Revised 2021 (Resolution 42)*

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 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 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 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 also acquire images of coronary arteries, cardiac chambers, valves, myocardium, and pericardium in order to view cardiac anatomy. Furthermore, MRI methods also permit the evaluation of regional and global cardiac function. Thus, CT and MRI continue to play an increasing role in comprehensive cardiac imaging. This document deals specifically with cardiac MRI applications.

The technical parameters and field of view (FOV) of a cardiac MRI examination need to be appropriately tailored to evaluate the cardiac anatomy and/or function in question. However, 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 [3-5]. In addition to examining the cardiac structures of interest, the interpreting imaging 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) and the manufacturer's guidelines are followed [6]. In addition, it has been shown that scanning pacemakers under certain strictly monitored conditions can be performed safely [7,8] (see Section IV). Other safety issues include radiofrequency (RF) heating of implants, those associated with MRI contrast agents and patient sedation. Although uncommon, gadolinium-based contrast agents can cause allergic reactions or can place patients at risk for nephrogenic systemic fibrosis (NSF) when administered in patients with renal failure. A significant percentage of cardiac MRIs are performed with intravenous contrast agents. For more information, refer to the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [9] and ACR Manual on Contrast Media [10].

Radiologists, because of their extensive experience with MRI, have an important role in its application to the heart. Most radiologists already supervise and interpret MRI and 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 "black-blood" fast spin-echo imaging [11]. "Bright-blood" gradient-echo–based 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 [12,13]. 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, angiographic 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 provides the ability to freely angulate the imaging plane prescription to image the heart in physiologically meaningful orientations. Furthermore, studies have shown that cardiac MRI is both precise and reproducible (intraobserver, interobserver, and/or interexamination) for the quantification of various cardiac parameters, such as chamber and stroke volumes, ejection fraction, cardiac output, or wall mass [14,15]. When either cine sequential tomographic or volumetric (3-D) 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) [16,17]. 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, strain encoding (SENC), and displacement encoding with stimulated echoes, (DENSE) permit calculation of in-plane and through-plane strain, yielding circumferential strain and longitudinal strain [18-20]. These studies can be performed at rest or during the intravenous administration of pharmacologic stress agents.

4. Phase-contrast MRI (PC-MRI) can provide information about tissue velocities on a pixel-by-pixel basis, which can estimate blood flow in terms of velocity and volume [21,22]. 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, pulmonary artery flow volume (Qp) to ascending aortic flow volume (systemic flow or Qs) to provide Qp/Qs 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 [23,24]. This procedure can be performed both at rest and during intravenous administration of a pharmacologic stress agent such as dipyridamole, adenosine, or regadenoson.

6. 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 [25,26]; to differentiate between ischemic and nonischemic cardiomyopathies; to determine the myocardial viability in patients with coronary artery disease; and to assess myocarditis and a variety of cardiomyopathies, including, but not limited to, sarcoidosis, amyloidosis, and hypertrophic cardiomyopathy [27]. 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 [28-34].

7. T2-weighted sequences and T2-mapping sequences can be used to detect myocardial edema in acute myocardial infarction and myocarditis [35,36]. T2*-weighted imaging can be used to detect iron content in the myocardium [37].

8. Myocardial T1-mapping methods show some potential in assessing diffuse fibrotic and infiltrative processes [36,38]. Noncontrast (native) T1 mapping is useful for identification of acute myocarditis, amyloid, and Fabry disease based on abnormal T1 times compared with healthy individuals.

9. Use of 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 RF ablation for treatment of atrial fibrillation [39]. MRA is also very useful for assessing great vessel anatomy in congenital heart disease [40]. 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) [9].

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 LV function, MRI, because of its double oblique 2-D and 3-D data acquisition capability, is considered to be more accurate and reproducible [41]. MRI is also less subject to variability due to patient body habitus or emphysema when compared with 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 [42] 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, an axial cine stack and a 2-chamber right ventricle long-axis view (RV-2 chamber, outflow tract (RVOT), or right inflow and outflow view) can also be performed.

Parameters recommended to be routinely reported in a functional cardiac MRI examination may include [43,44] 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 from contiguous short-axis slices 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). Cardiac MRI is particularly helpful when accurate assessment of regional or global LV function is critical for patient management and prognosis, such as in assessment of cardiomyopathy severity and response to treatment, evaluation for cardiac transplant, timing for adult congenital heart disease surgery, risk stratification after myocardial infarction, and others.

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 quantitatively assessing RV function with parameters such as RV end-diastolic volume (RVEDV), RV end-systolic volume (RVESV), RVEDV index and RVESV index (RVEDVI and RVESVI, respectively; 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 suspected arrhythmogenic RV cardiomyopathy (ARVC) or dysplasia (ARVC or ARVD), in which reduced global RV function and regional RV WMAs constitute diagnostic criteria for disease [45,46]. RV size and function assessment, along with pulmonary MRA, is useful in evaluating and following patients with pulmonary arterial hypertension [47,48]. Finally, precise assessment of RV size and function is critical for informing need for intervention in adult patients with congenital heart diseases.

B. Acquired Heart Disease

1. Assessment and differentiation of ischemic and nonischemic cardiomyopathies

In acute myocardial infarction, 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 the of LGE provide information that is useful to determine prognosis [49,50].

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 useful in detecting areas of myocardial damage and replacement fibrosis [51]. Although late iodinated contrast enhancement can be seen with CT, the contrast to noise ratio of enhancing foci is much higher with MRI because of its 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 [52] and scarring in nonischemic cardiomyopathies [53,54]. 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 [55]. LGE is also indicated for the diagnosis of chronic or acute myocarditis [52,56,57] and infiltrative disease processes, such as cardiac sarcoid or amyloidosis [58]. In chronic ischemic cardiomyopathy, MRI evaluation of regional wall thickness, regional WMAs, and LGE may be used to evaluate the likelihood of functional recovery after percutaneous or surgical revascularization [59]. 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 2018, a panel of experts [60] suggested updating the Lake Louise criteria for the cardiac MR diagnosis of myocarditis [52], proposing a combination of 2 findings

a. Presence of myocardial edema as evidenced by abnormal myocardial T2 signal (global or regional increase of myocardial T2 relaxation time [T2 mapping] or an increased signal intensity in T2-weighted images)

b. Myocardial injury, as demonstrated by a T1 abnormality (increased myocardial T1 [eg, early gadolinium enhancement or T1 mapping], increased extracellular volume, or nonischemic pattern of LGE), is highly sensitive and specific for establishing the diagnosis. A recent meta-analysis revealed that newer T1 mapping and T2 mapping techniques were perhaps more accurate and promising successors for traditional T1-based MR markers and T2-based MR markers for diagnosis of myocarditis [36].

2. 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, with cardiac MRI providing the added benefit of assessment of the extent of LGE myocardial scar tissue [61], 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 [41]. In hemochromatosis, MRI is indicated for qualitative assessment of myocardial iron overload or quantitative assessment using calculated T2* values of the interventricular septum [62]. In the assessment of ARVC, a combination of global or regional RV WMAs and abnormal RVEDVI or RVEF measured by MRI may be either a major or minor ARVC criteria for the diagnosis [45].

Cardiac MRI findings in combination can strongly suggest the diagnosis of specific cardiomyopathies, such as amyloidosis and hypertrophic cardiomyopathy [63]. For example, amyloidosis is characterized by concentrically increased LV mass, decreased LVEDV, decreased LVEF, biatrial enlargement, and pleural/pericardial effusions, along with a characteristic LGE pattern of global subendocardial enhancement, and diffusely abnormal T1 signal of myocardium. Hypertrophic cardiomyopathy may present with characteristic LV wall thickness equal to or greater than 15 mm, which is predominant in the septum, and hinge point LGE distribution.

3. 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 [23,24]. 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 [64]. 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 [65]. Multicenter and single-center studies have shown cardiac perfusion MRI to be as accurate as single-photon emission CT (SPECT) or PET for the diagnosis of obstructive coronary artery disease [24,66-69]. With more wide use of cardiac perfusion MR, cardiac MR has been increasingly found to provide useful prognostic information for patient management [70-72].

   High-dose dobutamine stress MRI may also be performed to detect ischemia as inducible WMAs [73]. Dosing should not be above 40 μg/kg/min. One milligram of atropine at the highest dobutamine dose can be administered to achieve a submaximal target heart rate [73,74]. Dobutamine stress may be performed in the MRI environment safely; however, for administration of dobutamine at high levels (>10 μg/kg/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 WMA 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 μg/kg/min) can be administered to determine myocardial viability through qualitative and quantitative assessment of myocardial thickening and improvement in wall motion [75].

   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 electrocardiogram (ECG) 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 [65,74].

4. 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) [76], 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 [77]. 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 [78-80].

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 [81]. MRI can help identify hemorrhagic and neoplastic effusions [82,83]. 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 RV outflow tract. Characteristics of constrictive pericarditis include conical deformation of the ventricles, atrial and caval dilatation, and abnormal motion of the interventricular septum [84].

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 [85]. 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 [86].

6. Coronary artery disease
   Although cardiac MRI can depict acquired disease of the proximal coronary arteries using a variety of techniques [87], clinical application is limited at this time due to the higher spatial resolution of coronary CT. Some contrast-enhanced and whole-heart coronary MRA methods suggest increased sensitivity for flow-limiting stenoses using these techniques [88], which allows stenotic disease and aneurysms to 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 [39]. These data may be provided electronically to the referring clinician, who may use them 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. Pulmonary vein anatomy depicted by MRA may be coupled with 3-D volumetric LGE MRI post-RF ablation in order to visualize the location of the ablation scar [76].

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, which can be particularly useful for operative planning in complex congenital heart disease cases.

Although echocardiography remains the first-line imaging modality, it is well known and accepted that 3-D and accurate functional assessment of cardiac MRI is especially important in pediatric patients with complex congenital heart disease and in adult patients after initial repair 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 septal defects (ASDs) or ventricular septal defects (VSDs), 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 VSDs. In adults with right-sided chamber enlargement, hypertrophy, or dysfunction of unknown etiology, cardiac MRI is very useful in identifying otherwise occult ASDs or PAPVC. Cardiac MRI is useful for ASD sizing prior to percutaneous device closure [89]. 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 and quantification of right heart enlargement by MR volumetry compares favorably with other imaging techniques and enables decision making regarding conservative therapy versus surgery [90].

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 ventricular size and function in the setting of congenital heart disease [91]. Cardiac MR can provide meaningful insight into clinical prognosis, timing for repair, repair success, and early indication for the need of additional interventions [92,93]. For example, MRI parameters (RVEDVI, RVESVI, biventricular ejection fraction, late enhancement) and ECG parameters (QRS duration on the resting ECG >180 ms) are the best predictors of adverse clinical outcome in patients with repaired tetralogy of Fallot (TOF) [94]. 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 [95]. 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 can be 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 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 [96,97].

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 [82].

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 [98].

5. Coronary artery anomalies
   Cardiac MRI can detect anomalous origins and the course of the coronary arteries. Significant anomalies, such as abnormal course of a coronary artery between the aorta and pulmonary artery, can be determined along with detection of high-risk features, such as intramural or intramyocardial course [99]. Anomalous coronary artery origin from the pulmonary artery (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 [100]. Cardiac MRI can assess the course of coronary arteries relative to conduits, grafts, and sternum prior to catheter-based vascular stenting/pulmonary valve replacement or repeat sternotomy in patients with congenital heart disease. Evaluation of myocardial perfusion using stress agents can also be performed in the setting of anomalous coronaries, coronary vasculitis, or coronary reimplantation in congenital heart disease.

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) [101].

III. QUALIFICATIONS AND RESPONSIBILITIES OF PERSONNEL

See the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [9] for physician qualifications to interpret noncardiac MRI examinations. Of note, that practice parameter specifically states that additional qualifications are needed for cardiac MRI interpretation.

A. Physician

The physician is responsible 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 ensuring 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) [9] 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. CME in cardiac anatomy, physiology, pathology, and cardiac MRI

      and

      ii. The interpretation, reporting, and/or supervised review of cardiac MRI examinations

      or

   b. Completion 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

      The interpretation, reporting, and/or supervised review of cardiac MRI examinations

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) [9] for all anatomic areas requires more extensive training and experience in MRI, with an emphasis on cardiac MRI. In addition to specific

[2]The 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.

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 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 MRI cases in a supervised situation with an emphasis on thoracic MRI and cardiac MRI, including the interpretation, reporting, and/or supervised review of cardiac MRI examinations

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 ensured primarily on the basis of continuing experience, interpretation or review of a sufficient number of examinations in order to maintain the physician's skills.

5. Continuing medical education (CME)

The physician's CME should be in accordance with the ACR Practice Parameter for Continuing Medical Education (CME) [102] of approved education 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. Qualified 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 in 1 or more subfields of medical physics. The ACR considers certification, continuing education, and experience in the appropriate subfield(s) to demonstrate that an individual is competent to practice in 1 or more subfields of 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, the American Board of Science in Nuclear Medicine (ABSNM), or the American Board of Medical Physics (ABMP).

A qualified medical physicist/MR scientist should meet the ACR Practice Parameter for Continuing Medical Education (CME) [102] ~~[102]~~.

The appropriate subfield of medical physics for this practice parameter is diagnostic medical physics (previous medical physics certification categories to include radiological physics, diagnostic radiological physics, and diagnostic imaging physics are also acceptable). (ACR Resolution 17, adopted in 1996 – revised in 2008, 2012, 2022, Resolution 41f)

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 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 NMR 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, with a desired focus on cardiac imaging. 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. Non-Physician Radiology Provider (NPRP)

NPRPs are all Non-Physician Providers (eg, RRA, RPA, RA, PA, NP, ...) who assist with or participate in portions of the practice of a radiologist-led team (Radiologists = diagnostic, interventional, neurointerventional radiologists, radiation oncologists, and nuclear medicine physicians). The term "NPRP" does not include radiology, CT, US, NM MRI technologists, or radiation therapists who have specific training for radiology related tasks (eg, acquisition of images, operation of imaging and therapeutic equipment) that are not typically performed by radiologists.

The term 'radiologist-led team' is defined as a team supervised by a radiologist (ie, diagnostic, interventional, neurointerventional radiologist, radiation oncologist, and nuclear medicine physician) and consists of additional healthcare providers including RRAs, PAs, NPs, and other personnel critical to the provision of the highest quality of healthcare to patients. (ACR Resolution 8, adopted 2020).

1. Registered Radiologist Assistant (RRA)

An RRA is an advanced level radiographer who is certified and registered as a "Registered Radiologist Assistant" by the American Registry of Radiologic Technologists (ARRT) after successful completion of an advanced academic program encompassing an American Society of Radiologic Technologists (ASRT) RRA curriculum and a radiologist-directed clinical preceptorship.

Under radiologist supervision, the RRA may perform patient assessment, patient management, and selected examinations as delineated in the ACR Statement "Radiologist Assistant: Roles and Responsibilities" subject to state law (see the ACR Digest of Council Actions Appendix H). The RRA transmits to the supervising

radiologist those observations that have a bearing on diagnosis. Performance of diagnostic interpretations (preliminary, final, or otherwise) remains outside the scope of practice of the RRA. RRAs performing invasive or non-invasive procedures should function under radiologist supervision and as part of radiologist-led teams. (Adopted 2006 Resolution 34, 2016 Resolution 1-c, Revised in 2020 Resolution 11).

The RRA 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 ensuring patient comfort and safety in preparing and positioning the patient for the MRI examination to include proper positioning of the ECG leads and obtaining the MRI data in a manner suitable for interpretation by the physician.

The technologist performing cardiac MRI should be certified by the 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 policy[3] 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 ensure competence, all technologists must be evaluated by the supervising physician [103].

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 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 [104]. Prior to MRI, patient 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 [105]. 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 [8]. In instances in which device type or its safety cannot be determined, risk/benefit should be determined by the appropriate imaging physician (in consultation with the referring cardiologist), and patient should be informed and/or consented for the procedure.

Regarding 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 with iodinated media. For pretreatment considerations in these patients, please see the ACR Manual on Contrast Media [10]. 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 [104]. The physician should also be available to treat adverse reactions to IV

[3] See the ACR–SPR Practice Parameter for the Use of Intravascular Contrast Media.

contrast media as described in the ACR–SPR Practice Parameter for the Use of Intravascular Contrast Media [106] and the ACR Manual on Contrast Media [10].

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.

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 [107]. For more information, see the ACR-SIR Practice Parameter for Minimal and/or Moderate Sedation/Analgesia [108]. 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 and navigator gating, and/or fast single-shot techniques may be required. Feed-and-sleep/wrap techniques can be attempted to avoid use of sedation in infants [109].

For additional information on MRI safety, the reader should see the ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI) [9] and the ACR Guidance Document on MR Safe Practices 2020 [104].

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 – revised in 2016, Resolution 12-b)

The supervising physician must have adequate understanding of the indications, risks, and benefits of the imaging 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 that are 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) [101]).

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 [106]).

Pediatric patients or patients suffering from anxiety or claustrophobia may require sedation or additional assistance, including child life support and patient entertainment systems that might alleviate anxiety. 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 Minimal and/or Moderate Sedation/Analgesia [108].

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 [110,111]

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

Cardiac MRI techniques must be optimized for the wide range of indications for cardiac imaging and may be highly variable because of 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 LV 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 (less in small children). Depending on the pulse sequence used, this could be accomplished, for example, by using 8-mm-thick slices and 2-mm-thick gaps between the slices for a 2-D acquisition in adult-sized patients. In addition, horizontal and long-axis cine views of the left ventricle are routinely acquired. LV 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 ECG and will involve suspended respiration, typically at resting lung volume during the acquisition. Acquired temporal resolution preferably should be ≤40 ms (25 cardiac phases preferred); interpolation methods (eg, view sharing) are desirable to display reconstructed cine images at less than the acquired temporal resolution.

Balanced steady-state free precession gradient-echo imaging has been demonstrated to result in faster cine images of the heart with a high blood pool–to–myocardium contrast, 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. 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 echo time (TE) scans. Very high ETLs 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 (0.1-0.2 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 (3-5 mL/s) of the gadolinium chelate, usually at low dose (0.025-0.05 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 (TI) is optimized to suppress normal myocardium (typically 175-275 ms) during the washout phase (eg, 5-30 minutes) of gadolinium chelate distribution. Precise TI depends on the gadolinium chelate dose, time after administration, and individual patient pharmacokinetics, and it must be determined for each individual being scanned using a Look-Locker–like T1 scout sequence. 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) [112]. 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 [113]. MRA using gadolinium-enhanced techniques is frequently used in conjunction with other cardiac MRI methods and 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 steady-state free precession (SSFP) MRA methods may also be useful in assessing not only coronary arteries but also great vessels and cardiac anatomy [114]. For detailed sequences of the option of contrast and noncontrast MRA studies, see the ACR–NASCI–SPR Practice Parameter for the Performance of Body Magnetic Resonance Angiography (MRA) [101]

MRI tissue tagging is a technique in which RF 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 WMAs in selected cases. For example, MRI tagging lines applied perpendicular to the free wall of the RV may be useful to determine the relative motion of the pericardium compared with the myocardium in patients with suspected constrictive pericarditis.

When available, techniques including 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. Compressed sensing–based imaging sequences provide highly accelerated solutions to angiography, cine, and other cardiovascular applications and are being made available from all major MRI vendors [115].

The analysis of cardiac MRI examinations is optimally performed using a separate imaging workstation. Separate cardiac imaging software is usually required to evaluate 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 [116].

When reporting information regarding myocardial function, perfusion, viability, or infarction, the 17-segment model should be used [42]. WMAs 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

Equipment monitoring should be in accordance with the ACR–AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance (MR) Imaging Equipment [110].

Scanners for clinical cardiac MRI should be in accordance with the recommendations in the ACR–AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance (MR) Imaging Equipment [110]. 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 RF power deposition (specific absorption rate), and maximum acoustic noise levels.

MRI scanners used for cardiac MRI performance should have field strength of ≥1.0T and a slew rate of at least 70 mT/m/s. At the time of writing, cardiac MRI is most commonly performed at 1.5T; however, field strength of up to 3.0T can be used. MRI scanners should be equipped with a localized multichannel RF 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 MRI or any MRA 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 *ACR Position Statement on Quality Control & 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).

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 or with any contrast medium or pharmaceutical to be administered [111].

ACKNOWLEDGEMENTS

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

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

ACR
Vincent B. Ho, MD, MBA, Chair
Anil Kumar Attili, MBBS
Beverley Newman, MD
Phillip M. Young, MD

NASCI
Jacobo Kirsch, MD
Karen Ordovas, MD

SPR
David Biko, MD
Ramkumar Krishnamurthy, PhD
Christopher Lam, MD
Maryam Ghadimi Mahani, MD

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

Klaus Hagspiel, MD, Chair
Lucia Flors Blasco, MD, PhD
Larissa Braga Casaburi, MD, MPH, MHA
Yoo Jin Lee, BS, MS, MD
Ashley Prosper, MD
Steven S. Raman, MD
Andrew L. Rivard, MD
Phillip M. Young, MD

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

Terry L. Levin, MD, FACR, Chair
John B. Amodio, MD, FACR
Jesse Berman, MD
Tara M. Catanzano, MB, BCh
Harris L. Cohen, MD, FACR
Kassa Darge, MD, PhD
Dorothy L. Gilbertson-Dahdal, MD
Lauren P. Golding, MD
Safwan S. Halabi, MD
Jason Higgins, DO
Jane Sun Kim, MD
Jennifer A Knight, MD
Jessica Kurian, MD
Matthew P. Lungren, MD, MPH
Helen R. Nadel, MD
Erica Poletto, MD
Richard B. Towbin, MD, FACR
Andrew T. Trout, MD
Esben S. Vogelius, MD

Andrew B. Rosenkrantz, MD, Chair, Commission on Body Imaging
Richard A. Barth, MD, FACR, Chair, Commission on Pediatric Radiology
David B. Larson, MD, MBA, Chair, Commission on Quality and Safety
Mary S. Newell, MD, FACR, Chair, Committee on Practice Parameters and Technical Standards

Comment Reconciliation Committee
Derrick Siebert, MD, Chair
Kurt Schoppe, MD, Co-Chair
Anil Kumar Attili, MBBS
Richard A. Barth, MD, FACR
David Biko, MD
Richard Duszak Jr., MD, FACR
Klaus Hagspiel, MD
Vincent B. Ho, MD, MBA
Jacobo Kirsch, MD
Amy Kotsenas, MD, FACR
Ramkumar Krishnamurthy, PhD
Christopher Lam, MD
David B. Larson, MD, MBA
Paul A. Larson, MD, FACR
Terry L. Levin, MD, FACR
Maryam Ghadimi Mahani, MD
Raja Muthupillai, PhD
Mary S. Newell, MD, FACR
Beverley Newman, MD
Karen Ordovas, MD
Andrew B. Rosenkrantz, MD
Phillip M. Young, MD

REFERENCES

1. Krishnamurthy R, Cheong B, Muthupillai R. Tools for cardiovascular magnetic resonance imaging. Cardiovasc Diagn Ther 2014;4:104-25.
2. Ripley DP, Motwani M, Plein S, Greenwood JP. Established and emerging cardiovascular magnetic resonance techniques for the assessment of stable coronary heart disease and acute coronary syndromes. Quant Imaging Med Surg 2014;4:330-44.

3. Sohns JM, Schwarz A, Menke J, et al. Prevalence and clinical relevance of extracardiac findings at cardiac MRI. J Magn Reson Imaging 2014;39:68-76.
4. Karius P, Schuetz GM, Schlattmann P, Dewey M. Extracardiac findings on coronary CT angiography: a systematic review. J Cardiovasc Comput Tomogr 2014;8:174-82 e1-6.
5. Mahani MG, Morani AC, Lu JC, et al. Non-cardiovascular findings in clinical cardiovascular magnetic resonance imaging in children. Pediatric radiology 2016;46:473-82.
6. Wollmann CG, Thudt K, Kaiser B, Salomonowitz E, Mayr H, Globits S. Safe performance of magnetic resonance of the heart in patients with magnetic resonance conditional pacemaker systems: the safety issue of the ESTIMATE study. J Cardiovasc Magn Reson 2014;16:30.
7. Nazarian S, Hansford R, Roguin A, et al. A prospective evaluation of a protocol for magnetic resonance imaging of patients with implanted cardiac devices. Ann Intern Med 2011;155:415-24.
8. Indik JH, Gimbel JR, Abe H, et al. 2017 HRS expert consensus statement on magnetic resonance imaging and radiation exposure in patients with cardiovascular implantable electronic devices. Heart Rhythm 2017;14:e97-e153.
9. American College of Radiology. ACR practice parameter for performing and interpreting magnetic resonance imaging (MRI). Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/MR-Perf-Interpret.pdf. Accessed January 14, 2020.
10. American College of Radiology. ACR manual on contrast media. Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/IVCM.pdf. Accessed January 14, 2020.
11. Simonetti OP, Finn JP, White RD, Laub G, Henry DA. "Black blood" T2-weighted inversion-recovery MR imaging of the heart. Radiology 1996;199:49-57.
12. Kunz RP, Oellig F, Krummenauer F, et al. Assessment of left ventricular function by breath-hold cine MR imaging: Comparison of different steady-state free precession sequences. J Magn Reson Imaging 2005;21:140-8.
13. Cawley PJ, Maki JH, Otto CM. Cardiovascular magnetic resonance imaging for valvular heart disease: technique and validation. Circulation 2009;119:468-78.
14. Barkhausen J, Ruehm SG, Goyen M, Buck T, Laub G, Debatin JF. MR evaluation of ventricular function: true fast imaging with steady-state precession versus fast low-angle shot cine MR imaging: feasibility study. Radiology 2001;219:264-9.
15. Moon JC, Lorenz CH, Francis JM, Smith GC, Pennell DJ. Breath-hold FLASH and FISP cardiovascular MR imaging: left ventricular volume differences and reproducibility. Radiology 2002;223:789-97.
16. Kacere RD, Pereyra M, Nemeth MA, Muthupillai R, Flamm SD. Quantitative assessment of left ventricular function: steady-state free precession MR imaging with or without sensitivity encoding. Radiology 2005;235:1031-5.
17. Messroghli DR, Bainbridge GJ, Alfakih K, et al. Assessment of regional left ventricular function: accuracy and reproducibility of positioning standard short-axis sections in cardiac MR imaging. Radiology 2005;235:229-36.
18. Castillo E, Lima JA, Bluemke DA. Regional myocardial function: advances in MR imaging and analysis. Radiographics 2003;23 Spec No:S127-40.
19. Kar J, Knutsen AK, Cupps BP, Pasque MK. A validation of two-dimensional in vivo regional strain computed from displacement encoding with stimulated echoes (DENSE), in reference to tagged magnetic resonance imaging and studies in repeatability. Ann Biomed Eng 2014;42:541-54.
20. Pan L, Stuber M, Kraitchman DL, Fritzges DL, Gilson WD, Osman NF. Real-time imaging of regional myocardial function using fast-SENC. Magnetic resonance in medicine 2006;55:386-95.
21. Myerson SG. Heart valve disease: investigation by cardiovascular magnetic resonance. J Cardiovasc Magn Reson 2012;14:7.
22. Hsiao A, Tariq U, Alley MT, Lustig M, Vasanawala SS. Inlet and outlet valve flow and regurgitant volume may be directly and reliably quantified with accelerated, volumetric phase-contrast MRI. J Magn Reson Imaging 2014.
23. Schwitter J, Wacker CM, Wilke N, et al. Superior diagnostic performance of perfusion-cardiovascular magnetic resonance versus SPECT to detect coronary artery disease: The secondary endpoints of the multicenter multivendor MR-IMPACT II (Magnetic Resonance Imaging for Myocardial Perfusion Assessment in Coronary Artery Disease Trial). J Cardiovasc Magn Reson 2012;14:61.

24. Greenwood JP, Maredia N, Younger JF, et al. Cardiovascular magnetic resonance and single-photon emission computed tomography for diagnosis of coronary heart disease (CE-MARC): a prospective trial. Lancet 2012;379:453-60.
25. Kim RJ, Fieno DS, Parrish TB, et al. Relationship of MRI delayed contrast enhancement to irreversible injury, infarct age, and contractile function. Circulation 1999;100:1992-2002.
26. El Aidi H, Adams A, Moons KG, et al. Cardiac magnetic resonance imaging findings and the risk of cardiovascular events in patients with recent myocardial infarction or suspected or known coronary artery disease: a systematic review of prognostic studies. J Am Coll Cardiol 2014;63:1031-45.
27. Cummings KW, Bhalla S, Javidan-Nejad C, Bierhals AJ, Gutierrez FR, Woodard PK. A pattern-based approach to assessment of delayed enhancement in nonischemic cardiomyopathy at MR imaging. Radiographics 2009;29:89-103.
28. Ordovas KG, Higgins CB. Delayed contrast enhancement on MR images of myocardium: past, present, future. Radiology 2011;261:358-74.
29. Becker MAJ, Cornel JH, van de Ven PM, van Rossum AC, Allaart CP, Germans T. The Prognostic Value of Late Gadolinium-Enhanced Cardiac Magnetic Resonance Imaging in Nonischemic Dilated Cardiomyopathy: A Review and Meta-Analysis. JACC Cardiovasc Imaging 2018;11:1274-84.
30. Weng Z, Yao J, Chan RH, et al. Prognostic Value of LGE-CMR in HCM: A Meta-Analysis. JACC Cardiovasc Imaging 2016;9:1392-402.
31. Di Marco A, Anguera I, Schmitt M, et al. Late Gadolinium Enhancement and the Risk for Ventricular Arrhythmias or Sudden Death in Dilated Cardiomyopathy: Systematic Review and Meta-Analysis. JACC Heart Fail 2017;5:28-38.
32. Yue T, Chen BH, Wu LM, Xu JR, Pu J. Prognostic Value of Late Gadolinium Enhancement in Predicting Life-Threatening Arrhythmias in Heart Failure Patients With Implantable Cardioverter-Defibrillators: A Systematic Review and Meta-Analysis. J Magn Reson Imaging 2020;51:1422-39.
33. Yang F, Wang J, Li W, et al. The prognostic value of late gadolinium enhancement in myocarditis and clinically suspected myocarditis: systematic review and meta-analysis. Eur Radiol 2020;30:2616-26.
34. Coleman GC, Shaw PW, Balfour PC, Jr., et al. Prognostic Value of Myocardial Scarring on CMR in Patients With Cardiac Sarcoidosis. JACC Cardiovasc Imaging 2017;10:411-20.
35. Nassenstein K, Nensa F, Schlosser T, et al. Cardiac MRI: T2-Mapping Versus T2-Weighted Dark-Blood TSE Imaging for Myocardial Edema Visualization in Acute Myocardial Infarction. Rofo 2014;186:166-72.
36. Kotanidis CP, Bazmpani MA, Haidich AB, Karvounis C, Antoniades C, Karamitsos TD. Diagnostic Accuracy of Cardiovascular Magnetic Resonance in Acute Myocarditis: A Systematic Review and Meta-Analysis. JACC Cardiovasc Imaging 2018;11:1583-90.
37. Baksi AJ, Pennell DJ. T2* imaging of the heart: methods, applications, and outcomes. Top Magn Reson Imaging 2014;23:13-20.
38. Sibley CT, Noureldin RA, Gai N, et al. T1 Mapping in cardiomyopathy at cardiac MR: comparison with endomyocardial biopsy. Radiology 2012;265:724-32.
39. Hamdan A, Charalampos K, Roettgen R, et al. Magnetic resonance imaging versus computed tomography for characterization of pulmonary vein morphology before radiofrequency catheter ablation of atrial fibrillation. Am J Cardiol 2009;104:1540-6.
40. Raman FS, Nacif MS, Cater G, et al. 3.0-T whole-heart coronary magnetic resonance angiography: comparison of gadobenate dimeglumine and gadofosveset trisodium. Int J Cardiovasc Imaging 2013;29:1085-94.
41. Grothues F, Smith GC, Moon JC, et al. Comparison of interstudy reproducibility of cardiovascular magnetic resonance with two-dimensional echocardiography in normal subjects and in patients with heart failure or left ventricular hypertrophy. Am J Cardiol 2002;90:29-34.
42. Cerqueira MD, Weissman NJ, Dilsizian V, et al. Standardized myocardial segmentation and nomenclature for tomographic imaging of the heart. A statement for healthcare professionals from the Cardiac Imaging Committee of the Council on Clinical Cardiology of the American Heart Association. Circulation 2002;105:539-42.
43. Douglas PS, Hendel RC, Cummings JE, et al. ACCF/ACR/AHA/ASE/ASNC/HRS/NASCI/RSNA/SAIP/SCAI/SCCT/SCMR 2008 Health Policy Statement on Structured Reporting in Cardiovascular Imaging. J Am Coll Cardiol 2009;53:76-90.

44. Hudsmith LE, Petersen SE, Francis JM, Robson MD, Neubauer S. Normal human left and right ventricular and left atrial dimensions using steady state free precession magnetic resonance imaging. J Cardiovasc Magn Reson 2005;7:775-82.
45. Marcus FI, McKenna WJ, Sherrill D, et al. Diagnosis of arrhythmogenic right ventricular cardiomyopathy/dysplasia: proposed modification of the task force criteria. Circulation 2010;121:1533-41.
46. te Riele AS, Bhonsale A, James CA, et al. Incremental value of cardiac magnetic resonance imaging in arrhythmic risk stratification of arrhythmogenic right ventricular dysplasia/cardiomyopathy-associated desmosomal mutation carriers. J Am Coll Cardiol 2013;62:1761-9.
47. Kawut SM, Al-Naamani N, Agerstrand C, et al. Determinants of right ventricular ejection fraction in pulmonary arterial hypertension. Chest 2009;135:752-9.
48. Ley S, Mereles D, Puderbach M, et al. Value of MR phase-contrast flow measurements for functional assessment of pulmonary arterial hypertension. Eur Radiol 2007;17:1892-7.
49. Lipinski MJ, McVey CM, Berger JS, Kramer CM, Salerno M. Prognostic value of stress cardiac magnetic resonance imaging in patients with known or suspected coronary artery disease: a systematic review and meta-analysis. J Am Coll Cardiol 2013;62:826-38.
50. Lockie T, Nagel E, Redwood S, Plein S. Use of cardiovascular magnetic resonance imaging in acute coronary syndromes. Circulation 2009;119:1671-81.
51. Choi KM, Kim RJ, Gubernikoff G, Vargas JD, Parker M, Judd RM. Transmural extent of acute myocardial infarction predicts long-term improvement in contractile function. Circulation 2001;104:1101-7.
52. Friedrich MG, Sechtem U, Schulz-Menger J, et al. Cardiovascular magnetic resonance in myocarditis: A JACC White Paper. J Am Coll Cardiol 2009;53:1475-87.
53. Lim RP, Srichai MB, Lee VS. Non-ischemic causes of delayed myocardial hyperenhancement on MRI. AJR Am J Roentgenol 2007;188:1675-81.
54. Machii M, Satoh H, Shiraki K, et al. Distribution of late gadolinium enhancement in end-stage hypertrophic cardiomyopathy and dilated cardiomyopathy: differential diagnosis and prediction of cardiac outcome. Magn Reson Imaging 2014;32:118-24.
55. McCrohon JA, Moon JC, Prasad SK, et al. Differentiation of heart failure related to dilated cardiomyopathy and coronary artery disease using gadolinium-enhanced cardiovascular magnetic resonance. Circulation 2003;108:54-9.
56. Camastra GS, Cacciotti L, Marconi F, Sbarbati S, Pironi B, Ansalone G. Late enhancement detected by cardiac magnetic resonance imaging in acute myocarditis mimicking acute myocardial infarction: location patterns and lack of correlation with systolic function. J Cardiovasc Med (Hagerstown) 2007;8:1029-33.
57. Laissy JP, Hyafil F, Feldman LJ, et al. Differentiating acute myocardial infarction from myocarditis: diagnostic value of early- and delayed-perfusion cardiac MR imaging. Radiology 2005;237:75-82.
58. Crawford T, Mueller G, Sarsam S, et al. Magnetic resonance imaging for identifying patients with cardiac sarcoidosis and preserved or mildly reduced left ventricular function at risk of ventricular arrhythmias. Circ Arrhythm Electrophysiol 2014;7:1109-15.
59. Kim RJ, Wu E, Rafael A, et al. The use of contrast-enhanced magnetic resonance imaging to identify reversible myocardial dysfunction. N Engl J Med 2000;343:1445-53.
60. Ferreira VM, Schulz-Menger J, Holmvang G, et al. Cardiovascular Magnetic Resonance in Nonischemic Myocardial Inflammation: Expert Recommendations. J Am Coll Cardiol 2018;72:3158-76.
61. Bogaert J, Olivotto I. MR Imaging in Hypertrophic Cardiomyopathy: From Magnet to Bedside. Radiology 2014;273:329-48.
62. Westwood MA, Wonke B, Maceira AM, et al. Left ventricular diastolic function compared with T2* cardiovascular magnetic resonance for early detection of myocardial iron overload in thalassemia major. J Magn Reson Imaging 2005;22:229-33.
63. Maceira AM, Joshi J, Prasad SK, et al. Cardiovascular magnetic resonance in cardiac amyloidosis. Circulation 2005;111:186-93.
64. Futamatsu H, Wilke N, Klassen C, et al. Evaluation of cardiac magnetic resonance imaging parameters to detect anatomically and hemodynamically significant coronary artery disease. Am Heart J 2007;154:298-305.
65. Abbasi SA, Heydari B, Shah RV, et al. Risk stratification by regadenoson stress magnetic resonance imaging in patients with known or suspected coronary artery disease. Am J Cardiol 2014;114:1198-203.
66. Chung SY, Lee KY, Chun EJ, et al. Comparison of stress perfusion MRI and SPECT for detection of myocardial ischemia in patients with angiographically proven three-vessel coronary artery disease. AJR Am J Roentgenol 2010;195:356-62.

67. Schwitter J, Wacker CM, van Rossum AC, et al. MR-IMPACT: comparison of perfusion-cardiac magnetic resonance with single-photon emission computed tomography for the detection of coronary artery disease in a multicentre, multivendor, randomized trial. Eur Heart J 2008;29:480-9.
68. Schwitter J, Wacker CM, Wilke N, et al. MR-IMPACT II: Magnetic Resonance Imaging for Myocardial Perfusion Assessment in Coronary artery disease Trial: perfusion-cardiac magnetic resonance vs. single-photon emission computed tomography for the detection of coronary artery disease: a comparative multicentre, multivendor trial. Eur Heart J 2013;34:775-81.
69. Noel CV, Krishnamurthy R, Moffett B, Krishnamurthy R. Myocardial stress perfusion magnetic resonance: initial experience in a pediatric and young adult population using regadenoson. Pediatric radiology 2017;47:280-89.
70. Greenwood JP, Ripley DP, Berry C, et al. Effect of Care Guided by Cardiovascular Magnetic Resonance, Myocardial Perfusion Scintigraphy, or NICE Guidelines on Subsequent Unnecessary Angiography Rates: The CE-MARC 2 Randomized Clinical Trial. JAMA 2016;316:1051-60.
71. Nagel E, Greenwood JP, McCann GP, et al. Magnetic Resonance Perfusion or Fractional Flow Reserve in Coronary Disease. N Engl J Med 2019;380:2418-28.
72. Kwong RY, Ge Y, Steel K, et al. Cardiac Magnetic Resonance Stress Perfusion Imaging for Evaluation of Patients With Chest Pain. J Am Coll Cardiol 2019;74:1741-55.
73. Charoenpanichkit C, Hundley WG. The 20 year evolution of dobutamine stress cardiovascular magnetic resonance. J Cardiovasc Magn Reson 2010;12:59.
74. Pujadas S, Reddy GP, Weber O, Lee JJ, Higgins CB. MR imaging assessment of cardiac function. J Magn Reson Imaging 2004;19:789-99.
75. Potter DD, Araoz PA, McGee KP, Harmsen WS, Mandrekar JN, Sundt TM, 3rd. Low-dose dobutamine cardiac magnetic resonance imaging with myocardial strain analysis predicts myocardial recoverability after coronary artery bypass grafting. J Thorac Cardiovasc Surg 2008;135:1342-7.
76. Badger TJ, Daccarett M, Akoum NW, et al. Evaluation of left atrial lesions after initial and repeat atrial fibrillation ablation: lessons learned from delayed-enhancement MRI in repeat ablation procedures. Circ Arrhythm Electrophysiol 2010;3:249-59.
77. Srichai MB, Junor C, Rodriguez LL, et al. Clinical, imaging, and pathological characteristics of left ventricular thrombus: a comparison of contrast-enhanced magnetic resonance imaging, transthoracic echocardiography, and transesophageal echocardiography with surgical or pathological validation. Am Heart J 2006;152:75-84.
78. Pazos-Lopez P, Pozo E, Siqueira ME, et al. Value of CMR for the differential diagnosis of cardiac masses. JACC Cardiovasc Imaging 2014;7:896-905.
79. Esposito A, De Cobelli F, Ironi G, et al. CMR in assessment of cardiac masses: primary benign tumors. JACC Cardiovasc Imaging 2014;7:733-6.
80. Beroukhim RS, Prakash A, Buechel ER, et al. Characterization of cardiac tumors in children by cardiovascular magnetic resonance imaging: a multicenter experience. J Am Coll Cardiol 2011;58:1044-54.
81. Alraies MC, AlJaroudi W, Yarmohammadi H, et al. Usefulness of Cardiac Magnetic Resonance-Guided Management in Patients With Recurrent Pericarditis. Am J Cardiol 2014.
82. Axel L. Assessment of pericardial disease by magnetic resonance and computed tomography. J Magn Reson Imaging 2004;19:816-26.
83. Wang ZJ, Reddy GP, Gotway MB, Yeh BM, Hetts SW, Higgins CB. CT and MR imaging of pericardial disease. Radiographics 2003;23 Spec No:S167-80.
84. Meltser H, Kalaria VG. Cardiac tamponade. Catheter Cardiovasc Interv 2005;64:245-55.
85. Caruthers SD, Lin SJ, Brown P, et al. Practical value of cardiac magnetic resonance imaging for clinical quantification of aortic valve stenosis: comparison with echocardiography. Circulation 2003;108:2236-43.
86. Didier D, Ratib O, Lerch R, Friedli B. Detection and quantification of valvular heart disease with dynamic cardiac MR imaging. Radiographics 2000;20:1279-99; discussion 99-301.
87. Kim WY, Danias PG, Stuber M, et al. Coronary magnetic resonance angiography for the detection of coronary stenoses. N Engl J Med 2001;345:1863-9.
88. Yang Q, Li K, Liu X, et al. 3.0T whole-heart coronary magnetic resonance angiography performed with 32-channel cardiac coils: a single-center experience. Circ Cardiovasc Imaging 2012;5:573-9.
89. Piaw CS, Kiam OT, Rapaee A, et al. Use of non-invasive phase contrast magnetic resonance imaging for estimation of atrial septal defect size and morphology: a comparison with transesophageal echo. Cardiovasc Intervent Radiol 2006;29:230-4.

90. Hundley WG, Li HF, Lange RA, et al. Assessment of left-to-right intracardiac shunting by velocity-encoded, phase-difference magnetic resonance imaging. A comparison with oximetric and indicator dilution techniques. Circulation 1995;91:2955-60.
91. Grothues F, Moon JC, Bellenger NG, Smith GS, Klein HU, Pennell DJ. Interstudy reproducibility of right ventricular volumes, function, and mass with cardiovascular magnetic resonance. Am Heart J 2004;147:218-23.
92. Haggerty CM, Restrepo M, Tang E, et al. Fontan hemodynamics from 100 patient-specific cardiac magnetic resonance studies: a computational fluid dynamics analysis. J Thorac Cardiovasc Surg 2014;148:1481-9.
93. Lu JC, Dorfman AL, Attili AK, Ghadimi Mahani M, Dillman JR, Agarwal PP. Evaluation with cardiovascular MR imaging of baffles and conduits used in palliation or repair of congenital heart disease. Radiographics 2012;32:E107-27.
94. Lewis MJ, O'Connor DS, Rozenshtien A, et al. Usefulness of magnetic resonance imaging to guide referral for pulmonary valve replacement in repaired tetralogy of Fallot. Am J Cardiol 2014;114:1406-11.
95. Oosterhof T, van Straten A, Vliegen HW, et al. Preoperative thresholds for pulmonary valve replacement in patients with corrected tetralogy of Fallot using cardiovascular magnetic resonance. Circulation 2007;116:545-51.
96. Brown DW, Gauvreau K, Powell AJ, et al. Cardiac magnetic resonance versus routine cardiac catheterization before bidirectional glenn anastomosis in infants with functional single ventricle: a prospective randomized trial. Circulation 2007;116:2718-25.
97. Fogel MA, Pawlowski TW, Whitehead KK, et al. Cardiac magnetic resonance and the need for routine cardiac catheterization in single ventricle patients prior to Fontan: a comparison of 3 groups: pre-Fontan CMR versus cath evaluation. J Am Coll Cardiol 2012;60:1094-102.
98. Devos DG, Kilner PJ. Calculations of cardiovascular shunts and regurgitation using magnetic resonance ventricular volume and aortic and pulmonary flow measurements. Eur Radiol 2010;20:410-21.
99. Bunce NH, Lorenz CH, Keegan J, et al. Coronary artery anomalies: assessment with free-breathing three-dimensional coronary MR angiography. Radiology 2003;227:201-8.
100. Mavrogeni S, Papadopoulos G, Hussain T, Chiribiri A, Botnar R, Greil GF. The emerging role of cardiovascular magnetic resonance in the evaluation of Kawasaki disease. Int J Cardiovasc Imaging 2013;29:1787-98.
101. American College of Radiology. ACR–NASCI–SPR practice parameter for the performance of body magnetic resonance angiography (MRA). Available at:: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/Body-MRA.pdf. Accessed January 14, 2020.
102. American College of Radiology. ACR practice parameter for continuing medical education (CME). Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/CME.pdf. Accessed January 14, 2020.
103. American Registry of Radiologic Technologists. Continuing Education Requirements for Renewal of Registration. https://www.arrt.org/. Accessed January 5, 2015.
104. Kanal E, Barkovich AJ, Bell C, et al. ACR guidance document on MR safe practices: 2013. J Magn Reson Imaging 2013;37:501-30.
105. Cohen JD, Costa HS, Russo RJ. Determining the risks of magnetic resonance imaging at 1.5 tesla for patients with pacemakers and implantable cardioverter defibrillators. Am J Cardiol 2012;110:1631-6.
106. American College of Radiology. ACR–SPR practice parameter for the use of intravascular contrast media. Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/IVCM.pdf. Accessed January 14, 2020.
107. Cutter TW. Radiologists and anesthesiologists. Anesthesiol Clin 2009;27:95-106.
108. American College of Radiology. ACR–SIR practice parameter for sedation/analgesia. Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/Sed-Analgesia.pdf. Accessed January 14, 2020.
109. Shariat M, Mertens L, Seed M, et al. Utility of feed-and-sleep cardiovascular magnetic resonance in young infants with complex cardiovascular disease. Pediatr Cardiol 2015;36:809-12.
110. American College of Radiology. ACR-AAPM technical standard for diagnostic medical physics performance monitoring of magnetic resonance imaging (MRI) equipment. Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/MR-Equip.pdf. Accessed January 14, 2020.
111. Sawyer-Glover AM, Shellock FG. Pre-MRI procedure screening: recommendations and safety considerations for biomedical implants and devices. J Magn Reson Imaging 2000;12:510.
112. Kellman P, Arai AE, McVeigh ER, Aletras AH. Phase-sensitive inversion recovery for detecting myocardial infarction using gadolinium-delayed hyperenhancement. Magnetic resonance in medicine 2002;47:372-83.

113. Schubert T, Bieri O, Pansini M, Stippich C, Santini F. Peak velocity measurements in tortuous arteries with phase contrast magnetic resonance imaging: the effect of multidirectional velocity encoding. Invest Radiol 2014;49:189-94.
114. Pasqua AD, Barcudi S, Leonardi B, Clemente D, Colajacomo M, Sanders SP. Comparison of contrast and noncontrast magnetic resonance angiography for quantitative analysis of thoracic arteries in young patients with congenital heart defects. Ann Pediatr Cardiol 2011;4:36-40.
115. Axel L, Otazo R. Accelerated MRI for the assessment of cardiac function. The British journal of radiology 2016;89:20150655.
116. American College of Radiology. ACR practice parameter for communication of diagnostic imaging findings. Available at: https://www.acr.org/-/media/ACR/Files/Practice-Parameters/CommunicationDiag.pdf. Accessed January 14, 2020.

---

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

Development Chronology of This Practice Parameter
2006 (Resolution 9, 16g, 34, 35, 36)
Revised 2011 (Resolution 25)
Amended 2014 (Resolution 39)
Revised 2016 (Resolution 5)
Amended 2020 (Resolution 8)
Revised 2021 (Resolution 42)
Amended 2022 (Resolution 41f)