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ACR–NASCI–SPR PRACTICE PARAMETER FOR THE PERFORMANCE AND INTERPRETATION OF CARDIAC MAGNETIC RESONANCE IMAGING (MRI)

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 care¹. 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*, ___ N.W.2d ___ (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).

A. Cardiac magnetic resonance imaging (MRI) is an established imaging modality, well recognized for its value in the initial assessment and monitoring of a wide range of diseases of the heart and surrounding related structures (eg, pericardium) [1,2]. Historically, imaging has played a critical role in the diagnosis and evaluation of acquired and congenital cardiac disease, beginning with chest radiography and fluoroscopy and progressing to coronary angiography and cardiac catheterization, echocardiography, and nuclear medicine. All of these modalities have a well-established role in patient care. Multidetector computed tomography (MDCT) and MRI, with appropriately equipped scanners, can now acquire images of coronary arteries, cardiac chambers, valves, myocardium, and pericardium in order to view cardiac anatomy and to assess cardiac function. Thus, CT and MRI continue to play an increasing role in comprehensive cardiac imaging. This document deals specifically with cardiac MRI applications.

Although the technical parameters and field of view of a cardiac MRI examination will appropriately be tailored to evaluate the cardiac anatomy and/or function in question, the images obtained will also show adjacent anatomy, often including portions of the lungs, mediastinum, spine, and upper abdomen. Furthermore, cardiac MRI protocols may involve evaluation of extracardiac vascular structures within and beyond the thorax, which may reveal clinically significant noncardiac findings [3,4]. In addition to examining the cardiac structures of interest, the interpreting physician is responsible for examining all the visualized noncardiac structures and must report any clinically relevant abnormalities of these adjacent structures. In some cases, these structures may be seen only on localizing (scout) images.

Cardiac MRI also presents potential patient safety issues. These issues pertain primarily to the strong magnetic field and its potential impact on implanted devices. It should be noted that many devices, including several cardiac pacemakers, are now MRI conditional, permitting safe MR imaging in these patients when Food and Drug Administration (FDA) guidelines are followed [5]. In addition, it has been shown that scanning standard pacemakers under certain strictly monitored conditions can be performed safely [6] (see section IV). Other safety issues include those associated with MRI contrast agents and patient sedation. Although uncommon, contrast agents can cause allergic reactions or can place patients at risk for nephrogenic systemic fibrosis (NSF) when administered in patients with renal failure. It is estimated that nearly half of all MR imaging studies performed are contrast enhanced. For more information, refer to the [ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) [7].

Radiologists, because of their extensive experience in MRI, have an important role in its application to the heart. Most radiologists already supervise and interpret MRI and computed tomography (CT) scans of the chest (which include basic evaluation of the pericardium, heart size, and cardiac masses) and perform MR angiography (MRA). Their knowledge of structures beyond the heart provides added value in cardiac imaging. They already supervise MRI equipment performance, standard operating procedures, safety regulations, and personnel. Their prior experience with MRI shortens their learning curve for cardiac MRI applications.

B. MRI has the following important attributes and capabilities that make it advantageous for evaluating the adult or pediatric heart:

1. High natural contrast exists between the intracardiac/intravascular blood pool and the surrounding cardiac and vascular structures due to inherent tissue characteristics. For example, cardiac anatomy and pericardial and mediastinal abnormalities can be depicted with “dark-blood” spin-echo imaging [8]. “Bright-blood” gradient-echo cine sequences can be used to show cardiac anatomy, myocardial wall motion and thickening, artifacts generated by turbulent blood flow and valve leaflet motion, and valve disease [9,10]. Consequently, contrast agents are not routinely required for discrimination of the blood pool and evaluation of cardiac function. Contrast administration has become a key component in MR myocardial perfusion techniques and late gadolinium enhancement (LGE) imaging for viability and

cardiomyopathies. The excellent soft-tissue differentiation capabilities of MRI also permit delineation of cardiac structures (eg, ventricular myocardium) and paracardiac structures related to the great vessels, pericardium, and mediastinum.

2. MRI is a 3-D and/or multiplanar imaging modality that provides the capability for precise and reproducible (intraobserver, interobserver, and/or interexamination) quantification of cardiac parameters, such as chamber and stroke volumes, ejection fraction, cardiac output, or wall mass [11,12]. When either cine sequential tomographic or volumetric images are acquired, the resulting 3-D data series permits direct measurement of cardiac volumes or mass without the use of any assumed formulas or geometric models.
3. Quantitative measures arising from cine MRI techniques can be used to assess more complex features of cardiac function such as intracardiac shunts (eg, ventricular or atrial septal defect shunt volume) and valve regurgitation (eg, mitral regurgitant fraction) [13,14]. These measurements depend on differences in stroke volume between the 2 ventricles. Standard cine MRI techniques allow the assessment of regional ventricular function (eg, systolic wall thickening). More advanced techniques such as tagged (eg, spatial modulation of magnetization [SPAMM]) gradient-echo imaging and displacement encoding with stimulated echoes permit calculation of circumferential strain [15,16]. These studies can be performed at rest or during the intravenous administration of pharmacologic stress agents.
4. Velocity flow mapping permits measurement of blood flow from the standpoint of flow velocity or flow volume using phase-contrast MRI [17,18]. Practical uses include stroke volume determination, direct valvular regurgitation quantification (eg, diastolic retrograde flow volume divided by systolic antegrade flow volume in the ascending aorta or main pulmonary artery for determining aortic or pulmonic regurgitant fraction), indirect valvular regurgitant fraction assessment (difference between left ventricular [LV] stroke volume by cine imaging and aortic flow by velocity coding), assessment of stenosis severity based on measurement of peak and mean systolic velocities, and shunt quantification (eg, ascending aortic flow volume to pulmonary artery flow volume ratio).
5. First-pass perfusion utilizing near-real-time or real-time monitoring of the appearance of a rapidly administered MRI contrast agent (eg, gadolinium chelate) can be used to evaluate the adequacy of delivery of blood (ie, perfusion) to the myocardial tissue based on patterns of tissue enhancement; time-intensity curves may be analyzed to quantify the degree of hypoperfusion in ischemic or infarcted myocardium [19,20]. This procedure can be performed both at rest and during intravenous administration of a pharmacologic stress agent such as dipyridamole, adenosine, or regadenoson.
6. Late gadolinium contrast-enhanced (LGE) myocardial viability MRI methods can be used to evaluate the steady-state distribution of the contrast medium. This has several important applications: to detect the presence of acutely necrotic myocardium or chronic scar [21,22]; in differentiating between ischemic and nonischemic cardiomyopathies; and in assessing myocarditis and a variety of cardiomyopathies, including, but not limited to, sarcoidosis, amyloidosis, and hypertrophic cardiomyopathy [23]. This method can be used alone or with cine imaging to assess the transmural extent of acute or chronic myocardial infarction, to predict wall motion recovery after revascularization, or in combination with first-pass stress perfusion to assess ischemic but viable versus nonviable myocardial tissue. The LGE technique has also been shown to be useful for prognostic characterization of ischemic and nonischemic myocardial diseases [24].
7. T2-weighted sequences and T2-mapping sequences can be used to detect myocardial edema in acute myocardial infarction and myocarditis [25]. T2*-weighted imaging can be used to detect iron content in the myocardium [26].

8. Newer myocardial T1-mapping methods show some potential in assessing diffuse fibrotic and infiltrative processes [27]. Noncontrast T1 mapping is useful for identification of Fabry disease and amyloidosis based on abnormal T1 times compared to individuals.
9. Use of MR angiography (MRA) is essential to many comprehensive cardiac MRI examinations, especially those of the coronary arteries and great vessels. MRA methods have been used to assess pulmonary venous anatomy before and after radiofrequency (RF) ablation for treatment of atrial fibrillation [28]. MRA is also very useful for assessing great vessel anatomy in congenital heart disease [29]. MRA methods as they pertain to assessment of the coronary arteries, pulmonary veins, and congenital heart disease are discussed later in this document.

C. Cardiac MRI should be performed only for a valid medical reason. Although it is not possible to detect all abnormalities by using cardiac MRI, adherence to the following parameters will enhance the probability and accuracy of their detection.

Application of these parameters should be in accordance with the [ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) [7].

II. INDICATIONS

Primary indications for cardiac MRI include, but are not limited to, assessment of the following:

A. Cardiac Anatomy and Ventricular Function

Although echocardiography is the usual first imaging examination for assessment of left ventricular (LV) function, MRI, because of its 3-D data acquisition, is considered to be more accurate and reproducible [30]. MRI is also less subject to variability due to patient body habitus or emphysema than echocardiography. Qualitative assessment of regional ventricular wall motion abnormalities (WMAs) and quantitative assessment of LV function are appropriate in most MRI examinations of the heart. Qualitative assessment of regional WMA should use the standard 17-segment model [31] and the following terms: normal, hyperkinetic, hypokinetic, akinetic, or dyskinetic. LV qualitative and quantitative function should be performed using short-axis views from base to apex. In addition, to provide complete qualitative analysis, LV vertical long-axis (2-chamber), horizontal long-axis (4-chamber), and left ventricular outflow tract (3-chamber) views should be performed. For assessment of acquired right heart disease, a 2-chamber right ventricle outflow (RVOT) or right in- and outflow view can also be performed.

Parameters recommended to be routinely reported in a functional cardiac MRI examination may include [32,33] LV end-diastolic volume (LVEDV), LV end-systolic volume (LVESV), LVEDV and LVESV index (LVEDVI and LVESVI), (LVEDV or LVESV divided by body surface area), LV stroke volume, LV ejection fraction (LVEF), LV mass index, and LV end-diastolic and end-systolic diameters. Routine uses of the Simpson rule (summation of end-systolic and end-diastolic areas multiplied by slice thickness for calculating LVESV and LVEDV, respectively) to calculate LVEF is recommended. If necessary, volumes may be calculated from long-axis slices using the area-length method, although this is less accurate than quantitation based on the Simpson rule. Diastolic dysfunction may also be assessed using velocity flow imaging through the mitral valve in order to assess E/A ratios (early [E] and late atrial [A] phases of LV filling). Specific indications for assessment of regional or global LV function include indeterminate or discrepant echocardiography results or situations where serial assessment of change in LV function is important (eg, following patients after myocardial infarction or drug trials or following response to medication, valvular regurgitation, or intracardiac shunts).

Right ventricular (RV) size as well as global and regional wall motion may be assessed qualitatively and reported. Cardiac MRI is the recommended first-line diagnostic test for assessing RV function RV end-diastolic volume (RVEDV), RV end-systolic volume (RVESV), RVEDV index and RVESV index (RVEDVI and RVESVI; RVEDV or RVESV divided by body surface area), RV stroke volume, RV ejection fraction (RVEF) by applying the Simpson rule to short-axis slices. A common indication for RV assessment is to

evaluate patients for suspected arrhythmogenic RV cardiomyopathy (ARVC) or dysplasia (ARVC or ARVD), where reduced global RV function and regional RV WMAs constitute diagnostic criteria for disease [34,35]. Right ventricular size and function assessment, along with pulmonary MRA, is useful in evaluating and following patients with pulmonary arterial hypertension [36,37].

B. Acquired Heart Disease

1. Assessment and differentiation of ischemic and nonischemic cardiomyopathies

In acute myocardial infarction (MI), cardiac MRI is useful in identifying myocardial edema and characterization of tissue necrosis and microvascular obstruction. In acute or chronic myocardial infarction, wall motion, LV function assessment, and extent of LGE provide information that is useful to determine prognosis [38,39].

The performance of LGE may be useful in differentiation of ischemic from nonischemic cardiomyopathies. Myocardial LGE is a specific feature of cardiac MRI that may be extremely useful in detecting areas of myocardial damage and fibrosis [40]. Although late iodinated contrast enhancement can be seen with CT, the contrast to noise ratio of enhancing foci is much higher with MRI due to the ability to suppress normally enhancing myocardium using inversion recovery technique. A subendocardial or transmural pattern of enhancement corresponding to a vascular territory distinguishes ischemic scar from other causes of enhancement such as myocarditis [41] and scarring in nonischemic cardiomyopathies [42,43]. Cardiac MRI with evaluation of global/regional function and LGE is indicated in the evaluation of dilated cardiomyopathy to exclude the diagnosis of ischemic cardiomyopathy, and its absence can obviate the need for cardiac catheterization in many patients [44]. LGE is also helpful in the diagnosis of chronic or acute myocarditis [41,45,46] and infiltrative disease processes such as cardiac sarcoid or amyloidosis [47]. In chronic ischemic cardiomyopathy, MRI evaluation of regional wall thickness, regional WMAs, and late hyperenhancement may be used to evaluate the likelihood of functional recovery after percutaneous or surgical revascularization [48]. LGE can also assist in surgical planning for ischemic aneurysms of the heart and be used to identify ventricular thrombus in association with ischemic scar. In the diagnosis of myocarditis, a combination of at least 2 of the 3 findings—presence of edema on short tau inversion recovery (STIR) imaging, early myocardial enhancement indicative of hyperemia, and LGE—may increase sensitivity [41].

Assessment of regional and global myocardial thickness may provide adjunctive value to echocardiography in patients with suspected myocardial infarction, myocarditis, or cardiomyopathy. In particular, patients with atypical hypertrophic cardiomyopathy, such as apical hypertrophy, may be better assessed with cardiac MRI than echocardiography, and cardiac MRI provides the added benefit of assessment of extent of late gadolinium-enhanced (LGE) myocardial scar tissue [49], which has been known to correlate with risk of arrhythmia. Cardiac MRI is considered the gold standard in the assessment of myocardial mass because it is more accurate and reproducible than echocardiography [30]. In hemochromatosis, MRI may be used for qualitative assessment of myocardial iron overload or quantitative assessment using calculated T2* values of the interventricular septum [50]. It has been reported that it can also be used to assess fatty infiltration of the heart in suspected ARVC. However, the optimal scanning approach and the sensitivity and specificity of MRI for detecting intramural fat in this condition have not yet been established, and it is not currently a diagnostic criterion for ARVC. Rather, a combination of global or regional RV wall motion abnormalities and abnormal RVEDVI or RVEF may be either a major or minor ARVC criteria [34].

Besides detecting iron and fat, cardiac MRI rarely provides tissue-specific information relevant to infiltrative diseases of the heart, but it may provide a pattern of LGE, wall thickness, and wall motion that may suggest a specific diagnosis [51]. For example, amyloidosis is characterized by concentrically increased LV mass, decreased LVEDV, decreased LVEF, biatrial enlargement, and pleural/pericardial effusions, along with a characteristic myocardial enhancement pattern.

2. Chronic myocardial ischemia and viability assessed through the use of pharmacologic agents
MRI perfusion imaging during gadolinium infusion can be used to detect areas of perfusion abnormality at rest or during pharmacologically induced stress [19,20]. Diagnosis of perfusion abnormalities can be performed qualitatively, although use of semiquantitative parametric imaging using features related to the upslope of the perfusion curve may improve accuracy of diagnosis. Cardiac MRI is capable of quantifying perfusion and perfusion reserve, but the tools to do this are not yet widely available [52]. The combination of resting perfusion and LGE imaging may provide adjunctive information in chronic ischemia to differentiate among normal, ischemic but viable (hibernating), and nonviable myocardium. MRI perfusion may also be performed in conjunction with vasodilator stress agents such as adenosine, regadenoson, or dipyridamole to detect inducible ischemia. Precautions and contraindications specific to the chosen vasodilatory agent as described in the package insert and in the literature should be followed [53]. The relative merits of perfusion MRI compared with single-photon emission computed tomography (SPECT) or positron emission tomography (PET) in clinical practice have not been definitely established. However, recent studies have shown superior diagnostic capability of cardiac MRI in patients with global (balanced) perfusion defects, which can be challenging to identify on SPECT [54].

High-dose dobutamine stress MRI may also be performed to detect ischemia as inducible wall motion abnormalities [55]. Dosing should not be above 40 $\mu\text{g}/\text{kg}/\text{min}$. One mg of atropine at the highest dobutamine dose can be administered to achieve a submaximal target heart rate [55,56]. Dobutamine stress may be performed in the MRI environment safely; however, for administration of dobutamine at high levels ($>10 \mu\text{g}/\text{kg}/\text{min}$), a separate satellite monitor/workstation in addition and adjacent to the scanning console in the control room for real-time monitoring of WMAs by the imaging physician while scanning is going on is highly recommended for safe practice. Images should be rigorously monitored by a physician and assessed for induced wall motion abnormality at each increment of dobutamine as the images are acquired. The physician should observe regional wall motion in the long and short axis at each stress level, and the examination should be stopped if new regional WMAs are seen. The physician should be prepared to treat any induced ischemia or arrhythmia with medications, including beta-blockers and nitrates. An external cardiac defibrillator should also be readily available.

Lower-dose dobutamine (at levels of 5 and then 10 $\mu\text{g}/\text{kg}/\text{min}$) can be administered to determine myocardial viability through qualitative and quantitative assessment of myocardial thickening and improvement in wall motion [57].

When stress agents are administered, patients should be hemodynamically monitored (blood pressure, heart rate, SaO₂, and rhythm assessment) throughout the MRI examination. A 12-lead EKG should be obtained before and after the examination and compared for differences suggestive of induced ischemia or infarction. As with vasodilatory agents, all precautions and contraindications specific to dobutamine administration as described in the vendor's package insert and in the literature should be observed [53,56].

3. Cardiac masses
Most cardiac masses are initially identified on echocardiography. Cardiac MRI is indicated to evaluate tumors with regard to specific tissue characterization (fat containing, cystic, fibrotic, etc) [58], origin, relationship to chambers and valves, and myocardial-extracardiac extension. MRI features such as signal characteristics, susceptibility effects, enhancement pattern, and extension from central venous thrombosis can be helpful in differentiating thrombus from tumor [59]. Cardiac MRI is the optimal imaging method for evaluating paracardiac masses as it allows evaluation of mediastinal, pericardial, and myocardial involvement in a single study [60-62].
4. Pericardial disease
Cardiac MRI can be used to evaluate the size and location of pericardial effusions, help differentiate simple from complex or loculated fluid collections, and assess for pericardial thickening [63]. MRI can help to identify hemorrhagic and neoplastic effusions [64,65]. Tamponade and constrictive pericarditis can be detected by evaluating anatomic and functional characteristics using both standard cine imaging

and tagged cine MRI. A major characteristic of tamponade is diastolic collapse of the right ventricular outflow tract. Characteristics of constrictive pericarditis include conical deformation of the ventricles, atrial and caval dilatation, and abnormal motion of the interventricular septum [66].

5. Valvular disease

Using phase-contrast techniques and functional assessment, cardiac MRI has the capability to evaluate congenital or acquired cardiac valve stenosis and/or insufficiency. Aortic and pulmonic valve stenoses can be assessed by phase-contrast determination of peak systolic velocity combined with the modified Bernoulli equation [67]. In addition, direct planimetry of the aortic valve on high-resolution cine images can be performed. Aortic and mitral valvular regurgitant fractions may be measured quantitatively by calculating the difference between aortic root velocity flow mapping and LV stroke volume using the Simpson rule or by direct interrogation by the ratio of backward flow to forward flow. Right-sided valves can be assessed similarly. Anatomic and blood flow characteristics can determine the type and degree of valve abnormality and the functional impact on adjacent cardiac chambers [68].

6. Coronary artery disease

Although cardiac MRI can depict acquired disease of the proximal coronary arteries using a variety of techniques [69], clinical application is limited at this time due to the higher spatial resolution of coronary CT. Some contrast-enhanced and whole-heart coronary MR angiography methods suggest increased sensitivity for flow-limiting stenoses using these techniques [70], and stenotic disease and aneurysms can be detected. Characterization of atherosclerotic plaque and determination of coronary blood flow are research applications that may become clinically valuable in the future.

7. Pulmonary vein assessment

Contrast-enhanced MRA techniques may be used, timed to the left atrium, to assist in defining the anatomy of pulmonary veins prior to RF ablation for treatment of atrial fibrillation [28]. These data may be provided electronically to the referring clinician, who may use it in conjunction with electrophysiology (EP) mapping systems to couple EP information with the MR-depicted anatomy. Pulmonary vein assessment may also be performed to assess pulmonary vein stenoses, a complication of RF ablation therapy. PV anatomy depicted by MRA may be coupled with 3-D volumetric LGE MRI postRF ablation in order to visualize the location of the ablation scar [58].

C. Congenital Heart Disease

The initial diagnosis and assessment of congenital heart disease in infants is almost always accomplished with echocardiography. In both pediatric and adult patients, cardiac MRI may complement echocardiography diagnosis when complete visualization of the anatomy, especially the right heart, aortic arch, or anomalous pulmonary veins, is limited by the acoustic window. Standard flow quantification can provide additional physiological information difficult to obtain by echocardiography. In addition to standard assessment of the heart, 3-D and 4-D contrast-enhanced MRA with multiplanar and 3-D reconstruction and multidirectional quantitative blood flow (4-D flow) can provide essential anatomic and functional information.

Although echocardiography remains the first-line imaging modality, it is well known and accepted that the 3-D and accurate functional assessment of cardiac MRI is especially important in patients with complex congenital heart disease not only in the newborn period but in patients with newly recognized congenital heart disease or in whom monitoring of cardiac anatomy and function are necessary in order to determine the need for further interventional or surgical palliation of disease.

1. Congenital shunts

Specific forms of atrial (ASD) or ventricular septal defects (VSD) and often partial anomalous venous connection (PAPVC) that are difficult to identify or characterize on echocardiography may benefit from MRI assessment. Specific examples include sinus venous defects and apical muscular VSD. In adults with right-sided chamber enlargement, hypertrophy, or dysfunction of unknown etiology, cardiac MRI is

very useful in identifying otherwise occult ASD or PAPVC. Cardiac MRI is useful for ASD sizing prior to percutaneous device closure [71]. In all forms of congenital shunts, quantification of shunt volume (pulmonary to systemic flow ratio, otherwise known as the Qp:Qs ratio) by MR flow velocity mapping compares favorably to other imaging techniques and enables decision making regarding conservative therapy versus surgery [72].

2. Complex congenital anomalies

Cardiac MRI is the most accurate technique for quantifying ventricular mass and volumes and is considered the reference standard for evaluating RV size and function in the setting of congenital heart disease [73]. MRI parameters (RVEDVI, RVESVI, biventricular ejection fraction, late enhancement) and EKG parameters (QRS duration on the resting EKG >180 milliseconds) are the best predictors of adverse clinical outcome in patients with treated tetralogy of Fallot (TOF) [74]. The optimal timing of pulmonary valve replacement for patients with corrected TOF is still undetermined but is influenced by MRI parameters of RV size and function [75]. Multiplanar assessment of the RV in short- and long-axis stacks in patients with some entities such as Ebstein anomaly increases accuracy of RV volume and function measurements.

Cardiac MRI also depicts ventricular and vascular anatomy in complex cases of TOF, pulmonary atresia, tricuspid atresia, and univentricular hearts [76,77]. Cardiac MRI has been used to assist in surgical decision making regarding univentricular repair, one and a half ventricle repair, or biventricular repair in patients who have 2 functioning ventricles but also have factors preventing biventricular repair like straddling atrioventricular (AV) valves, unfavorable location of the VSD, or suboptimal ventricular morphology or function. Cardiac MRI can replace cardiac catheterization for routine evaluation of cardiovascular morphology and function prior to superior cavopulmonary connection or Fontan procedure in the majority of patients undergoing single-ventricle repair [78,79].

3. Pericardial anomalies

Congenital pericardial abnormalities can be evaluated for size and location, and complete absence of the pericardium can be differentiated from partial defects. Complications such as entrapment of the left atrial appendage can be detected [64].

4. Congenital valve disease

Cardiac MRI has the capability to evaluate for congenital cardiac valve morphology and for stenosis and/or insufficiency (eg, bicuspid aortic valve, cleft mitral valve, Ebstein anomaly of the tricuspid valve, etc). Anatomic and blood flow characteristics can determine the type and degree of valve abnormality and the subsequent functional impact on adjacent cardiac chambers [80].

5. Coronary artery anomalies

Cardiac MRI can detect anomalous origins of the coronary arteries. Significant anomalies such as abnormal course of a coronary artery between the aorta and pulmonary artery can be determined [81]. Extracardiac anomalous coronary artery origin (eg, Bland-White-Garland syndrome) can also be identified. Other indications include assessment of aneurysms, stenoses, or thromboses of the native coronary arteries such as may occur in Kawasaki disease or Takayasu arteritis [82]. Cardiac MRI can assess coronary arteries relative to conduits, grafts, and sternum prior to repeat sternotomy in congenital heart disease patients.

6. Extracardiac vascular

Indications for evaluation of the aorta, pulmonary artery, pulmonary veins, and systemic veins in the setting of congenital heart disease are covered by the practice parameters for MRA. For further information, see the [ACR–NASCI–SPR Practice Parameter for the Performance of Body Magnetic Resonance Angiography \(MRA\)](#) [83].

III. QUALIFICATIONS AND RESPONSIBILITIES OF PERSONNEL

See the [ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) [7] for physician qualifications to interpret noncardiac MRI examinations. However, that practice parameter specifically states that additional qualifications are needed for cardiac MRI interpretation. The requirements set forth below went into effect on July 1, 2008.

A. Physician

The physician should have the responsibility for all aspects of the study, including, but not limited to, reviewing all indications for the examination, specifying the pulse sequences to be performed, specifying the imaging planes, specifying the use and dosage of contrast media, interpreting images, generating an official interpretation,² and assuring the quality of the images and the interpretation.

1. Physician with prior qualifications in general MRI

The radiologist or other physician who meets the qualifications of the [ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) [7] for all anatomic areas will have substantial knowledge of the physics of MRI; the principles of MR image acquisition and postprocessing, including use of diagnostic workstations; the design of MR protocols, including pulse sequences; and the rate and timing of contrast administration. The physician also will have substantial experience in MRI interpretation, including MRI of extracardiac thoracic structures that will be included in the cardiac MRI examination and MRA. Some of these physicians will also have substantial experience in other methods of cardiac MRI and in assessing cardiac function and/or will have specific experience in cardiac MRI. However, in order to achieve competency in all aspects of cardiac MRI, many physicians will require additional education in cardiac anatomy, physiology, pathology, and/or cardiac MRI.

The supervising and interpreting physician with prior qualifications in general MRI should also meet 1 of the following requirements:

- a. Training in cardiac MRI in a training program approved by the Accreditation Council for Graduate Medical Education (ACGME), the Royal College of Physicians and Surgeons of Canada (RCPSC), the Collège des Médecins du Québec, or the American Osteopathic Association (AOA) to include:
 - i. Education in cardiac anatomy, physiology, pathology, and cardiac MRI for a time equivalent to at least 30 hours of CME
 - and
 - ii. The interpretation, reporting, and/or supervised review of at least 50 cardiac MRI examinations in the last 36 months
 - or
- b. Completion of at least 30 hours of Category I CME in cardiac imaging, including:
 - i. Cardiac MRI, anatomy, physiology, and/or pathology, or documented equivalent supervised experience in a center actively performing cardiac MRI
 - and
 - ii. The interpretation, reporting, and/or supervised review of at least 50 cardiac MRI examinations in the last 36 months

2. Physician without prior qualifications in general MRI

The radiologist or other physician who does not meet the qualifications of the [ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) [7] for all anatomic areas requires more

²The ACR Medical Legal Committee defines official interpretation as that written report (and any supplements or amendments thereto) that attach to the patient's permanent record. In health care facilities with a privilege delineation system, such a written report is prepared only by a qualified physician who has been granted specific delineated clinical privileges for that purpose by the facility's governing body upon the recommendation of the medical staff.

extensive training and experience in MRI, with an emphasis on cardiac MRI. In addition to specific instruction in imaging interpretation, this training must include the physics of MRI, MRI safety, the principles of MRI acquisition and postprocessing, including use of diagnostic workstations, and the design of MRI protocols, including pulse sequences and the rate and timing of contrast administration. Some physicians will also require additional education in cardiac anatomy, physiology, and pathology.

The supervising and interpreting physician without prior qualifications in general MRI should meet the following requirements:

- a. Completion of an ACGME approved training program in the specialty practiced, plus 200 hours of Category I CME in MRI, including, but not limited to: MRI physics, recognition of MRI artifacts, safety, instrumentation, and clinical applications of MRI in cardiac and thoracic MRI
and
 - b. Supervision, interpretation, and reporting of at least 150 MRI cases in the past 36 months in a supervised situation with an emphasis on thoracic MRI and cardiac MRI, including the interpretation, reporting, and/or supervised review of at least 50 cardiac MRI examinations in the last 36 months
3. Pharmacologic stress testing and administration of other pharmacologic agents

Physicians performing pharmacologic stress testing or administering other pharmacologic agents as part of cardiac MRI should be knowledgeable about the administration, risks, and contraindications of the pharmacologic agents used, and should be capable of monitoring the patient throughout the procedure.

Personnel monitoring stress-induced studies should have current Advanced Cardiac Life Support (ACLS) certification.

4. Maintenance of competence

All physicians performing cardiac MRI examinations should demonstrate evidence of continuing competence in the interpretation and reporting of those examinations. If competence is assured primarily on the basis of continuing experience, interpretation or review of a minimum of 50 examinations every 3 years is recommended in order to maintain the physician's skills.

5. Continuing medical education

The physician's continuing medical education should be in accordance with the [ACR Practice Parameter for Continuing Medical Education \(CME\)](#) [84] of 150 hours of approved education every 3 years and should include CME in cardiac MRI as is appropriate to the physician's practice needs.

6. Additional training recommendations

Physicians supervising a cardiac MRI service (creating scan protocols, administering a quality assurance program, and/or training of others in cardiac MRI) are expected to have additional training in the performance, interpretation, and reporting of cardiac MRI examinations, the pathophysiology of congenital and acquired cardiac diseases, MRI technologies, and MRI safety.

B. Medical Physicist/MR Scientist

The personnel qualified to carry out acceptance testing and monitoring of MRI equipment for the purposes of this parameter include a Qualified Medical Physicist or a Qualified MR Scientist.

A Qualified Medical Physicist is an individual who is competent to practice independently one or more subfields in medical physics. The American College of Radiology considers certification, continuing education, and experience in the appropriate subfield(s) to demonstrate that an individual is competent to practice in one or more

subfields in medical physics, and to be a Qualified Medical Physicist. The ACR strongly recommends that the individual be certified in the appropriate subfield(s) by the American Board of Radiology (ABR), the Canadian College of Physics in Medicine, or by the American Board of Medical Physics (ABMP).

A Qualified Medical Physicist/MR Scientist should meet the [ACR Practice Parameter for Continuing Medical Education \(CME\)](#). (ACR Resolution 17, 1996 – revised in 2012, Resolution 42) [84]

The appropriate subfield of medical physics for this practice parameter is Diagnostic Medical Physics. (Previous medical physics certification categories including Radiological Physics, Diagnostic Radiological Physics, and Diagnostic Imaging Physics are also acceptable.)

A *Qualified MR Scientist* is an individual who has obtained a graduate degree in a physical science involving nuclear magnetic resonance (NMR) or MRI, by the American Board of Medical Physics (ABMP) in magnetic imaging physics.

These individuals should have 3 years of documented experience in a clinical MR environment.

The Qualified Medical Physicist/MR Scientist must be familiar with the principles of MRI safety for patients, personnel, and the public; the FDA’s guidance for MRI diagnostic devices; and other regulations pertaining to the performance of the equipment being monitored. The Qualified Medical Physicist/MR Scientist should be knowledgeable in the field of nuclear MR physics and familiar with MRI technology, including function, clinical uses, and performance specifications of MRI equipment, as well as calibration processes and limitations of the performance testing hardware, procedures, and algorithms. The Qualified Medical Physicist/MR Scientist should have a working understanding of clinical imaging protocols and methods of their optimization. This proficiency should be maintained by participation in continuing education programs of sufficient frequency to ensure familiarity with current concepts, equipment, and procedures.

The Qualified Medical Physicist/MR Scientist may be assisted in obtaining test data for performance monitoring by other properly trained individuals. These individuals must be properly trained and approved by the Qualified Medical Physicist/MR Scientist in the techniques of performing the tests, the function and limitations of the imaging equipment and test instruments, the reason for the tests, and the importance of the test results. The Qualified Medical Physicist/MR Scientist must review and approve all measurements.

C. Registered Radiologist Assistant

A registered radiologist assistant is an advanced level radiographer who is certified and registered as a radiologist assistant by the American Registry of Radiologic Technologists (ARRT) after having successfully completed an advanced academic program encompassing an ACR/ASRT (American Society of Radiologic Technologists) radiologist assistant curriculum and a radiologist-directed clinical preceptorship. Under radiologist supervision, the radiologist assistant may perform patient assessment, patient management and selected examinations as delineated in the Joint Policy Statement of the ACR and the ASRT titled “Radiologist Assistant: Roles and Responsibilities” and as allowed by state law. The radiologist assistant transmits to the supervising radiologists those observations that have a bearing on diagnosis. Performance of diagnostic interpretations remains outside the scope of practice of the radiologist assistant. (ACR Resolution 34, adopted in 2006)

The radiologist assistant performing cardiac MRI should have advanced certification in MRI and should have supervised experience in performing cardiac MRI examinations. The radiologist assistant’s continuing education credits should include continuing education in cardiac CT performance as is appropriate to his or her practice needs. Basic life support (BLS) and automatic defibrillator (AED) training is recommended.

D. Radiologic Technologist

The technologist should participate in assuring patient comfort and safety in preparing and positioning the patient for the MRI examination, including proper positioning of the electrocardiogram (ECG) leads, and in obtaining the MRI data in a manner suitable for interpretation by the physician.

The technologist performing cardiac MRI should be certified by the American Registry of Radiologic Technologists (ARRT) or the Canadian Association of Medical Radiation Technologists (CAMRT). It is recommended that the technologist performing cardiac MRI have advanced certification in MR. Each technologist should have supervised experience in performing cardiac MRI examinations and in the intravenous administration of conventional MR contrast media. If intravenous contrast material is to be administered, the qualifications for technologists performing intravenous injections should be in compliance with current ACR policy³ and with existing operating procedures or manuals at the imaging facility. The technologist's continuing education credits should include continuing education in cardiac MRI as is appropriate to his or her practice needs. Basic life support (BLS) and automatic defibrillator (AED) training is recommended.

Any technologist practicing MRI scanning should be licensed in the jurisdiction in which he or she practices, if state licensure exists. To assure competence, all technologists must be evaluated by the supervising physician [85].

IV. SAFETY GUIDELINES AND POSSIBLE CONTRAINDICATIONS

In all cases, a risk/benefit analysis for each patient should be performed prior to MRI scanning. The cardiac MRI physician should have thorough knowledge of patient safety, including proper patient and/or accompanying person screening, specific absorption rate (SAR) limits, possible neurological effects, tissue heat deposition, risks and benefits of contrast media administration, and contraindications for performance of MRI, such as certain implantable devices [86]. Prior to MRI, patients screening should include determination of implantable devices, and operators should determine whether the devices are "MR safe," "MR conditional," or "not MR safe." Although the performance of MRI in patients with pacemakers or implantable cardioverter defibrillators (ICDs) that are not MRI conditional has been reported, this practice is not currently routine and should only occur under strictly monitored conditions and parameters [87]. In addition, each case should be reviewed for risk/benefit. If cardiac MRI is to be performed in patients with a pacemaker or other non-MRI-conditional device, it is recommended that proper personnel be present during the examination. They should include a physician or technical staff that is capable of programming or adjusting the implanted device should reprogramming be required.

In regard to the administration of intravenous (IV) contrast media, the physician should supervise patient selection to identify those patients for whom IV contrast media administration may present an increased risk or be contraindicated. Reactions occur less frequently with gadolinium-based contrast media in comparison to iodinated media. For pretreatment considerations in these patients, please see the [ACR Manual on Contrast Media](#) [88]. In patients with severely impaired renal function, the risk of nephrogenic systemic fibrosis (NSF) should be compared against the potential benefits for contrast-enhanced MRI using gadolinium-based contrast media and/or alternate non-MRI forms of imaging [86]. The physician should also be available to treat adverse reactions to IV contrast media as described in the [ACR-SPR Practice Parameter for the Use of Intravascular Contrast Media](#) [89] and the [ACR Manual on Contrast Media](#) [88].

When exercise or pharmacologic stress is performed or hemodynamically unstable patients are studied, a physician must always be present. Life-support instruments, medications, and ACLS-trained personnel must be available in the immediate vicinity of the stress laboratory. Baseline blood pressure measurement and electrocardiographic tracing should be obtained before performing pharmacologic stress. Heart rhythm and blood pressure must be monitored during stress and recovery.

³See the [ACR-SPR Practice Parameter for the Use of Intravascular Contrast Media](#).

As described in section III.A.3, during dobutamine administration a second (satellite) viewing station is suggested to permit direct comparison of wall motion at the various dobutamine dose levels to wall motion in images obtained at lower dose levels. This workstation is in addition to the console used by the MR technologist for scanning purposes.

In young children undergoing cardiac MRI and in some adult patients, sedation may be required. When sedation is necessary, it must be administered in accordance with institutional policy and state and federal law by a qualified practitioner with training in cardiopulmonary resuscitation [90]. For more information, see the [ACR-SIR Practice Parameter for Sedation/Analgesia](#) [91]. MRI practitioners should be aware that sedated patients may be unable to follow directions and adequately perform breath holding. Thus, modified imaging protocols to include multiple averages, real-time respiratory gating, and/or fast single-shot techniques may be required.

For additional information on MRI safety, the reader should see the [ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) [7] and the [ACR Guidance Document on MR Safe Practices: 2013](#) [86].

Peer-reviewed literature pertaining to MRI safety should be reviewed on a regular basis

V. SPECIFICATIONS OF THE EXAMINATION

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

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

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

The supervising physician must have complete understanding of the indications, risks, and benefits of the examination, as well as alternative imaging procedures. The physician must be familiar with potential hazards associated with MRI, including potential adverse reactions to contrast media. The physician should be familiar with the findings of 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 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 should be screened and interviewed prior to the examination to exclude individuals who may be at risk by exposure to the MR environment (see the [ACR-NASCI-SPR Practice Parameter for the Performance of Body Magnetic Resonance Angiography \(MRA\)](#) [83]).

Certain indications require administration of IV contrast media. IV contrast enhancement should be performed using appropriate injection protocols and in accordance with the institution's policy on IV contrast utilization (see the [ACR–SPR Practice Parameter for the Use of Intravascular Contrast Media](#) [89]).

Pediatric patients or patients suffering from anxiety or claustrophobia may require sedation or additional assistance. Administration of moderate sedation or general anesthesia may enable achievement of the examination, particularly in young children. If moderate sedation is necessary, refer to the [ACR–SIR Practice Parameter for Sedation/Analgesia](#) [91].

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 [92,93]

A phased-array surface coil should be used unless precluded by patient body habitus. The heart is a small structure, so the field of view should be reduced to maintain adequate spatial resolution. An adequate signal to noise ratio should also be maintained.

Cardiac MRI techniques must be optimized for the wide range of indications for cardiac imaging and may be highly variable due to advances in MRI scanner software and hardware. However, most examinations will include short-axis and long-axis cine images of the heart obtained for ventricular function. For left ventricular function, images in the true short-axis plane of the heart should be obtained from just above the mitral valve plane to the apex of the heart at approximately 1-cm intervals. Depending on the pulse sequence used, this could be accomplished, for example, using 8-mm-thick slices and 2-mm-thick gaps between the slices for a 2-D acquisition. In addition, horizontal and long-axis cine views of the left ventricle are routinely acquired. Left ventricular outflow tract views may also be routinely obtained, particularly for patients referred for hypertrophic cardiomyopathy. On most MRI systems, cine image acquisition should be gated to the R wave of the electrocardiogram and will involve suspended respiration, typically at resting lung volume during the acquisition. Acquired temporal resolution preferably should be ≤ 40 milliseconds; interpolation methods (eg, view sharing) are desirable to display reconstructed cine images at less than the acquired temporal resolution.

Steady-state free precession gradient-echo imaging has been demonstrated to result in faster high-quality cine images of the heart and is now preferred. Segmented fast gradient-echo images with flow compensation are useful in some circumstances, including 3T cardiac cine MRI. If metal artifacts are present from adjacent hardware, fast gradient-echo images may be useful to reduce the extent of those artifacts.

For cardiac indications that require assessment of paracardiac structures, inflammatory/infiltrative disease of the heart, or cardiac tumors, T1-weighted, T2-weighted, and/or T2*-weighted images of the heart may be helpful. Since these images are gated to the cardiac cycle, T1-weighted images typically have intermediate, or proton density, weighting, especially at low heart rates. The imaging planes should be tailored to the pathology that is present, but transaxial images are often suitable. Images should be gated to the R wave of the electrocardiogram used to obtain T1-weighted or T2-weighted images. Double inversion recovery fast/turbo spin-echo techniques have been implemented and are preferred for fast/turbo spin-echo images to suppress blood signal. Echo train lengths (ETLs) with this sequence are usually < 40 ; even shorter ETLs (< 10) may be required for short effective-TE scans. Very high echo train lengths associated with single-shot techniques (eg, "HASTE" or single-shot fast spin-echo) result in excessive blurring of intracardiac detail and, if possible, should be avoided as the sole means of tissue characterization.

Administration of intravenous gadolinium chelates (0.1 to 0.2 mmol/kg) for myocardial enhancement may be required for certain cardiac indications, including, but not limited to, evaluation of masses/cysts, pericardium,

myocardial perfusion, inflammation, infiltrative diseases, fibrosis, or infarction. Myocardial perfusion evaluation additionally requires rapid bolus administration (3 to 5 mL/s) of the gadolinium chelate, usually at low dose (0.025 to 0.05 mmol/kg). Postgadolinium images of the heart are T1-weighted images acquired using fast/turbo spin-echo, double inversion recovery fast/turbo spin-echo, or gradient-echo techniques. Evaluation of myocardial infarction/scar or fibrosis is optimally performed using an inversion-prepared gradient-echo technique. In this method, the inversion time is optimized to suppress normal myocardium (TI typically 175 to 275 milliseconds) during the washout phase (eg, 5 to 30 minutes) of gadolinium chelate distribution. Precise TI depends on the gadolinium chelate dose time after administration and individual patient pharmacokinetics and must be determined for each individual being scanned. A more robust alternative is phase-sensitive inversion recovery (PSIR) methods, which remove background phase but preserve the sign of magnetization during inversion recovery (IR) [94]. These PSIR methods allow for more leeway in the T1 setting while still providing optimal normal myocardial nulling.

Phase-contrast imaging of the heart may be used for a variety of indications related to quantification of flow. The velocity-encoding gradient should be set to a value higher than the maximum expected velocity of blood. Phase-contrast images are acquired either parallel or perpendicular to the direction of flow, depending on the indication. Newer “4-D” (3-directional, time-resolved, phase-encode) sequences are currently available on some MRI systems and may be of benefit, particularly in tortuous arteries [95]. MRA using gadolinium-enhanced techniques is frequently used in conjunction with other cardiac MRI methods. It may provide additional useful information regarding the status of the aorta, pulmonary artery, pulmonary veins, coronary arteries, and vena cava. Noncontrast-enhanced navigator respiratory-gated SSFP MRA methods may also be useful in assessing not only coronary arteries but also great vessels and cardiac anatomy [96].

MRI tissue tagging is a technique in which radiofrequency bands are applied to the heart at end diastole. Cine images are then acquired, and the motion of the bands, or tags, is observed. MRI tagging may provide additional visual indication of focal wall motion abnormalities in selected cases. For example, MRI tagging lines applied perpendicular to the free wall of the right ventricle may be useful to determine the relative motion of the pericardium compared to the myocardium in patients with suspected constrictive pericarditis.

When available, techniques such as parallel imaging and partial Fourier methods may be used to shorten patient breath-holds. Real-time cine imaging (obtained without ECG gating) may be used for patients with arrhythmia or suspected constrictive pericarditis. On most current MRI scanners, the temporal resolution of this approach is low. Thus, real-time imaging is currently used to supplement other gated methods.

The analysis of cardiac MRI examinations is optimally performed using a separate imaging workstation. Separate cardiac imaging software is usually required for evaluating cardiac function, blood flow (from phase-contrast images), and 3-D MRA.

VI. DOCUMENTATION

Reporting should be in accordance with the [ACR Practice Parameter for Communication of Diagnostic Imaging Findings](#) [97]. When reporting information regarding myocardial function, perfusion, viability, or infarction, the 17-segment model should be used [31]. Wall motion abnormalities should be described using conventional terminology such as hyperkinetic, hypokinetic, akinetic, or dyskinetic. Images should be labeled with the patient identification, facility identification, examination date, and the side (right or left) of the anatomic site imaged.

VII. EQUIPMENT SPECIFICATIONS

Scanners for clinical cardiac MRI must be accredited by the ACR, and 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](#) [92]. The MRI equipment specifications and performance should 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.

MRI scanners used for cardiac MRI performance should have field strength of ≥ 1.0 Tesla and have a slew rate of at least 70 mT/m/s. At the time of writing, cardiac MRI is most commonly performed at 1.5 Tesla however, field strength of up to 3.0 Tesla can be used. MRI scanners should be equipped with a localized multichannel radiofrequency surface coil and ECG gating. Ideally, ECG gating capabilities would include prospective triggering, retrospective gating, and triggered retrogating. Vectorcardiographic gating is the standard of care for cardiac MRI. An MRI-compatible power injector is required for performing myocardial perfusion MR imaging or any MR angiographic methods. A power injector is not required for late contrast-enhanced studies. The MRI scanner should be capable of fast 3-D gradient-echo imaging, steady-state imaging with free precession, phase-contrast flow quantification, fast multislice myocardial perfusion imaging, and late contrast-enhanced myocardial imaging. Parallel imaging and half-Fourier capabilities are desirable to permit shortened breath-hold requirements.

Commercial FDA-approved software for processing data (calculation of ejection fractions, reformatting angiographic data) should be available either as part of the MRI system or on a separate workstation. Postprocessing should be performed or supervised by the cardiac MRI physician.

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 *Position Statement on QC & Improvement, Safety, Infection Control, and Patient Education* on the ACR website (<http://www.acr.org/guidelines>).

Specific policies and procedures related to MRI safety should be in place, with documentation that is updated annually and compiled under the supervision and direction of the supervising MRI physician. Guidelines should be provided that deal with potential hazards associated with the MRI examination of the patient as well as to others in the immediate area. Screening forms must also be provided to detect those patients who may be at risk for adverse events associated with the MRI examination or with any contrast medium or pharmaceutical to be administered [93].

Equipment monitoring should be in accordance with the [ACR–AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance Imaging \(MRI\) Equipment](#) [92].

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

ACR

Pamela K. Woodard, MD, FACR, FAHA, FNASCI, Chair
David A. Bluemke, MD, PhD, FACR, FAHA, FNASCI
S. Bruce Greenberg, MD, FACR
E. Kent Yucel, MD, FACR, FAHA, FNASCI

NASCI

Jill E. Jacobs, MD, FACR, FAHA, FNASCI
Karen G. Ordovas, MD, MAS, FNASCI
Charles S. White, MD, FACR, FNASCI

SPR

Dianna M.E. Bardo, MD
Sadaf Bhutta, MD, MBBS
Mike Seed, MD, MBBS

Committee on Body Imaging (Cardiovascular)

(ACR Committee responsible for sponsoring the draft through the process)

Arthur E. Stillman, MD, PhD, FACR, Chair
Vincent B. Ho, MD, MBA, Vice-Chair
James P. Earls, MD
Travis S. Henry, MD
Lynne M. Hurwitz, MD
Jacobo Kirsch, MD
Andrew L. Rivard, MD
Richard D. White, MD, FACR

Committee on Practice Parameters – Pediatric Radiology

(ACR Committee responsible for sponsoring the draft through the process)

Beverly Newman, MB, BCh, BSc, FACR, Chair
Lorna P. Browne, MB, BCh
Timothy J. Carmody, MD, FACR
Brian D. Coley, MD, FACR
Lee K. Collins, MD
Monica S. Epelman, MD
Lynn Ansley Fordham, MD, FACR
Kerri A. Highmore, MD
Sue C. Kaste, DO
Tal Laor, MD
Terry L. Levin, MD
Marguerite T. Parisi, MD, MS
Sumit Pruthi, MBBS
Nancy K. Rollins, MD
Pallavi Sagar, MD

Lincoln L. Berland, MD, FACR, Chair, Commission on Body Imaging
Marta Hernanz-Schulman, MD, FACR, Chair, Commission on Pediatric Imaging
Jacqueline A. Bello, MD, FACR, Chair, Commission on Quality and Safety
Matthew S. Pollack, MD, FACR, Chair, Committee on Practice Parameters and Technical Standards

Comments Reconciliation Committee

Timothy L. Swan, MD, FACR, Chair
Andrew Moriarity, MD, Co-Chair
Dianna M.E. Bardo, MD
Jacqueline A. Bello, MD, FACR
Lincoln L. Berland, MD, FACR
Sadaf Bhutta, MD, MBBS
David A. Bluemke, MD, PhD, FACR, FAHA, FNASCI
S. Bruce Greenberg, MD, FACR
Marta Hernanz-Schulman, MD, FACR
William T. Herrington, MD, FACR
Vincent B. Ho, MD, MBA

Jill E. Jacobs, MD, FACR, FAHA, FNASCI
Terry L. Levin, MD
Beverly Newman, MB, BCh, BSc, FACR
Karen G. Ordovas, MD, MAS, FNASCI
Matthew S. Pollack, MD, FACR
Mike Seed, MD, MBBS
Arthur E. Stillman, MD, PhD, FACR
Charles S. White, MD, FACR, FNASCI
Pamela K. Woodard, MD, FACR, FAHA, FNASCI
E. Kent Yucel, MD, FACR, FAHA, FNASCI

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