Magnetic resonance imaging (MRI) is an established imaging modality, recognized for its value in the assessment and monitoring of a wide range of cardiac pathology. It can provide physiologic as well as anatomic information. Image interpretation requires both well-developed MRI skills and knowledge of cardiac pathology. Radiologists, because of their extensive experience in MRI, have an important role in its application in the heart. The guidelines presented here are an educational tool designed to assist practitioners in providing the best possible patient care via the diagnostic methods of cardiac MRI. American College of Radiology requirements for physicians and personnel performing and interpreting cardiac MRI, which will become applicable by July 1, 2008, are also presented.

Key Words: Cardiac magnetic resonance imaging, MRI, cardiac pathology, ACR guideline, ACR requirements


PREAMBLE

These guidelines are an educational tool designed to assist practitioners in providing appropriate radiologic 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

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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 on 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.

INTRODUCTION

Cardiac magnetic resonance imaging (MRI) is an established imaging modality, well recognized for its value in the initial assessment and monitoring of a wide range of diseases of the heart and surrounding related structures (eg, the pericardium) [1,2]. Historically, imaging has had 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, ultrasound (echocardiography), and nuclear medicine. All of these modalities have well-established roles in patient care. Computed tomography (CT) (multidetector CT and electron beam CT) 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 will play an increasing role in comprehensive cardiac imaging. This document deals specifically with cardiac MRI applications.

Although the technical parameters and field of view of a cardiac MRI examination will appropriately be tailored to evaluate the cardiac anatomy and/or function in question, the images obtained will demonstrate adjacent anatomy, often including portions of the lungs, mediastinum, spine, and upper abdomen. Furthermore, cardiac MRI protocols may involve the evaluation of extracardiac vascular structures within and beyond the thorax. These studies may demonstrate clinically significant non-cardiac 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. The safety concerns for cardiac MRI pertain primarily to the strong magnetic field and its potential impact on implanted devices but also to MRI contrast agents and patient sedation. In addition, pharmacologic agents may be administered during MRI examinations.

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 CT scans of the chest (that include basic evaluation of the pericardium, heart size, and cardiac masses) and perform magnetic resonance 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 application.

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 and intravascular blood pools and the surrounding cardiac and vascular structures because of the lack of signal from the blood on “dark-blood” spin-echo MRI pulse sequences or the enhanced signal intensity from blood on “bright-blood” gradient-echo sequences [5,6]. Therefore, internal cardiovascular structures, such as the valves and the endocardial borders of the cardiac chambers, can be distinguished from the blood pools within the heart and great vessels. 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 magnetic resonance tissue perfusion and delayed-enhanced viability techniques. The excellent soft-tissue differentiation capabilities of MRI also permit the delineation of cardiac structures (eg, the ventricular myocardium) and paracardiac structures related to the heart and great vessels (eg, the pericardium and mediastinum).

2. Magnetic resonance imaging is a 3-D and/or multiplanar imaging modality that provides the capability for the precise and reproducible (intraobserver, interobserver, and/or interexamination) quantification of cardiac chamber cavity size or wall mass [7,8]. When
either sequential tomographic images or true-volume sets entirely encompassing the heart in the same cardiac phase are acquired, the resulting 3-D data series permits the 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 (eg, the ejection fraction), ventricular diastolic function (eg, filling rates), shunt quantity (eg, interatrial defect shunt volume), and valve regurgitation quantity (eg, mitral regurgitant volume) [9,10]. These measurements depend on cavity volume changes over the cardiac cycle or differences in stroke volume between the 2 ventricles. Cine MRI techniques with high temporal resolution of the cardiac cycle (preferably ≤50 msec), including standard cine and tagged (eg, spatial modulation of magnetization) gradient-echo imaging, allow the assessment of regional ventricular function (eg, systolic wall thickening or systolic circumferential strain) [11,12]. These studies can be performed at rest or during the intravenous (IV) administration of a pharmacologic stress agent such as dobutamine.

4. Velocity-encoded techniques permit the measurement of blood flow from the standpoint of flow velocity or flow volume [13,14]. Practical uses include stroke volume determination, valvular insufficiency quantification (eg, diastolic retrograde flow volume or systolic antegrade flow volume in the ascending aorta for determining aortic regurgitant fraction), the assessment of stenoses (eg, the measurement of peak systolic velocity beyond the stenotic aortic valve for transvalvular pressure gradient determination by the modified Bernoulli equation or by velocity-time integral methods) [13], and shunt calculation (eg, ascending aortic flow volume/pulmonary artery flow volume to determine Qp/Qs).

5. First-pass perfusion, using 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 on the basis of patterns of tissue enhancement; time-intensity curves may be analyzed to quantify the degree of underperfusion in ischemic or infarcted myocardium (fixed perfusion defect) [15,16]. This can be performed both at rest and during the IV administration of a pharmacologic stress agent such as adenosine.

6. Delayed contrast-enhanced viability MRI methods can be used to evaluate the steady-state distribution of the agent, most importantly to detect the presence of necrotic myocardium [17]. 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 assessing cardiomyopathies, myocarditis, and myocardial infiltrative processes.

7. Multiple noncontrast and contrast-medium-based MRI techniques are available to characterize cardiovascular tissue as follows: cystic vs solid, transudative vs exudative, simple vs complex, hypervascular vs hypovascular, necrotic vs viable, edematous vs normal water content, calcified vs noncalcified, fibrotic vs nonfibrotic, and fat vs soft tissue [18,19].

8. Angiographic techniques (ie, MRA) are often discussed separately; nonetheless, they are essential to many comprehensive cardiovascular MRI examinations, especially those of the coronary arteries and great vessels. Magnetic resonance angiographic methods as they pertain to assessment of the coronary arteries are included in this document.

Cardiovascular MRI should be performed only for a valid medical reason. Although 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. The application of these guidelines should be in accordance with the ACR Practice Guideline for Performing and Interpreting Magnetic Resonance Imaging (MRI).

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 will become applicable by July 1, 2008.

Physician

The physician shall 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 agents, interpreting images, generating an official interpretation,2

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

Physician With Prior Qualifications in General MRI. A 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 magnetic resonance image acquisition and postprocessing, including the use of diagnostic workstations; the design of magnetic resonance 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 on the cardiac MRI examination and MRA. Some of these physicians will also have substantial experience in other methods of cardiac imaging, assessing cardiac function, and/or experience specifically 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, or cardiac MRI.

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

1. training in cardiac MRI in a training program approved by the Accreditation Council for Graduate Medical Education or the American Osteopathic Association, including:
   a. education in cardiac anatomy, physiology, pathology, and cardiac MRI for a time equivalent to at least 30 hours of continuing medical education (CME); and
   b. the interpretation, reporting, and/or supervised review of at least 50 cardiac MRI examinations in the last 36 months, or
2. the completion of at least 30 hours of category I CME in cardiac imaging, including:
   a. cardiac MRI, anatomy, physiology, or pathology and/or documented equivalent supervised experience in a center actively performing cardiac MRI; and
   b. the interpretation, reporting, and/or supervised review of at least 50 cardiac MRI examinations in the past 36 months.

Physician Without Prior Qualifications in General MRI. A 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 training in imaging interpretation, this training must include the physics of MRI; MRI safety; the principles of MRI acquisition and postprocessing, including the 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.

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

1. the completion of a training program approved by the Accreditation Council for Graduate Medical Education in the specialty practiced, plus 200 hours of category I CME in MRI, including, but not limited to, MRI physics, the recognition of MRI artifacts, safety, instrumentation, and the clinical applications of MRI in cardiac and thoracic MRI; and
2. the 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 to include the interpretation, reporting, and/or supervised review of at least 50 cardiac MRI examinations in the past 36 months.

Pharmacologic Stress Testing and the 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 certification.

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 a physician’s skills.

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.

Medical Physicist or Magnetic Resonance 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 magnetic resonance 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 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) or, for MRI, by the American Board of Medical Physics (ABMP) in magnetic imaging physics.

The appropriate subfields of medical physics for this guideline are Therapeutic Radiological Physics, Diagnostic Radiological Physics, Medical Nuclear Physics, and Radiological Physics.

A Qualified Magnetic Resonance Scientist is an individual who has obtained a graduate degree in a physical science involving nuclear magnetic resonance or MRI by the American Board of Medical Physics (ABMP) in magnetic imaging physics. These individuals have 3 years of documented experience in a clinical MR environment.

The continuing education of a Qualified Medical Physicist/MR Scientist should be in accordance with the ACR Practice Guideline of Continuing Medical Education (CME). 2006 (Res. 16g)

A qualified medical physicist or magnetic resonance scientist must be familiar with the principles of MRI safety for patients, personnel, and the public; the US Food and Drug Administration guidance for MRI diagnostic devices; and other regulations pertaining to the performance of the equipment being monitored. A qualified medical physicist or magnetic resonance scientist shall be knowledgeable in the field of nuclear magnetic resonance physics and familiar with MRI technology, including the function, clinical uses, and performance specifications of MRI equipment, as well as calibration processes and the limitations of the performance testing hardware, procedures, and algorithms. A qualified medical physicist or magnetic resonance scientist shall have a working understanding of clinical imaging protocols and methods of their optimization. This proficiency shall be maintained by participation in continuing education programs of sufficient frequency to ensure familiarity with current concepts, equipment, and procedures.

A qualified medical physicist or magnetic resonance 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 or magnetic resonance 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. A qualified medical physicist or magnetic resonance scientist must review and approve all measurements.

**Radiologist Assistant**

A 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, a 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 (2006, Res. 34).

**Radiologic Technologist**

A technologist should participate in ensuring patient comfort and safety; in preparing and positioning a patient for an MRI examination, including the proper positioning of electrocardiographic 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 or the Canadian Association of Medical Radiation Technologists. It is recommended that the technologist performing cardiac MRI have advanced certification in magnetic resonance. Each technologist should have supervised experience in the performance of cardiac MRI examinations and in the IV administration of conventional magnetic resonance contrast agent. If IV contrast material is to be administered, qualifications for technologists performing IV injections should be in compliance with current ACR policy statements and existing operating procedures or manuals at the imaging facility.

The technologist’s continuing education credits

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3 See the ACR Practice Guideline for the Use of Intravascular Contrast Media.
4 The ACR approves of the injection of contrast material and diagnostic levels of radiopharmaceuticals by certified or licensed radiologic technologists and radiologic nurses under the direction of a radiologist or their physician designee who is personally and immediately available, if the practice is in compliance with institutional and state regulations. There must be prior written approval by the medical director of the radiology department or service of such individuals, such approval process having followed established policies and procedures, and the radiologic technologists and radiologic nurses who have been so approved maintain documentation of continuing medical education related to the materials being injected and to the procedures being performed (1987, 1997. Resolution 1-H).

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should include continuing education in cardiac MRI as is appropriate to the technologist’s practice needs. Basic life support and automatic defibrillator training is recommended.

Any technologist practicing MRI scanning should be licensed in the jurisdiction in which they practice, if state licensure exists. To ensure competence, all technologists must be evaluated by the supervising physician.

INDICATIONS

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

Acquired Heart Disease

Dynamic Cardiac Anatomy and Ventricular Function. Generally speaking, echocardiography is a reasonable first test for left ventricular (LV) function, although MRI, because of its 3-D data acquisition, is considered to be more accurate and reproducible [21]. The qualitative assessment of regional ventricular wall motion abnormalities (WMAs) and the quantitative assessment of LV function are appropriate in most MRI examinations of the heart. The qualitative assessment of regional WMAs should use the standard 17-segment model and the following terms: normal, hyperkinetic, hypokinetic, akinetic, or dyskinetic. Left ventricular quantitative function should be performed using short-axis views from base to apex. In addition, to provide complete qualitative analysis, LV 2-chamber, 4-chamber, and 3-chamber long-axis views should be performed.

Parameters recommended to be routinely reported in a functional MRI examination include: LV end-diastolic volume or LV end-diastolic volume index (LV end-diastolic volume divided by body surface area), LV end-systolic volume, LV stroke volume, LV ejection fraction, LV mass index, and LV end-diastolic and end-systolic diameter. The routine use of Simpson’s rule for calculating the LV ejection fraction is recommended, although in patients without significant regional WMAs, the area-length method may be a satisfactory alternative. Diastolic dysfunction may also be assessed using flow quantification methods to assess E/A ratios (early [E] and late, or atrial [A], phases of LV filling). Specific indications for the assessment of regional or global LV function include indeterminate or discrepant echocardiographic results or situations in which the serial assessment of change in LV function is important (eg, following patients after myocardial infarction, LV hypertrophy, valvular regurgitation, or atrial septal defects).

Right ventricular (RV) size as well as global and regional wall motion may be assessed qualitatively and reported. Magnetic resonance imaging is the recommended first-line diagnostic test for assessing RV function (RV ejection fraction and RV end-diastolic volume) 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, for which global and regional RV WMAs constitute diagnostic criteria for disease.

Assessment of Cardiomyopathies, Myocardial Fibrosis, and Infarction. The 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 MRI than echocardiography. Magnetic resonance imaging is considered the gold standard in the assessment of myocardial mass because it is more accurate and reproducible than echocardiography [21]. In hemochromatosis, MRI may be used for the qualitative and/or quantitative assessment of myocardial iron overload. It can also be used to assess fatty infiltration of the heart in suspected arrhythmogenic RV cardiomyopathy. 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 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 4 cardiac chambers. Myocardial delayed hyperenhancement is a specific feature of cardiac MRI that may be extremely useful in detecting areas of myocardial damage and fibrosis [22]. A subendocardial or transmural pattern of enhancement distinguishes ischemic scar from other causes of enhancement, such as myocarditis [23] and scarring in nonischemic cardiomyopathy [24]. Cardiac MRI with the evaluation of global and regional function and myocardial delayed hyperenhancement is indicated in the evaluation of dilated cardiomyopathy to exclude ischemia as the cause and obviate the need for cardiac catheterization in many patients. Myocardial delayed hyperenhancement may also be helpful in the diagnosis of chronic or acute myocarditis. 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. It can also assist in surgical planning for ischemic aneurysms of the heart and be used to identify ventricular thrombus in association with ischemic scar.

Myocardial Ischemia and Viability Assessed Through the Use of Pharmacologic Agents. Magnetic resonance perfusion imaging during gadolinium infusion can be used to detect areas of perfusion abnor-
mality at rest or during pharmacologically-induced stress. The diagnosis of perfusion abnormalities can be performed qualitatively, although the use of semi-quantitative parametric imaging using features related to the upslope of the perfusion curve may improve the accuracy of diagnosis. Magnetic resonance imaging is capable of quantifying perfusion and perfusion reserve, but the tools to do this are not yet widely available. Resting perfusion imaging may provide adjunctive information in chronic ischemia to differentiate among normal, ischemic but viable (hibernating), and nonviable myocardium. However, the major indication for perfusion MRI is in conjunction with vasodilatory stress agents such as adenosine 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 [25,26]. The relative merits in clinical practice of perfusion MRI have not been definitely established.

High-dose dobutamine stress MRI may also be performed to detect ischemia as inducible WMAs. High-dose dobutamine should be administered at a maximum of 4 stress levels, if starting at a dose of 10 μg/kg/min and at a maximum of 5 stress levels if starting at a dose of 5 μg/kg/min, at 3 to 5 minutes per level. Dosing should not be greater than 40 μg/kg/min. No more than 1 mg of atropine at the highest dobutamine dose should be administered to achieve a submaximal heart rate [25]. Dobutamine stress may be performed in the MRI environment safely; however, for the administration of dobutamine at high levels (>10 μg/kg/min), a separate satellite monitor or workstation in addition and adjacent to the scanning console in the control room is suggested. Images should be rigorously monitored by a physician and assessed for induced WMAs at each increment of dobutamine as the images are acquired. The physician should observe regional wall motion in the long and short axes 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 with medications, including β blockers and nitrates. An external cardiodefibrillator should also be available. Perfusion MRI with gadolinium can be performed at peak dobutamine stress and may provide additional diagnostic information.

Lower dose dobutamine (at levels of 5 and then 10 μg/kg/min) can be administered to determine myocardial viability through the qualitative and quantitative assessment of myocardial thickening and improvement in wall motion.

With the administration of all stress agents, patients should be hemodynamically monitored (blood pressure, heart rate, SaO₂, and rhythm assessment) throughout the magnetic resonance examination. Twelve-lead electrocardiograms should be obtained prior to 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 [25].

Functional MRI, myocardial delayed hyperenhancement, and perfusion MRI may be used to diagnose segments with regional ischemia and acute myocardial infarction in acute coronary syndromes. Serial electrocardiography and enzyme assessment remain the diagnostic standard for acute coronary syndromes, but cardiac MRI may be helpful in cases in which clinical examinations, electrocardiography, and enzymes are indeterminate.

Characterization of Cardiac Masses. Most cardiac masses are initially identified on echocardiography. Magnetic resonance imaging is indicated to evaluate tumors with regard to specific tissue characterization (fat containing, cystic, fibrotic, etc), origin, relationship to chambers and valves, and myocardial-extracardiac extension. Magnetic resonance imaging features such as susceptibility effects, enhancement pattern, and extension from central venous thrombosis can be helpful in differentiating thrombus from tumor. Magnetic resonance imaging is the optimal imaging method for evaluating pericardial masses because it allows the evaluation of mediastinal, pericardial, and myocardial involvement in a single study [27,28].

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. Magnetic resonance imaging tissue characterization can also help determine the etiology of effusions (eg, transudative, exudative, hemorrhagic, or neoplastic) [29,30]. Tamponade and constrictive pericarditis can be detected by evaluating anatomic and functional characteristics. 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 [31]. Assessment of effusions can also be coupled with delayed contrast-enhanced assessment of the myocardium to assess for myocarditis.

Valvular Disease. Using phase contrast techniques and functional assessment, cardiac MRI has the capability to evaluate congenital or acquired cardiac valve stenosis or insufficiency. Aortic and pulmonic valve stenoses can be assessed by the phase contrast determination of peak systolic velocity combined with the modified Ber-
noulli equation. In addition, direct planimetry of the aortic valve on high-resolution cine images can be performed. 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 [32].

Coronary Artery Disease. Although MRI can depict acquired proximal disease of the coronary arteries [33], the clinical application is limited at this time. Stenotic disease and aneurysms can be detected, and such findings could be of clinical importance in some patients. However, this is not indicated in the routine evaluation of coronary artery disease. The characterization of atherosclerotic plaque and the 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 [34].

Congenital Heart Disease

Congenital Shunts. Magnetic resonance imaging may be used to quantify and follow RV and LV volumes and function as well as pulmonary-to-aortic flow ratios over time [35]. Specific forms of atrial or ventricular septal defects that are difficult to identify or characterize on echocardiography may benefit from MRI assessment and Qp/Qs quantification. Magnetic resonance angiography of the chest can be used to identify shunts due to anomalies of pulmonary venous return and can also assess the aorta and pulmonary arteries if desired.

Complex Congenital Anomalies. Magnetic resonance imaging with MRA and/or flow measurement may be helpful in cases of complex congenital anomalies to assist in situs determination, chamber identification, chamber size, global function, atrioventricular and ventricular-arterial relationships, and intracardiac or extracardiac shunts [36].

Pericardial Anomalies. Congenital pericardial defects can be evaluated for size and location, and the complete absence of the pericardium can be differentiated from partial defects. Complications such as entrapment of the left atrial appendage can be detected [29].

Congenital Valve Disease. Cardiac MRI has the capability to evaluate for congenital cardiac valve stenosis or insufficiency (eg, bicuspid aortic valves, 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 [32].

Coronary Artery Anomalies. Magnetic resonance imaging can be useful in detecting anomalous origins of the coronary arteries. Significant anomalies such as the abnormal positioning of a coronary artery between the aorta and RV outflow tract can be determined [37]. Extracardiac anomalous coronary artery origin (eg, Bland-White-Garland syndrome) can also be determined. Other indications include the assessment of aneurysms or stenoses of the native coronary arteries such as may occur in Kawasaki’s disease or Takayasu’s arteritis.

SAFETY GUIDELINES AND POSSIBLE CONTRAINDICATIONS

A cardiac MRI physician should have thorough knowledge of patient safety, including specific absorption rate limits, possible neurologic effects, tissue heat deposition, and contraindications to MRI such as implantable devices [38].

With regard to the administration of 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 contrast reactions occur less frequently with gadolinium-based contrast agents in comparison with iodinated agents, some patients may require pretreatment to allow safe contrast administration. 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 [39,40].

When exercise or pharmacologic stress is performed or hemodynamically unstable patients are studied, a physician must always be present. Life support instruments, medications, and personnel trained in advanced cardiac life support 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 monitoring must be performed during stress and recovery.

As described above in “Myocardial Ischemia and Viability Assessed Through the Use of Pharmacologic Agents,” during dobutamine administration, a second (satellite) viewing station is suggested to permit the direct comparison of wall motion at the various dobutamine dose levels with wall motion at images obtained at lower dose levels. This workstation is in addition to the console used by the magnetic resonance 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 White Paper on Magnetic Resonance Safety.

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

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 the proper performance and interpretation of the examination.

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

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

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 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.

Patient Selection

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

Certain indications require administration of IV contrast media. Intravenous contrast enhancement should be performed using appropriate injection protocols and in accordance with the institution’s policy on IV contrast use. (See the ACR Practice Guideline for the Use of Intravascular Contrast Media.)

Patients suffering from anxiety or claustrophobia may require sedation or additional assistance. The administration of moderate or “conscious” sedation may enable the achievement of the examination. If moderate sedation is necessary, refer to the ACR Practice Guideline for Adult Sedation/Analgesia or the ACR Practice Guideline for Pediatric Sedation/Analgesia.

Facility Requirements

An appropriately equipped emergency cart must be immediately available to treat adverse reactions associated with administered medications. The cart should be monitored for inventory and drug expiration dates on a regular basis and comply with institutional policies.

Examination Technique

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

Magnetic resonance imaging 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. 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 2-D acquisition. In addition, horizontal and long-axis cine views of the left ventricle are routinely acquired. 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 less than or equal to 50 msec: interpolation methods (eg, view sharing) are desirable to display reconstructed cine images at less than the acquired temporal resolution. Segmented fast gradient-echo images with flow compensation have traditionally been used for cine imaging. More recently, 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.
For cardiac indications that require the assessment of cardiac morphology, T1-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. Conventional spin-echo or fast or turbo spin-echo images have traditionally been used to obtain T1-weighted or T2-weighted images. These sequences can be used in combination with inflow saturation bands to produce dark-blood images. More recently, double inversion recovery fast or turbo spin-echo techniques have been implemented. Since these images are usually obtained in a breath hold, there is excellent reduction of motion artifacts as well as good suppression of the blood pool, resulting in high-quality black-blood images. Echo train lengths with this sequence are usually less than 40; even shorter echo train lengths (<10) may be required for short-effective-echo-time scans; very high echo train lengths associated with single-shot techniques result in excessive blurring of intracardiac detail and, if possible, should be avoided.

The administration of IV gadolinium chelates (0.1 to 0.2 mmol/kg) for myocardial enhancement may be required for certain cardiac indications, including but not limited to the evaluation of masses or cysts, pericardium, myocardial perfusion, inflammation or infarction. Myocardial perfusion evaluation additionally requires rapid bolus administration (3 to 5 ml/sec) of the gadolinium chelate. Postgadolinium images of the heart are T1-weighted images acquired using spin-echo, fast or turbo spin-echo, double inversion recovery fast or turbo spin-echo, or gradient-echo techniques. The evaluation of myocardial infarction or 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 (typically 175 to 250 msec) during the washout phase (eg, 5 to 30 minutes) of gadolinium chelate distribution. Precise T1 is dependent on gadolinium dose time after administration and individual patient pharmacokinetics and must be determined for each individual being scanned.

Phase contrast imaging of the heart may be used for a variety of indications related to the 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. Magnetic resonance angiography using gadolinium-enhanced techniques is frequently used in conjunction with other cardiac MRI methods. Magnetic resonance angiography may provide additional useful information regarding the status of the aorta, pulmonary artery, pulmonary veins, coronary arteries, and vena cava.

Magnetic resonance imaging 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. Magnetic resonance imaging 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 right ventricle may be useful to determine the relative motion of the pericardium compared with the myocardium in patients with suspected constrictive pericarditis.

When available, techniques such as parallel imaging and partial Fourier methods may be used to shorten patient breath holds.

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

**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 [41]. 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.

**EQUIPMENT SPECIFICATIONS**

Scanners for clinical cardiac MRI should be accredited by the ACR with equipment performance monitoring in accordance with the ACR Technical Standard for Diagnostic Medical Physics Performance Monitoring of MRI Equipment [42]. The MRI equipment specifications and performance shall 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.

Magnetic resonance imaging scanners used for cardiac MRI performance should be 1.0-Tesla strength or above and have a slew rate of at least 70 mT/meter/sec. At the time of writing, the best proven field strength for performance of cardiac MRI is 1.5 Tesla. It may be that in the future, cardiac imaging can be routinely carried out at 3.0
Tesla, but at the time of writing, substantial challenges exist for performing certain pulse sequences.

Magnetic resonance imaging scanners should be equipped with a localized multichannel radiofrequency surface coil and electrocardiographic gating. Ideally, electrocardiographic gating capabilities would include prospective triggering, retrospective gating, and triggered retrogating. Vectorcardiographic gating is desirable but not essential. An MRI-compatible power injector is required for performing myocardial perfusion MRI or any MRA methods. A power injector is not required for delayed 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, 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 software approved by the Food and Drug Administration for processing data (calculation of ejection fractions, reformatting angiographic data) should be available either as part of the magnetic resonance system or on a separate workstation. Postprocessing should be performed or supervised by the cardiac MRI physician.

QUALITY CONTROL AND IMPROVEMENT, SAFETY, INFECTION CONTROL, AND PATIENT EDUCATION CONCERNS

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 Concerns, appearing elsewhere in the ACR Practice Guidelines and Technical Standards book.

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 agent or pharmaceutical to be administered [43].

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

REFERENCES


