Revised 2020 (Resolution 43)*

ACR–ASNR–SNIS–SPR PRACTICE PARAMETER FOR THE PERFORMANCE OF CERVICOCEREBRAL 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 in light of 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 the condition of the patient, limitations of available resources, or advances in knowledge or technology subsequent to publication of this document. However, a practitioner who employs an approach substantially different from the guidance in this document is advised to document in the patient record information sufficient to explain the approach taken.

The practice of medicine involves not only the science, but also the art of dealing with the prevention, diagnosis, alleviation, and treatment of disease. The variety and complexity of human conditions make it impossible to always reach the most appropriate diagnosis or to predict with certainty a particular response to treatment. Therefore, it should be recognized that adherence to 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 sole 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 American Society of Neuroradiology (ASNR), the Society of NeuroInterventional Surgery (SNIS), and the Society for Pediatric Radiology (SPR).

Magnetic resonance angiography (MRA) is a general term that refers to various MRA techniques used for the diagnostic evaluation, quantitative or qualitative severity assessment, and surveillance of vascular diseases of the brain, head, and neck. MRA is a rapidly evolving technology; therefore, general recommendations can be made regarding imaging techniques. Detailed imaging protocols have been omitted to avoid promoting obsolete methodology. The practitioner should periodically review the imaging protocols and update them as needed using resources from the literature, major MR manufacturers, and professional imaging society meetings and their websites (eg, ASNR, International Society for Magnetic Resonance in Medicine, Society of Cardiovascular Magnetic Resonance, Society for Magnetic Resonance Angiography, and other similar resources).

MRA has valuable attributes for the imaging assessment of a wide spectrum of vascular diseases [1,2]. Compared with radiographic catheter-based angiography, it is noninvasive without risk of vascular injury, ischemic neurological complications, or iodinated contrast reactions. Compared with vascular ultrasound, it is less operator dependent, has greater freedom from interference by body habitus, and provides greater three-dimensional (3-D) capability. These benefits must be balanced against the limitations and technical artifacts of MRA, such as degraded image quality due to patient motion, slow or turbulent flow, and/or susceptibility effects. In general, MRA has lower spatial resolution in comparison with computed tomography (CT) or digital subtraction angiography, but emerging high-resolution MRA techniques have the potential to replace current examination techniques [3-9]. The ACR Manual on Contrast Media provides detailed recommendations for the use of contrast agents in at-risk groups [10].

Children typically demonstrate a different spectrum of neurovascular conditions. Imaging protocols tailored for adult patients may not be optimal or appropriate in the pediatric setting. Cervicocerebral MRA can provide valuable information regarding flow conditions, congenital/developmental vascular anomalies/abnormalities, and acquired pathology that may involve the pediatric brain and spine without the concern for radiation to the developing central nervous system. Successful MRA evaluation in pediatric patients is more complex and poses unique technical and safety issues [11]. In general, fast intracranial flow in pediatric patients can be leveraged for time-of-flight (TOF) MRA sequences in most cases, avoiding contrast administration and reducing the need for technically challenging contrast enhanced (CE)-MRA. The size of the pediatric patient requires MRA scanning with a decreased field of view (FOV) to delineate smaller structures. Finally, sedation may be necessary in order to limit motion artifacts and obtain a diagnostic-quality examination.

Application of this practice parameter should be in accordance with the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [12] and the ACR–SIR Practice Parameter for Sedation/Analgesia [13].

II. INDICATIONS

A. Adult and Pediatric Indications for Cervicocerebral MRA

MRI/MRA is typically the imaging modality of choice for the initial evaluation of the cervicocerebral vasculature in children [14]. It is a noninvasive and low-risk examination free of ionizing radiation as compared with conventional endovascular (catheter) or CT angiographic procedures. Studies of pediatric stroke that compared MRA with conventional angiography found MRA to be accurate in delineating stenosis and/or occlusion and able to demonstrate vascular anatomy in a variety of pathological conditions [15-22]. In some clinical instances, follow-up CT or catheter angiography may be necessary to further characterize the abnormality.

Indications for cervicocerebral MRA include, but are not limited to, the detection and evaluation of the following:

1. Atherosclerotic or nonatherosclerotic steno-occlusive disease, thromboembolism or vasospasm in the setting of cerebral ischemia, and infarction [23-27]
2. Traumatic injury to cervicocerebral vessels, including dissection [28-30]
3. Intracranial or extracranial aneurysms, pseudoaneurysms, and venous varices [24,25,27,31-35]
4. Cerebral intracranial or extracranial, congenital or acquired arteriovenous malformations (AVMs), vein of Galen malformations, dural venous malformations, arteriovenous fistulas, proliferative angiopathy, hemangiomas, venous malformations, lymphatic malformations, or other low-flow vascular malformations [24,25,27,36-40]
5. Etiology of intracranial/intraspinal hemorrhage
6. Vasculitis and vasculopathy including, but not limited to, collagen vascular disease [41,42]; flow-meditated dilatation; sickle cell [43]; moyamoya disease or steno-occlusive vasculopathy [44]; and nonatherosclerotic, noninflammatory vasculopathy
7. Tumor vascular supply, tumor invasion, encasement, or constriction of vasculature
8. Localization of relevant vascular anatomy/pathology for preoperative and/or radiation treatment planning
9. Relevant vascular anatomy/pathology for preprocedural and/or postprocedural evaluation and determining the effect of therapeutic interventions, including endovascular embolization and/or stent placement in treatment of stenosis, dissections, aneurysms, AVMs, tumor embolization [25], and/or posttreatment changes following interventional/surgical procedures or radiation therapy [45,46]
10. Soft-tissue vascular anomalies in the head and neck [47]
11. Vascular status following extracorporeal membrane oxygenation (ECMO)
12. Pulsatile tinnitus, bruits, and neuralgia that might result from vascular etiology
13. Dural venous sinus thrombosis and intracranial venous steno-occlusive disease [36,37,40]

B. Evaluation of the aortic arch and subclavian arteries in adults and children may require separate techniques and sequences. Indications include, but are not limited to, the detection and evaluation of the following [48-50]:

1. Dissection of the aorta and/or great vessels
2. Aneurysm of the aorta and/or great vessels
3. Atherosclerotic occlusive disease of the great vessels and subclavian steal
4. Congenital abnormalities of the aorta, including coarctation, double aortic arch, and aberrant subclavian artery
5. Superior vena cava syndrome or unilateral upper-extremity edema
6. Normal vascular anatomy versus aneurysms/masses for preoperative planning

III. QUALIFICATIONS AND RESPONSIBILITIES OF PERSONNEL

See the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [12].

IV. SAFETY GUIDELINES AND POSSIBLE CONTRAINDICATIONS

See the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [12] and the ACR Guidance Document on MR Safe Practices: 2013 [51].

Peer-reviewed literature pertaining to MR safety should be reviewed on a regular basis [1,21].

V. SPECIFICATIONS OF THE EXAMINATION

The written or electronic request for Cervicocerebral 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, benefits, and risks of the examination as well as alternative imaging procedures. The physician must be familiar with potential hazards associated with MRI, including incompatible devices and potential adverse reactions to contrast media. The physician should be familiar with relevant ancillary studies that the patient may have undergone (see the ACR Practice Parameter for Communication of Diagnostic Imaging Findings [52]). 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 must also understand 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

The physician responsible for the examination should supervise patient selection and preparation and be available in person or by phone for consultation. Patients must be screened and interviewed prior to the examination to exclude individuals who may be at risk by exposure to the MR environment (eg, incompatible metallic implants surgical devices, etc). See the ACR MR Guidance Document on MR Safe Practices: 2013 [51].

Certain indications require administration of intravenous (IV) contrast media. IV contrast enhancement should be performed using appropriate injection protocols and in accordance with the institution's policy on IV contrast used. Patients receiving contrast agents should be evaluated for potential risk of nephrogenic systemic fibrosis (NSF) according to the recommendations in the chapter on NSF in the ACR Manual on Contrast Media [10].

Patients suffering from anxiety or claustrophobia may require sedation or additional assistance. Administration of moderate sedation may enable achievement of a successful examination. If moderate sedation is necessary, refer to the ACR–SIR Practice Parameter for Sedation/Analgesia [13]. Additional considerations and equipment may be required in critically ill or intubated patients under general anesthesia.

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.

C. Examination Technique

MRA is a general term that refers to a diverse group of MR pulse sequences. Multiple methods can be used to generate signal from flowing blood, and each method may be performed with a variety of coils, acquisition sequences, and display techniques. TOF gradient recall echo (GRE) techniques rely on flow-related enhancement to generate images of blood flow within the vascular lumen. Anatomic vascular images and quantitative measurements of flow velocity can be obtained using phase-contrast (PC) MRA techniques in which the image contrast is generated by velocity-induced phase shifts. CE MRA relies on enhancement of the blood signal by paramagnetic contrast agents and typically uses rapid, 3-D T1-weighted gradient-echo acquisitions. CE MRA can provide higher spatial resolution with first-pass techniques or temporal resolution with time-resolved 4-D techniques [53-56]. Vascular images can also be generated by arterial spin-labeling (ASL), and blood can be directly imaged using methods such as inflow inversion recovery [57-59]. Practitioners using MRA must understand the artifacts and limitations of each imaging technique. The most common MRA sequences utilize 2-D and 3-D TOF, 3-D PC, 3-D CE, and 4-D CE time-resolved techniques.

1. Noncontrast TOF MRA

   In 2-D TOF MRA acquisitions, contrast between flowing blood and stationary surrounding tissue is generated by acquiring multiple thin slices oriented perpendicular to the direction of blood flow to maximize the signal enhancement due to inflow of blood within vascular structures. These 2-D slices are combined to form a 3-D volume data set. Vascular structures are isolated from the surrounding tissue by projecting the pixels with maximum intensity into multiple planar views called maximum intensity projection (MIP) images. 3-D TOF techniques directly acquire a 3-D volume. Multiple 3-D volumes using short echo time/repetition time (TE/TR) sequences are typically obtained with overlapping edges to provide coverage of the region of interest. Focused assessment of the vascular structures from the 3-D volume data can also be displayed with planar- and volume-rendered MIP imaging [60-63].

   MRA data sets can also be displayed as 2-D source images. The supervising physician should always review the source images in an effort to improve diagnostic accuracy. Review of the source images can reduce possible confusion of T1 shortening related to proteinaceous cysts, fat, or thrombus with flow-related enhancement; assist in diagnosis by differentiating overlapping structures, differentiate artifacts caused by tissue motion due to swallowing, cardiac pulsation, or respiration between sequential 2-D slices; and identify artifacts that can cause spurious increase or decrease in flow-related signal [64].

   Rotating displays of 3-D volumetric MIP images allow separation of vessels that are superimposed on routine planar projections. The supervising physician should be familiar not only with MIP displays but also with surface displays, volume displays, and multiplanar reformatting techniques, including their strengths and limitations. The type and frequency of artifacts will vary with each display technique; thus, the supervising physician must understand the potential errors with each method [65].

2. CE MRA

   CE 3-D MRA combines a fast T1-weighted gradient-echo acquisition with an IV-administered paramagnetic contrast agent [66]. Such contrast-based agents reduce the T1 relaxation time of blood and nearly eliminate saturation effects, thus leading to a more accurate assessment of vascular stenosis. CE MRA has been evaluated for use in assessing the cervical carotid and vertebral arteries, the intracranial arteries as well as the aortic arch, ascending great vessels, and descending thoracic aorta. CE MRA has been successful in demonstrating atherosclerotic occlusive diseases, dissections, aneurysms, congenital anomalies, vascular malformations, and vascular infiltration by tumor. It does not routinely require cardiac gating, which makes it a more widely applicable technique in patients with cardiac arrhythmias. Furthermore, respiratory artifacts can be reduced by breath-holding, and artifacts seen in TOF MRA due to slow or turbulent flow-related enhancement or in-plane dephasing encountered with vascular tortuosity are markedly reduced. These advantages make CE MRA very useful for imaging of the aortic arch, great vessels, and cervical vasculature but can also improve visualization of the intracranial circulation.

   Rapid cervical and intracranial circulation (typically 8-10 seconds) makes CE MRA of the cervicocerebral vasculature particularly challenging. Arch and cervicocerebral MRA studies require very accurate timing of the acquisition in relation to the contrast bolus; this may be performed with the utilization of one of the bolus-timing sequences outlined below. If the images are obtained too early, the arterial structures may not be visualized. Late acquisition will result in reduced arterial signal, venous opacification/contamination, and soft-tissue enhancement. Ideally, the center of the k-space is scanned during the first pass of the bolus [67].

CE MRA is optimized when the center of the k-space is sampled near the peak arterial concentration of the contrast. Centric encoding is an example of a vascular imaging technique that improves capture of the arterial phase of the bolus and reduces venous contamination. Three basic CE MRA techniques have been developed to improve arterial phase k-space filling: test bolus timing, fluoroscopic triggering, and time-resolved imaging [27,68-73]. For test bolus timing, an initial small test dose is first administered, and continuous 2-D imaging is performed to determine the optimal imaging time interval. For fluoroscopic triggering, a rapid real-time 2-D gradient echo is acquired during the injection of the entire bolus, allowing the MR technologist or an automatic trigger based on a preplaced region of interest to initiate the acquisition such that the center of the k-space is sampled during maximum arterial enhancement. Time-resolved MRA imaging is performed with rapid scanning repeatedly over the region of interest, with oversampling of the central lines of the k-space every few seconds. Increased temporal resolution of time-resolved MRA imaging allows delineation of the arterial and venous phases, arteriovenous shunting, and early venous drainage for the assessment of cervical spinal or intracranial AVMs and fistulas.

Contrast injection rates of 2 to 4 mL/sec generate a bolus profile with a 5-7-second arterial phase. This is desirable because most techniques require several seconds to sample the center of the k-space. The contrast injection volume may vary based on the size and condition of the patient [70]. For example, very large patients or those with poor cardiac output may require a timing bolus and a larger volume of contrast in order to offset the effects of contrast dilution in the blood pool. The use of a power injector facilitates control of the injection rate and helps to standardize the protocol. Following contrast injection, the power injector can rapidly switch and inject a saline flush to optimize the bolus. In pediatric patients, the combined demands of smaller bolus volume and rapid circulation time require that the injection rate be adjusted to the patient body habitus. The size and location of the IV also needs special consideration in young children.

Finally, saturation (SAT) bands are less effective when the intravascular T1 signal is significantly reduced. In CE MRA, a poorly timed contrast bolus with undesirable venous enhancement cannot be overcome by the selective placement of SAT bands, and the relevant arterial anatomy may be obscured [74-76].

3. PC MRA

PC MRA techniques are based on the protons that move through a magnetic field, and 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 analogous to that obtained with the TOF technique and dependent on the protons' directional flow velocity. When the proper velocity encoding is selected, 2-D PC MRA imaging data can also be used to measure flow velocity or flow volume. Flow quantification with 2-D PC MRA techniques across intracranial vertebrobasilar stenoses has shown promise as a predictor of ischemic stroke in the posterior intracranial circulation [77]. Contrast may be used to augment the signal obtained from blood flow in PC MRA acquisitions. In some instances, it is necessary to gate the PC MRA acquisition to the cardiac cycle for optimum flow assessment. When 3-D PC MRA is utilized for flow quantification with time-resolved volumetric acquisitions, it is frequently called 4-D flow MRI/MRA; its utilization in the hemodynamic characterization of intracranial aneurysms and AVMs is a topic of ongoing research [57,78-82].

4. ASL MRA

Investigations with continuous, pseudocontinuous, and inflow inversion recovery ASL methods have demonstrated clinical feasibility for MRA but are more commonly utilized for perfusion imaging [58,59]. ASL has significant limitations with respect to MRA imaging, including the requirement of reasonably high arterial velocities and knowledge of flow direction and therefore is not widely used in clinical practice.

5. MR Vessel Wall Imaging

High-field (>3T), high-resolution (<1 mm voxels) MR vessel wall imaging (VWI) protocols are optimized to image cervical and intracranial arterial wall pathology with 2-D or 3-D black-blood MRI (BB MRI) using multiple tissue weightings (pre- and postcontrast T1-, proton density, and/or T2-weighted sequences). Depending on 2-D versus 3-D scan protocols and vendor-specific sequences, various blood, fat, and cerebrospinal fluid (CSF) suppression techniques have been described, including spin echo, spatial pre--

saturation (or SAT) band, double inversion recovery, intravoxel phase dispersion, diffusion sensitizing gradients, flow-sensitive dephasing (FSD), or delay alternating with nutation for tailored excitation (DANTE). Although carotid MR VWI protocols are typically 2-D BB MRI sequences, isotropic 3-D BB MRI sequences are often employed for intracranial MR VWI for volumetric coverage and multiplanar reformatted reconstructions of this tortuous vasculature, but with increased scanning times [83]. Despite BB MRI sequences being developed to evaluate vessel wall pathology, the vessel lumen is also well delineated with higher sensitivity for stenosis and higher specificity for vessel occlusions than TOF MRA, with near equivalent accuracy to CT angiography (CTA)/digital subtraction angiography methodologies [84-86].

Cervical MR VWI may be valuable in the diagnostic assessment of dissections and high-risk carotid and vertebral atherosclerotic disease. Specific biomarkers of carotid atherosclerosis with histopathological correlation have been shown to be associated with cerebrovascular ischemic events, including plaque volume/thickness, thin/ruptured fibrous cap, lipid-rich necrotic core, intraplaque, hemorrhage, and/or adventitial enhancement. Preliminary evidence suggests that high-risk plaque features on MR VWI are associated with ischemic stroke risk that may be independent to the North American Symptomatic Carotid Endarterectomy Trial (NASCET) criteria for symptomatic carotid stenosis, although further investigation is warranted [87-93].

Intracranial MR VWI has been an evolving adjunctive technique to better characterize various neurovascular pathologies over standard luminal imaging. Multiple studies have proposed high-risk or culprit intracranial atherosclerotic plaque features associated with symptomatic ischemia, including eccentric plaque thickness/irregularity, positive (adaptive) vessel wall remodeling, intraplaque hemorrhage, and plaque enhancement. Other intracranial MR VWI findings, such as the concentric pattern and presence/absence of vessel wall enhancement, may assist in diagnosing and differentiating inflammatory vasculitis, steno-occlusive vasculopathy/moya moya disease, and reversible cerebral vasoconstriction syndrome [83,94,95].

Early evidence suggests the value of MR VWI in the assessment of intracranial aneurysms, due to suspected pathology of neovascularization and inflammation of the vessel wall in the setting of an unstable atherosclerotic plaque or intracranial aneurysm. Thick, circumferential, or pronounced aneurysm wall enhancement may be associated with ruptured aneurysms or unstable (symptomatic or enlarging) unruptured aneurysms with moderately high specificity [96-99]. However, few longitudinal and prospective studies have evaluated unruptured aneurysm wall enhancement as a predictor of aneurysm growth/rupture, independent of other known anatomic risk factors. Further studies are warranted to assess the role of MR VWI in the differentiation and risk stratification of neurovascular diseases, standardization of protocols, and technical considerations of contrast injection delays and turbulent flow artifacts [100,101]. MR VWI may be performed solely or as a part of a MRI or MRA examination.

6. MR Venography

Cervicocerebral MR venography (MRV) is useful in the evaluation of the intracranial and extracranial venous anatomy and its variants and developmental, structural, or flow abnormalities. Flow-related enhancement or contrast enhancement of the cervical and intracranial veins enables the assessment of venous patency, congenital or acquired stenosis, focal wall thickening, annulus, abnormal valves, webs, septa and flaps, dural venous sinus and cortical vein thrombosis, jugular vein thrombosis, idiopathic intracranial hypertension (IIH), and intracranial hypotension. Venous pathology has also been implicated in a number of other neurological diseases, such as exertional headache, cough headache, and transient global amnesia [102]. Dural venous sinus thrombosis accounts for 0.5% to 1% of all strokes and can be seen in a number of conditions—including dehydration, hypercoagulable states, infection, tumor invasion—in conjunction with oral contraceptives, and pregnancy, especially in the third trimester and during puerperium [102-104].

MRV offers several advantages to CT venography (CTV), including lack of ionizing radiation, improved thrombus visualization, and greater sensitivity for detecting parenchymal lesions, and venous infarcts.

Additionally, specific MRV techniques can provide functional flow information that is reproducible and allows assessment of flow impairment, hemodynamically significant venous stenosis, presence/absence of collateral venous drainage, and venous reflux [105,106].

Analogous to MRA, MRV sequences employ either 2-D TOF, 3-D PC, or 3-D CE techniques. Although ASL perfusion-weighted imaging (PWI) can identify hyperintense signal or a "bright sinus" appearance in the setting of dural venous sinus thrombosis with increased sensitivity compared with the susceptibility vessel sign or empty delta sign, it does not offer significant advantages to standard MRV techniques. Newer techniques, such as 2-D Cine PC MRV and 4-D MRA, have been studied for various quantitative flow applications [102,103,105-107]. MRV display protocols should be modified to focus on the cervicocerebral venous structures, utilizing planar- and volume-rendered MIP imaging as well as multiplanar reformatting techniques for 3-D CE MRV.

Noncontrast 2-D TOF MRV relies on flow-related enhancement to produce vascular images by manipulating the magnitude of magnetization (longitudinal magnetization vector), differentiating stationary tissue (low signal intensity) from blood flow (high signal intensity). In imaging the cervicocerebral venous system, an inferior saturation pulse is placed to eliminate arterial inflow signal. Advantages include operator independence, reproducibility, and a large FOV to visualize venous anatomy and pathology. Disadvantages of 2-D TOF MRV include stair-step artifact with 3-D MIP reconstructions, in-plane dephasing resulting in signal loss or "flow gaps" due to saturation, and flow parallel to the scan plane. T1 hyperintense signal or "T1 shine through" from intracellular or extracellular methemoglobin/thrombus may falsely simulate normal blood flow, and arachnoid granulations or hypoplastic dural sinuses may mimic venous thrombosis. 2-D TOF is also more sensitive to image degradation due to patient motion and misregistration, magnetic field inhomogeneities, and susceptibility artifact from air, calcium, or metal. 3-D TOF techniques are not typically used because of severe in-plane saturation effects and signal loss [102,106,107].

PC MRV (2-D or 3-D) uses velocity-induced phase shifts imparted on moving spins to distinguish flowing blood from the surrounding tissues. The signal from stationary tissue is suppressed by a bipolar gradient pulse of equal magnitude and opposite direction. Using a transverse magnetization vector, signal in flowing blood is linearly proportional to the velocity of the spins. Spins in blood moving toward the heart are assigned a hyperintense "bright" signal, and spins in blood moving away from the heart are assigned a hypointense "dark" signal. As opposed to high-velocity encoding (40-70 cm/sec) for arterial inflow, low velocity encoding (10-20 cm/sec) is required for venous flow. PC MRV offers the advantages of improved background tissue suppression, slow flow detection with smaller voxel sizes, flow direction, and quantification. Disadvantages include operator dependence on correct velocity encoding, long acquisition times as a result of applying multidirectional gradients, increased susceptibility to motion artifacts, and intravoxel dephasing/signal loss with turbulent flow. The acquisition time can be reduced by using high field strengths, parallel imaging, and optimized k-0 space sampling [102,103,106,108]. 2-D Cine PC sequences can also be utilized for accurate flow quantification in the cervicocerebral veins, preferably with cardiac gating and recommended velocity encoding of 50 cm/sec. At various levels (C2-3, C5-6, and C7-T1), a slice of interest is placed perpendicular to the vessel's longitudinal axis (flow direction) and flow rate is calculated from a flow velocity curve as a function of time [102]. Time-resolved 3-D PC MRA or 4-D flow MRI are evolving sequences to assess quantitative flow dynamics of the arteries and veins throughout the cardiac cycle, potentially allowing measurements of pressure gradients in the dural sinuses and jugular veins. However, longer acquisition and postprocessing times as well as lower spatial resolution limit clinical application in the smaller intracranial vasculature [102].

Utilizing 3-D CE MRV techniques to evaluate the superficial and deep intracranial veins and dural sinuses. It relies on T1 shortening of enhanced venous blood rather than flow-related enhancement, overcoming in-plane saturation artifacts seen with TOF techniques. Several other advantages of 3-D CE MRV techniques include a large FOV, isotropic volumetric imaging for multiplanar reformatting, higher spatial resolution, faster scan times, higher signal-to-noise ratios (SNR), and higher contrast-to-noise ratios (CNR). It may help differentiate acute from chronic venous thrombosis, with intense periadventitial enhancement seen with acute thrombosis. Intravascular webs/septae and arachnoid granulations are better delineated with 3-

D CE MRV techniques. It is also less susceptible to quality degradation by patient motion, magnetic field inhomogeneity, and susceptibility artifacts form air or metal [102]. Time-resolved CE MRA techniques provide dynamic visualization of both the arterial and venous phases and can be leveraged for assessment of arteriovenous shunts, albeit at a lower spatial resolution than standard 3-D CE MRA/MRV studies.

In addition, volumetric T1 postcontrast techniques (where flow suppression techniques are not utilized) with enhancement of the venous sinuses are also a useful technique in evaluating the venous sinuses, including to exclude venous thrombosis and identify stenosis as well as venous vascular variants.

VI. DOCUMENTATION

Reporting should be in accordance with the ACR Practice Parameter for Communication of Diagnostic Imaging Findings [52].

In addition to examining the vascular structures of interest, the MRA 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. When MRA/MRV techniques are used for determining carotid stenosis, the report should reflect the methodology and reference the criteria for percent stenosis outlined in the NASCET or based on methods validated against NASCET measurement [109-112]. Also, the percent stenosis must be calculated using the distal cervical ICA (internal carotid artery) diameter, where the walls are parallel, for the denominator. Similar to CTA, MRA with attention to the acquisition parameters and postprocessing techniques can provide cross-sectional measurements of stenosis that correlate with properly performed NASCET estimates of percent stenosis obtained with catheter angiography [113]. In the setting of near occlusion, it may not be accurate to calculate percent stenosis ratios in the presence of poststenotic arterial dilatation. Some MRA techniques may not be amenable to quantitative measurements, in which case qualitative assessment of stenosis should be provided.

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. Screening forms must also be provided to detect those patients who may be at risk for adverse events associated with the MRI examination [114-116].

VII. EQUIPMENT SPECIFICATIONS

Equipment performance monitoring should be in accordance with the ACR–AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance Imaging (MRI) Equipment [117].

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

A 3-D postprocessing workstation capable of creating multiplanar reformations, MIP images, and 3-D volume renderings or shaded surface displays is required. The workstation should also allow the direct measurement of vascular diameters and, when appropriate, path lengths and branch angles, either from source or reformatted images.

VIII. 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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