106].

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 in the report.

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 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 [107-109]. Screening forms must also be provided to detect those patients who may be at risk for adverse events associated with the MRI examination [110].

Peer-reviewed literature pertaining to MR safety should be reviewed on a regular basis [107-109].

For additional safety considerations, see the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [26], the ACR Guidance Document on MR Safe Practices 2020 [107], 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 radiofrequency 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 Imaging (MRI) 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).

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