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Revised 2011 (Resolution 25)*

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

PREAMBLE

These guidelines are an educational tool designed to assist practitioners in providing appropriate radiation oncology care for patients. They are not inflexible rules or requirements of practice and are not intended, nor should they be used, to establish a legal standard of care. For these reasons and those set forth below, the American College of Radiology cautions against the use of these guidelines 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 physician or medical physicist in light of all the circumstances presented. Thus, an approach that differs from the guidelines, 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 the guidelines 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 the guidelines. However, a practitioner who employs an approach substantially different from these guidelines 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 these guidelines 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 these guidelines is to assist practitioners in achieving this objective.

I. INTRODUCTION

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

A. Cardiac magnetic resonance imaging (MRI) is an established imaging modality, well recognized for its value in the initial assessment and monitoring of a wide range of diseases of the heart and surrounding related structures (e.g., 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, now can image the coronary arteries, cardiac chambers, valves, myocardium, and pericardium and can assess cardiac function. Thus, CT and MRI have played an increasing role in comprehensive cardiac imaging. This document deals specifically with cardiac MRI applications.

While the technical parameters and field of view of a cardiac MRI examination will appropriately be tailored to evaluate the cardiac anatomy and/or function in question, the images obtained will demonstrate 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. These studies may demonstrate clinically significant noncardiac findings [3-4]. In addition to examining the cardiac structures of interest, the interpreting physician is responsible for examining all the visualized noncardiac structures and must report any clinically relevant abnormalities of these adjacent structures. In some cases, these structures may be seen only on localizing (scout) images.

Cardiac MRI also presents potential patient safety issues. These issues pertain primarily to the strong magnetic field and its potential impact on implanted devices, but also to MRI contrast agents and patient sedation. While uncommon, contrast agents can cause allergic reactions or can place patients at risk for nephrogenic systemic fibrosis (NSF) when administered in certain patient populations. It is estimated that nearly half of all MR studies performed are contrast-enhanced. This concern has led to recent practice shifts incorporating a number of precautions recommended by the FDA and ACR [5-7].

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

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

1. High natural contrast exists between the intracardiac/intravascular blood pool and the surrounding cardiac and vascular structures due to inherent tissue characteristics. For example, cardiac anatomy and pericardial and mediastinal abnormalities can be depicted with “dark blood” spin-echo imaging. “Bright-blood” gradient echo sequences can be used to demonstrate flow and motion and to image valvular disease [8-9]. Consequently, contrast agents are not routinely required for discrimination of the blood pool, although contrast administration has become a key component in state-of-the-art time-resolved

MR tissue perfusion and delay-enhanced viability techniques. The excellent soft tissue differentiation capabilities of MRI also permit delineation of cardiac structures (e.g., ventricular myocardium) and paracardiac structures related to the heart and great vessels (e.g., pericardium and mediastinum).

2. MRI is a three-dimensional and/or multiplanar imaging modality that provides the capability for precise and reproducible (intraobserver, interobserver, and/or inter-examination) quantification of cardiac parameters, such as chamber and stroke volumes, cardiac output or wall mass [10-11]. When either sequential tomographic images or true-volume sets entirely encompassing the heart in the same cardiac phase are acquired, the resulting three-dimensional data series permits direct measurement of cardiac volumes or mass without the use of any assumed formulas or geometric models.
3. Cine MRI techniques can be used to assess routine measures of cardiac function such as global and regional ventricular systolic function (e.g., ejection fraction), ventricular diastolic function (e.g., filling rates), shunt quantification (e.g., interventricular defect shunt volume), and valve regurgitation quantification (e.g., mitral regurgitant fraction) [12-13]. These measurements depend on cavity volume changes over the cardiac cycle or differences in stroke volume between the two ventricles. Cine MRI techniques with high temporal resolution of the cardiac cycle (preferably less than or equal to 50 msec), including standard cine and tagged (e.g., spatial modulation of magnetization [SPAMM]) gradient echo imaging, allow the assessment of regional ventricular function (e.g., systolic wall thickening or systolic circumferential strain) [14-15]. These studies can be performed at rest or during the intravenous administration of a pharmacologic stress agent such as dobutamine.
4. Velocity-encoded techniques permit measurement of blood flow from the standpoint of flow velocity or flow volume [16-17]. Practical uses include: stroke volume determination, valvular regurgitation quantification (e.g., diastolic retrograde flow volume/systolic antegrade flow volume in ascending aorta for determining aortic regurgitant fraction), assessment of stenoses (e.g., measurement of peak systolic velocity beyond the stenotic aortic valve for transvalvular pressure gradient determination by modified Bernoulli equation, or by velocity-time integral

(VTI) methods) [16], and shunt calculation (e.g., ascending aortic flow volume/pulmonary artery flow volume to determine Qp/Qs).

5. First pass perfusion, utilizing near-real-time or real-time monitoring of the appearance of a rapidly administered MRI contrast agent (e.g., gadolinium chelate), can be used to evaluate the adequacy of delivery of blood (i.e., perfusion) to the myocardial tissue based on patterns of tissue enhancement; time-intensity curves may be analyzed to quantify the degree of underperfusion in ischemic or infarcted myocardium (fixed perfusion defect) [18-19]. This procedure can be performed both at rest and during intravenous administration of a pharmacologic stress agent such as adenosine or regadenoson.
6. Delayed contrast-enhanced viability MRI methods can be used to evaluate the steady-state distribution of the contrast medium, most importantly to detect the presence of necrotic myocardium or scar [20]. This method can be used alone or with cine imaging to assess the extent of myocardial infarction (transmural vs. subendocardial) to predict wall motion recovery after revascularization, or in combination with first pass stress perfusion to assess ischemic vs. nonviable myocardial tissue. The delayed contrast-enhanced technique has also been shown to be useful in differentiating between ischemic and nonischemic cardiomyopathies, and in assessing myocarditis and myocardial infiltrative processes [21].
7. Multiple noncontrast and contrast-medium-based MRI techniques are available to characterize cardiovascular abnormalities [22-25].
8. Angiographic techniques (i.e., MRA) are often discussed separately; nonetheless, they are essential to many comprehensive cardiovascular MRI examinations, especially those of the coronary arteries and great vessels. Most recently MRA methods coupled with cardiac MRI have been used to assess pulmonary venous anatomy before and after radiofrequency (rf) ablation treatment of atrial fibrillation [26]. MRA methods as they pertain to assessment of the coronary arteries and pulmonary veins are discussed later in this document.

C. Cardiovascular MRI should be performed only for a valid medical reason. While it is not possible to always detect all abnormalities by using cardiovascular MRI,

adherence to the following guidelines will enhance the probability and accuracy of their detection.

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

II. QUALIFICATIONS AND RESPONSIBILITIES OF PERSONNEL

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

A. Physician

The physician should have the responsibility for all aspects of the study, including, but not limited to, reviewing all indications for the examination, specifying the pulse sequences to be performed, specifying the imaging planes, specifying the use and dosage of contrast media, interpreting images, generating an official interpretation,¹ and assuring the quality of the images and the interpretation.

1. Physician with prior qualifications in general MRI

The radiologist or other physician who meets the qualifications of the [ACR Practice Guideline for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) 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

¹The 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.

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 one of the following requirements:

- a. Training in cardiac MRI in a training program approved by the Accreditation Council for Graduate Medical Education (ACGME), the Royal College of Physicians and Surgeons of Canada (RCPSC), the Collège des Médecins du Québec, or the American Osteopathic Association (AOA) to include:
 - i. Education in cardiac anatomy, physiology, pathology, and cardiac MRI for a time equivalent to at least 30 hours of CME.
and
 - ii. The interpretation, reporting, and/or supervised review of at least 50 cardiac MRI examinations in the last 36 months.
or
 - a. Completion of at least 30 hours of Category I CME in cardiac imaging, including:
 - i. Cardiac MRI, anatomy, physiology, and/or pathology, or documented equivalent supervised experience in a center actively performing cardiac MRI.
and
 - ii. The interpretation, reporting, and/or supervised review of at least 50 cardiac MRI examinations in the last 36 months.
2. Physician without prior qualifications in general MRI

The radiologist or other physician who does not meet the qualifications of the [ACR Practice Guideline for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) for all anatomic areas requires more extensive training and experience in MRI, with an emphasis on cardiac MRI. In addition to specific instruction in imaging interpretation, this training must include the physics of MRI, MRI safety, the principles of MRI acquisition and postprocessing, including use of diagnostic workstations, and the design of MRI protocols, including pulse sequences and the rate and timing of contrast administration. Some

physicians will also require additional education in cardiac anatomy, physiology, and pathology.

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

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

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

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

4. Maintenance of competence

All physicians performing cardiac MRI examinations should demonstrate evidence of continuing competence in the interpretation and reporting of those examinations. If competence is assured primarily on the basis of continuing experience, performance and interpretation of a minimum of 75 examinations every 3 years is recommended in order to maintain the physician's skills.

5. Continuing medical education

The physician's continuing medical education should be in accordance with the [ACR Practice Guideline for Continuing Medical Education \(CME\)](#) of 150 hours of approved education every 3 years, and should include CME in cardiac MRI

as is appropriate to the physician's practice needs.

6. Additional training recommendations

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

B. Medical Physicist/MR Scientist

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

A *Qualified Medical Physicist* is an individual who is competent to practice independently one or more subfields in medical physics. The ACR considers certification and continuing education and experience in the appropriate subfield(s) to demonstrate that an individual is competent to practice in one or more subfields in medical physics, and to be a Qualified Medical Physicist. The ACR recommends that the individual be certified in the appropriate subfield(s) by the American Board of Radiology (ABR), the Canadian College of Physics in Medicine, or for MRI, by the American Board of Medical Physics (ABMP) in magnetic resonance imaging physics.

The appropriate subfields of medical physics for this guideline are Diagnostic Radiological Physics and Radiological Physics. (ACR Resolution 17, 1996 – revised in 2008, Resolution 7)

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

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

A Qualified Medical Physicist/MR Scientist should meet the [ACR Practice Guideline for Continuing Medical Education \(CME\)](#). (ACR Resolution 17, 1996 – revised in 2008, Resolution 7)

The Qualified Medical Physicist/MR Scientist must be familiar with the principles of MRI safety for patients,

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

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

C. Registered Radiologist Assistant

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

The radiologist assistant performing cardiac MRI should have advanced certification in MRI and should have supervised experience in performing cardiac MRI examinations. The radiologist assistant's continuing education credits should include continuing education in cardiac CT performance as is appropriate to his or her

practice needs. Basic life support (BLS) and automatic defibrillator (AED) training is recommended.

D. Radiologic Technologist

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

The technologist performing cardiac MRI should be certified by the American Registry of Radiologic Technologists (ARRT) or the Canadian Association of Medical Radiation Technologists (CAMRT). It is recommended that the technologist performing cardiac MRI have advanced certification in MR. Each technologist should have supervised experience in performing cardiac MRI examinations and in the intravenous administration of conventional MR contrast media. If intravenous contrast material is to be administered, the qualifications for technologists performing intravenous injections should be in compliance with current ACR policy² and with existing operating procedures or manuals at the imaging facility. The technologist's continuing education credits should include continuing education in cardiac MRI as is appropriate to his or her practice needs. Basic life support (BLS) and automatic defibrillator (AED) training is recommended.

Any technologist practicing MRI scanning should be licensed in the jurisdiction in which he or she practices, if state licensure exists. To assure competence, all technologists must be evaluated by the supervising physician [27].

III. INDICATIONS

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

A. Acquired Heart Disease

1. Dynamic cardiac anatomy and ventricular function

Generally speaking, echocardiography is a reasonable first test for left ventricular (LV) function, although MRI, because of its three-dimensional data acquisition, is considered to be more accurate and reproducible [28]. 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 [29] and the following terms: normal, hyperkinetic, hypokinetic, akinetic, or dyskinetic. LV quantitative function should be performed using short axis views from base to apex. In addition, to provide complete qualitative analysis, LV vertical long axis (two chamber), horizontal long axis (four chamber), and left ventricular outflow tract (three chamber) views should be performed.

Parameters recommended to be routinely reported in a functional MRI examination may include [30-31]: LV end-diastolic volume (LVEDV) and LVEDV index (LVEDV divided by body surface area), LV stroke volume, LV ejection fraction (LVEF), LV mass index, and LV end diastolic and end systolic diameter. Routine uses of Simpson's rule (summation of end systolic and end diastolic areas for calculating LVEF and LVEDV, respectively) to then calculate LVEF is recommended. Diastolic dysfunction may also be assessed using flow quantification methods in order to assess E/A ratios (early [E] and late, or atrial [A] phases of LV filling). Specific indications for assessment of regional or global LV function include indeterminate or discrepant echocardiography results or situations where serial assessment of change in LV function is important (e.g., following patients after myocardial infarction, drug trials or following response to medication, valvular regurgitation or intracardiac shunts).

Right ventricular (RV) size as well as global and regional wall motion may be assessed qualitatively and reported. MRI is the recommended first-line diagnostic test for assessing RV function (RVEF, RVEDV, and RVEDVI) by applying Simpson's rule to short axis slices. The most common indication for RV assessment is to evaluate patients for suspected arrhythmogenic RV cardiomyopathy or dysplasia (ARVC or ARVD), where global and regional RV WMAs constitute diagnostic criteria for disease [32]. Right ventricular size and function assessment, along with pulmonary MRA, is useful in evaluating and following patients with pulmonary arterial hypertension [33-34].

2. Assessment of cardiomyopathies, myocardial fibrosis, and infarction

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

²See the [ACR Practice Guideline for the Use of Intravascular Contrast Media](#).

atypical hypertrophic cardiomyopathy, such as apical hypertrophy, may be better assessed with MRI than echocardiography [35]. MRI is considered the gold standard in the assessment of myocardial mass because it is more accurate and reproducible than echocardiography [28]. In hemochromatosis, MRI may be used for qualitative assessment of myocardial iron overload or quantitative assessment using calculated T2* values of the interventricular septum [36]. It can also be used to assess fatty infiltration of the heart in suspected ARVC. However, the optimal scanning approach as well as the sensitivity and specificity of MRI for detecting intramural fat in this condition have not been established. Besides detecting iron and fat, MRI rarely provides tissue-specific information relevant to infiltrative diseases of the heart, but it may provide a comprehensive pattern of wall thickness and wall motion of all four cardiac chambers. Some patterns, such as concentrically increased LV mass, decreased LVEDV, decreased LVEF, biatrial enlargement, and pleural/pericardial effusions may suggest a specific diagnosis [37].

Myocardial delayed hyper enhancement (MDH) is a specific feature of cardiac MRI that may be extremely useful in detecting areas of myocardial damage and fibrosis [38]. Although MDH can be seen with CT, the contrast-to-noise ratio of enhancing foci is much higher with MRI due to the ability to suppress normally enhancing myocardium using inversion preparation. A subendocardial or transmural pattern of enhancement distinguishes ischemic scar from other causes of enhancement such as myocarditis [39] and scarring in nonischemic cardiomyopathy [40-41]. Cardiac MRI with evaluation of global/regional function and MDH is indicated in the evaluation of dilated cardiomyopathy to make the diagnosis of ischemia very unlikely as the cause and can obviate the need for cardiac catheterization in many patients [42]. MDH may also be helpful in the diagnosis of chronic or acute myocarditis [43-44] and infiltrative disease processes such as cardiac sarcoid [45]. In chronic ischemic cardiomyopathy, the evaluation of regional wall thickness, regional WMAs, and delayed hyperenhancement may be used to evaluate the likelihood of functional recovery after percutaneous or surgical revascularization [46]. MDH can also assist in surgical planning for ischemic aneurysms of the heart and be used to identify ventricular thrombus in association with ischemic scar.

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 [47-48]. 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. MRI is capable of quantifying perfusion and perfusion reserve, but the tools to do this are not yet widely available [49]. The combination of resting perfusion and MDH imaging may provide adjunctive information in chronic ischemia to differentiate among normal, ischemic but viable (hibernating), and nonviable myocardium. MRI may also be performed in conjunction with vasodilator stress agents such as adenosine 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 [50-51]. The relative merits of perfusion MRI compared with single photon emission computed tomography (SPECT) or positron emission tomography (PET) in clinical practice have not been definitely established.

High dose dobutamine stress MRI may also be performed to detect ischemia as inducible wall motion abnormalities [52]. High dose dobutamine should be administered at a maximum of four stress levels if starting at a dose of 10 µg/kg/min, and at a maximum of five stress levels if starting at a dose of 5 µg/kg/min at 3 to 5 minutes per level. Dosing should not be above 40 µg/kg/min. No more than 1 mg of atropine at the highest dobutamine dose should be administered to achieve a submaximal target heart rate [51]. 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 while scanning is going on is highly recommended for safe practice. Images should be rigorously monitored by a physician and assessed for induced wall motion abnormality at each increment of dobutamine as the images are acquired. The physician should observe regional wall motion in the long and short axis at each stress level, and the examination should be stopped if new

regional WMAs are seen. The physician should be prepared to treat any induced ischemia or arrhythmia with medications, including beta blockers and nitrates. An external cardiodefibrillator should also be readily available. Perfusion MRI with gadolinium can be performed at peak dobutamine stress and may provide additional diagnostic information [53].

Lower dose dobutamine (at levels of 5 and then 10 $\mu\text{g}/\text{kg}/\text{min}$) can be administered to determine myocardial viability through qualitative and quantitative assessment of myocardial thickening and improvement in wall motion [54].

When stress agents are administered to patients, they should be hemodynamically monitored (blood pressure, heart rate, SaO₂, and rhythm assessment) throughout the MR examination. A 12-lead EKG should be obtained before and after the examination and compared for differences suggestive of induced ischemia or infarction. As with vasodilatory agents, all precautions and contraindications specific to dobutamine administration as described in the vendor's package insert and in the literature should be observed [51].

4. Acute coronary syndrome

Functional MRI, MDH, and resting perfusion MRI may be used to diagnose segments with regional ischemia and acute myocardial infarction in acute coronary syndromes (ACS). Serial ECG and enzyme assessment remain the diagnostic standard for ACS, but cardiac MRI may permit more rapid diagnosis and may be helpful in cases where clinical examination, ECG, and enzymes are indeterminate [55]. In the absence of chest pain or myocardial infarction, stress perfusion MRI may be necessary to detect or exclude the presence of obstructive coronary disease.

5. Characterization of cardiac masses

Most cardiac masses are initially identified on echocardiography. MRI is indicated to evaluate tumors with regard to specific tissue characterization (fat-containing, cystic, fibrotic, etc.) [56], origin, relationship to chambers and valves, and myocardial-extracardiac extension. MRI features such as susceptibility effects, enhancement pattern, and extension from central venous thrombosis can be helpful in differentiating thrombus from tumor [57]. MRI is the optimal imaging method for evaluating paracardiac masses, as it allows evaluation of mediastinal, pericardial, and myocardial involvement in a single study [58-59].

6. 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. MRI tissue characterization can also help determine the etiology of effusions (e.g., transudative, exudative, hemorrhagic, or neoplastic) [60-61]. Tamponade and constrictive pericarditis can be detected by evaluating anatomic and functional characteristics. A major characteristic of tamponade is diastolic collapse of the right ventricular outflow tract. Characteristics of constrictive pericarditis include conical deformation of the ventricles, atrial and caval dilatation, and abnormal motion of the interventricular septum [62]. Assessment of effusions can also be coupled with delayed contrast-enhanced assessment of the myocardium to assess for myocarditis.

7. 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 [16]. In addition, direct planimetry of the aortic valve on high resolution cine images can be obtained. Aortic and mitral valvular regurgitation fractions may be measured quantitatively by calculations based on aortic root phase contrast flow assessment and LV stroke volume. Pulmonic valvular regurgitation fractions may be measured quantitatively by calculations based on pulmonary outflow tract flow assessment. Anatomic and blood flow characteristics can determine the type and degree of valve abnormality, and the subsequent functional impact on adjacent cardiac chambers [63].

8. Coronary artery disease

Although MRI can depict acquired proximal disease of the coronary arteries [64], the clinical application is limited at this time. Some contrast-enhanced and whole heart coronary MR angiography methods suggest increased sensitivity for flow-limiting stenoses using these techniques [65], and stenotic disease and aneurysms can be detected. Such findings could be of clinical importance in patients who cannot receive iodinated contrast media even if premedicated for allergy. However, coronary MR angiography is not indicated in the routine evaluation of coronary artery disease.

Characterization of atherosclerotic plaque and determination of coronary blood flow are research applications that may become clinically valuable. Cardiac MRI can be used to evaluate the patency of and, indirectly, the presence of stenoses of coronary artery bypass grafts [66].

9. 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 [26]. These data may be provided electronically to the referring clinician who may use it in conjunction with electrophysiology (EP) mapping systems to couple EP information with the MR-depicted anatomy. Pulmonary vein assessment may also be performed to assess pulmonary vein stenoses, a complication of rf ablation therapy. PV anatomy depicted by MRA may be coupled with 3D volumetric delayed-enhanced contrast methods post rf ablation in order to visualize the location of ablation scar [56].

B. Congenital Heart Disease

1. Congenital shunts

Specific forms of atrial or ventricular septal defects (VSD) that are difficult to identify or characterize on echo may benefit from MRI assessment. Specific examples include sinus venous defects and apical muscular VSD. MRI may also identify ASD or partial anomalous pulmonary venous connection in adults with right-sided chamber enlargement, hypertrophy, or dysfunction of unknown etiology. MRI is useful for ASD sizing prior to percutaneous device closure [67]. In all forms of congenital shunts, quantification of shunt size (pulmonary to systemic flow ratio, otherwise known as the Qp:Qs ratio) by MR flow velocity mapping compares favorably to other imaging techniques, and enables decision making regarding conservative therapy versus surgery [68].

2. Complex congenital anomalies

MRI is the most accurate technique for quantifying ventricular mass and volumes, and should be considered the reference standard for evaluating RV size and function in the setting of congenital heart disease [69]. MRI parameters (RV end diastolic volume, RV end systolic volume, and biventricular ejection fraction) and EKG parameters (QRS duration on the resting EKG >180 msec) are the best predictors of adverse clinical outcome in patients with treated tetralogy of Fallot (TOF). 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 [70].

MRI also depicts ventricular and vascular anatomy in complex cases of TOF, pulmonary atresia, tricuspid atresia, and univentricular hearts [71]. MRI has been used to help surgical decision making regarding univentricular repair, one and a half ventricle repair, or biventricular repair in patients who have two functioning ventricles, but also have factors preventing biventricular repair like straddling atrioventricular (AV) valves, unfavorable location of the VSD or suboptimal ventricular morphology or function. MRI can replace cardiac catheterization for routine evaluation of cardiovascular morphology and function prior to superior cavopulmonary connection in the majority of patients undergoing single-ventricle repair [72].

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 [60].

4. Congenital valve disease

Cardiac MRI has the capability to evaluate for congenital cardiac valve morphology and for stenosis and/or insufficiency (e.g., bicuspid aortic valve, cleft mitral valve, Ebstein's 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 [63].

5. Coronary artery anomalies

MRI can detect anomalous origins of the coronary arteries. Significant anomalies such as abnormal positioning of a coronary artery between the aorta and right ventricular outflow tract can be determined [73]. Extracardiac anomalous coronary artery origin (e.g., 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's disease or Takayasu's arteritis [74-76].

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 guidelines for MRA. For further information, see the [ACR–NASCI–SPR Practice Guideline for the Performance of Pediatric and Adult Body Magnetic Resonance Angiography \(MRA\)](#).

IV. SAFETY GUIDELINES AND POSSIBLE CONTRAINDICATIONS

In all cases, a risk/benefit analysis for each patient should be performed prior to MRI scanning. The cardiac MRI physician should have thorough knowledge of patient safety, including proper patient and/or accompanying person screening, specific absorption rate (SAR) limits, possible neurological effects, tissue heat deposition, risks and benefits of contrast media administration, and contraindications for performance of MRI such as certain implantable devices [77-78]. Prior to MRI, patients screening should include determination of implantable devices, and operators should determine whether the devices are “MR safe,” “MR conditional,” or “not MR safe.” While the performance of MRI in patients with pacemakers or implantable cardioverter defibrillators (ICDs) has been reported, this practice should not be routine, and each case should be reviewed for risk/benefit. If MRI is to be performed, it is recommended that proper personnel be present during the examination. They should include a physician who is familiar with the patient’s arrhythmia history and implanted device and who is capable of programming or adjusting the implanted device should emergent reprogramming be required.

In regard to the administration of intravenous (IV) contrast media, the physician should supervise patient selection to identify those patients for whom IV contrast media administration may present an increased risk or be contraindicated. Although reactions occur less frequently with gadolinium-based contrast media in comparison to iodinated media, some patients may require pretreatment to allow safe contrast administration. In patients with 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 [77]. The physician should also be available to treat adverse reactions to IV contrast media as described in the [ACR Practice Guideline for the Use of Intravascular Contrast Media](#) and the [ACR Manual on Contrast Media](#) [79-80].

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 addition, the reader should see the [ACR Practice Guideline for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) and the ACR Guidance Document on MR Safety.

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

V. SPECIFICATIONS OF THE EXAMINATION

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

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

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

The supervising physician must have complete understanding of the indications, risks, and benefits of the examination, as well as alternative imaging procedures. The physician must be familiar with potential hazards associated with MRI, including potential adverse reactions to contrast media. The physician should be familiar with the findings of relevant ancillary studies that the patient may have undergone. The physician performing MRI interpretation must have a clear understanding and knowledge of the anatomy and pathophysiology relevant to the MRI examination.

The supervising physician must also understand the pulse sequences to be used and their effect on the appearance of the images, including the potential generation of image artifacts. Standard imaging protocols may be established and varied on a case-by-case basis when necessary. These protocols should be reviewed and updated periodically.

A. Patient Selection

The physician responsible for the examination should supervise patient selection and preparation and be available in person or by phone for consultation. Patients should be screened and interviewed prior to the examination to exclude individuals who may be at risk by exposure to the MR environment. (See the [ACR–NASCI–SPR Practice Guideline for the Performance of Pediatric and Adult Body Magnetic Resonance Angiography](#) [18].)

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 Practice Guideline for the Use of Intravascular Contrast Media](#).)

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

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 [81-82]

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

MRI techniques must be optimized for the wide range of indications for cardiac imaging and may be highly variable due to advances in MRI scanner software and hardware. However, most examinations will include short axis and long axis cine images of the heart obtained for

ventricular function. For left ventricular function, images in the true short axis plane of the heart should be obtained from just above the mitral valve plane to the apex of the heart at approximately 1 cm intervals. Depending on the pulse sequence used, this could be accomplished, for example, using 8 mm thick slices and 2 mm thick gaps between the slices for a two-dimensional acquisition. In addition, horizontal and long axis cine views of the left ventricle are routinely acquired. Left ventricular outflow tract views may also be routinely obtained, particularly for patients referred for hypertrophic cardiomyopathy. On most MRI systems, cine image acquisition should be gated to the R wave of the electrocardiogram and will involve suspended respiration, typically at resting lung volume during the acquisition. Acquired temporal resolution, preferably should be ≤ 50 msec; interpolation methods (e.g., view sharing) are desirable to display reconstructed cine images at less than the acquired temporal resolution.

Steady state free precession gradient echo imaging has been demonstrated to result in faster high quality cine images of the heart and is now preferred if this sequence is available. 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. Significant differences between steady state free precession and fast gradient echo cine images have been noted for determination of left ventricular mass, volume, and ejection fraction. Thus, “normal” values for left ventricular structure and function must be reported with respect to the imaging technique that was used.

For cardiac indications that require assessment of cardiac morphology, T1-weighted and/or T2-weighted images of the heart may be helpful. Since these images are gated to the cardiac cycle, T1-weighted images typically have intermediate, or proton density, weighting. 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 image. Echo train lengths (ETLs) with this sequence are usually <40 ; even shorter ETLs (<10) may be required for short effective-TE scans. Very high echo train lengths associated with single shot techniques (e.g., “HASTE” or single shot fast spin echo) results in excessive blurring of intracardiac detail and, if possible, should be avoided as the sole means of tissue characterization.

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

limited to evaluation of masses/cysts, pericardium, myocardial perfusion, inflammation, or infarction. Myocardial perfusion evaluation additionally requires rapid bolus administration (3 to 5 ml/sec) of the gadolinium chelate usually at low dose (0.025 to 0.05 mmol/kg). Postgadolinium images of the heart are T1-weighted images acquired using fast/turbo spin echo, double inversion recovery fast/turbo spin echo or gradient echo techniques. Evaluation of myocardial infarction/scar or fibrosis is optimally performed using an inversion prepared gradient echo technique. In this method, the inversion time is optimized to suppress normal myocardium (TI typically 175 to 275 msec) during the washout phase (e.g., 5 to 30 minutes) of gadolinium chelate distribution. Precise TI depends on the gadolinium chelate dose time after administration and individual patient pharmacokinetics and must be determined for each individual being scanned. Inversion recovery prepared steady state free precession techniques offer an additional approach to myocardial delayed enhancement imaging.

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 linear flow rate of blood. Phase contrast images are acquired either parallel or perpendicular to the direction of flow, depending on the indication. MRA using gadolinium-enhanced techniques is frequently used in conjunction with other cardiac MRI methods. It may provide additional useful information regarding the status of the aorta, pulmonary artery, pulmonary veins, coronary arteries, and vena cava.

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

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

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

VI. DOCUMENTATION

Reporting should be in accordance with the [ACR Practice Guideline for Communication of Diagnostic Imaging Findings](#). When reporting information regarding myocardial function, perfusion, viability, or infarction the 17-segment model should be used [29]. Wall motion abnormalities should be described using conventional terminology such as hyperkinetic, hypokinetic, akinetic, or dyskinetic. Images should be labeled with the patient identification, facility identification, examination date, and the side (right or left) of the anatomic site imaged.

VII. EQUIPMENT SPECIFICATIONS

Scanners for clinical cardiac MRI should be accredited by the ACR, and equipment performance monitoring should be in accordance with the [ACR Technical Standard for Diagnostic Medical Physics Performance Monitoring of MRI Equipment](#) [83]. The MRI equipment specifications and performance should meet all state and federal requirements. The requirements include, but are not limited to, specifications of maximum static magnetic strength, maximum rate of change of the magnetic field strength (dB/dt), maximum radiofrequency power deposition (specific absorption rate), and maximum acoustic noise levels.

MRI scanners used for cardiac MRI performance should have field strength of ≥ 1.0 Tesla and have a slew rate of at least 70 mT/meter/sec. At the time of writing, cardiac MRI is most commonly performed at 1.5 Tesla. Field strength of up to 3.0 tesla can be used for clinical examinations, but safety issues remain a challenge. MRI scanners should be equipped with a localized multi-channel radiofrequency surface coil and ECG gating. Ideally, ECG gating capabilities would include prospective triggering, retrospective gating, and triggered retrogating. Vectorcardiographic gating is the standard of care for cardiac MRI. An MRI-compatible power injector is required for performing myocardial perfusion MR imaging or any MR angiographic methods. A power-injector is not required for delayed contrast-enhanced studies. The MRI scanner should be capable of fast 3D gradient echo imaging, steady state imaging with free precession, phase-contrast flow quantification, and fast multislice myocardial perfusion imaging and delayed 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 MR system or on a separate workstation. Postprocessing should be performed or supervised by the cardiac MRI physician.

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

Policies and procedures related to quality, patient education, infection control, and safety should be developed and implemented in accordance with the ACR Policy on Quality Control and Improvement, Safety, Infection Control, and Patient Education appearing under the heading *Position Statement on QC & Improvement, Safety, Infection Control, and Patient Education* on the ACR web site (<http://www.acr.org/guidelines>).

Specific policies and procedures related to MRI safety should be in place with documentation that is updated annually and compiled under the supervision and direction of the supervising MRI physician. Guidelines should be provided that deal with potential hazards associated with the MRI examination of the patient as well as to others in the immediate area. Screening forms must also be provided to detect those patients who may be at risk for adverse events associated with the MRI examination or with any contrast medium or pharmaceutical to be administered [84].

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

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*Guidelines and 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 guidelines and standards published before 1999, the effective date was January 1 following the year in which the guideline or standard was amended, revised, or approved by the ACR Council.

Development Chronology of this Guideline

2006 (Resolution 9, 16g, 34, 35, 36)

2011 (Resolution 25)