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Magnetic Resonance Imaging: A Wealth of Cardiovascular Information

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ABSTRACT

Cardiac magnetic resonance imaging is a relatively new noninvasive imaging modality that provides insight into multiple facets of the human myocardium not available by other imaging modalities. This one test allows for the assessment of ventricular and valvular function, ischemic and nonischemic cardiomyopathies, congenital heart disease, and cardiac tumors. It has been coined by many as ''one-stop shopping.'' As with any imaging modality, it is important to understand not only the indications of the modality but also the patient's perspective and contraindications.

INTRODUCTION

Cardiac magnetic resonance imaging (cMRI) is the result of a series of technological achievements that provide an unparalleled ability to evaluate the *structural and hemodynamic* characteristics of the human heart. When applied in the appropriate clinical context, the information obtained from this modality of cardiac imaging can offer diagnostic and prognostic information otherwise unavailable to the clinician.

Although a full understanding of the mechanism of cMRI is not necessary to utilize the clinical information obtained from it, some understanding of the underlying physics is necessary to appreciate both its strengths and limitations. MRI has its roots in the fact that each atom with an odd number of nucleons has intrinsic magnetic properties. As one would expect of any magnet, placing such an atom into a magnetic field causes it to align itself relative to the field. At the atomic level, however, this is not a static alignment, but one in which the magnetic pole of the atom spins around that of the external magnetic field. When such a spinning atom is struck with radiofrequency energy at a particular frequency, it absorbs the energy and translates it into greater spin precession. This energy is maintained as potential energy for a time and subsequently released in the form of radiofrequency waves. MRI takes advantage of this principle by creating a series of strong magnetic field gradients and then using radiofrequency energy to bombard the structure being evaluated. The resultant changes in atomic precession and subsequent release of energy in the form of radiofrequency energy can be interpreted through a series of complex algorithms into a detailed map of tissue structure and composition.[1]

From a patient's perspective, cMRI generally takes 30–45 minutes to perform with the patient lying nearly flat during the study. To create an image of a beating heart, the patient must be able to perform several 7–15 second breath-holds and be in a relatively regular heart rhythm. If the patient is claustrophobic or is a child unable to cooperate, both mild sedation and general anesthesia are available. Since MRI is able to evaluate tissue composition, it is able to differentiate muscle, fat, water, and blood without any contrast agents. However, gadolinium use may be necessary for some studies, depending on the diagnosis. Gadolinium is not approved by the Food and Drug Administration for the use of cardiac imaging and has some relative contraindications discussed later.

Given that cMRI provides a noninvasive and nonradiating modality of imaging with unique soft tissue resolution capabilities, it is not surprising that it is rapidly developing a strong role in the diagnostic cardiovascular armamentarium. Although historically limited by the constraints of respiratory and cardiac motion, improvements in the fields of data acquisition algorithms and imaging hardware, as well as the use of respiratory and electrocardiographic gating, have led to subsequent improvement in spatial and temporal resolution. Cardiac MRI can now provide high spatial resolution images of the heart in every potential spatial plane without being limited by acoustic windows, as is echocardiography, and without the need to expose the patient to ionizing radiation or iodinated contrast, as in computed tomography. These advances have led to the effective

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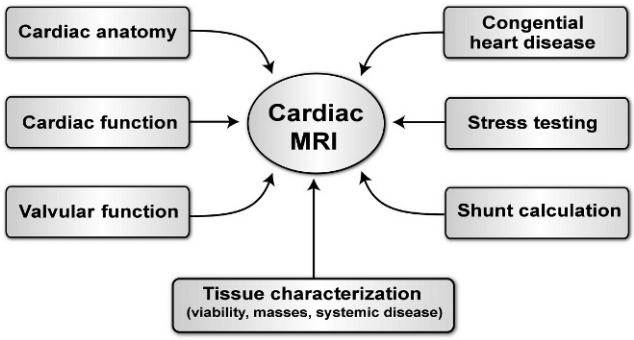

Figure 1. Uses of cardiac magnetic resonance imaging.

utilization of cMRI in evaluation of myocardial morphology, ventricular function, and myocardial tissue composition; structural and functional assessment of the coronary vessels; evaluation of arterial and venous vasculature; and assessment of flow dynamics to quantify valvular competence, regurgitant volumes, and intra- and extracardiac shunting (Figure 1).

Cardiac MRI uses seven basic pulse sequences for the assessment of cardiovascular disease: (1) *black blood imaging* for the assessment of cardiac morphology and the relationship of cardiac structures to each other and to surround structures, (2) *bright blood imaging* for creating cine, or ''movie,'' images of the heart, (3) *fat saturation imaging* for the assessment of fatty infiltration of cardiac masses and myocardium, (4) *velocity encoding mapping* for the measurement of blood flow, (5) *perfusion imaging* with gadolinium for the evaluation of vascularity, (6) *delayed hyperenhancement* (DHE) with gadolinium for the assessment of abnormal myocardial tissue composition, and (7) *angiography* with gadolinium for the assessment of the vasculature. A combination of all these technologies allows for the evaluation of various disease processes, such as pericardial thickening, cardiomyopathies, myocardial ischemia, coronary anatomy, valvular regurgitation, and congenital heart disease. We illustrate the various uses of cMRI through case examples.

CARDIAC MORPHOLOGY

With its great spatial resolution and ability to image in any plane, cMRI provides the ability to define the relationship of cardiac structures to each other and to other noncardiac structures. This is important in the evaluation of pericardial disease, cardiac tumor, and congenital heart disease. Both bright and black blood imaging are used for evaluation and diagnosis of such diseases (Figure 2).[2]

CARDIAC FUNCTION

In addition to provision of high-resolution cardiac still images, cMRI can produce a cine image by

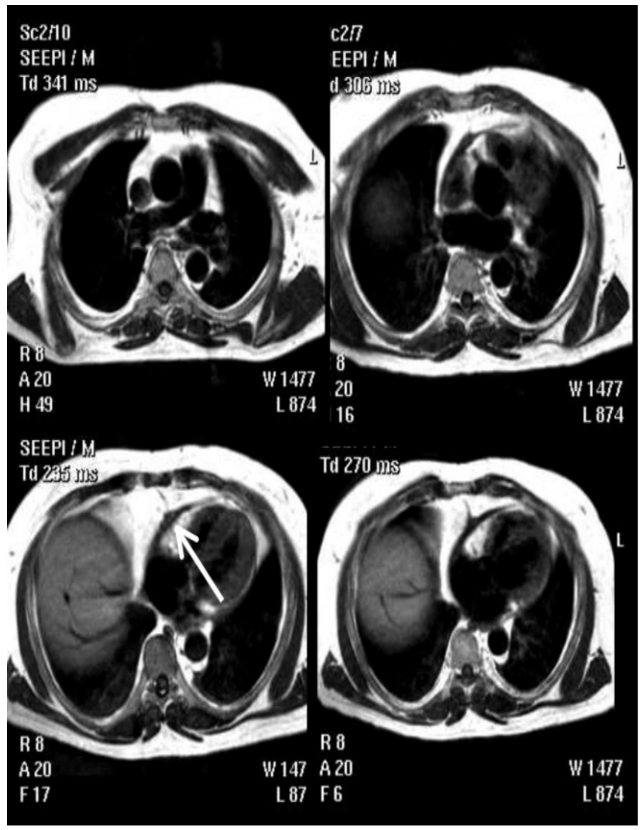

Figure 2. Case: 16-year-old male with ascites being referred to Ochsner for liver transplant. Echocardiogram showed normal left ventricular size and function. Cardiac magnetic resonance imaging: Black blood images. Diagnosis: Pericardial thickening (arrow), resulting in constrictive pericardial disease and hepatic congestion.

modifying the gradient echo technique, known as steady state free precession. This allows for the production of ''movies'' of the cardiac cycle with a high degree of temporal and spatial resolution. Given that a large proportion of the cardiac literature focuses on ventricular function and volumes in the determination of treatment algorithms, the use of cine MRI provides an invaluable tool in quantifying these important indices. Whereas echocardiography has been a mainstay of ejection fraction evaluation, it can be limited by (1) acoustic windows that fail to provide optimal endocardial definition and (2) geometric assumptions that become increasingly inaccurate in diseased hearts. Significant intra- and interobserver variability, in the range of 10–15%, is also a concern for quantitative evaluation of left ventricular function by echocardiography. Cardiac MRI uses two-dimensional planimetry in each systolic and diastolic cine frame to define instantaneous volumes from the base to the apex of the heart, thereby allowing direct quantification of ejection fraction, ventricular volumes, and mass with no reliance on acoustic windows. This

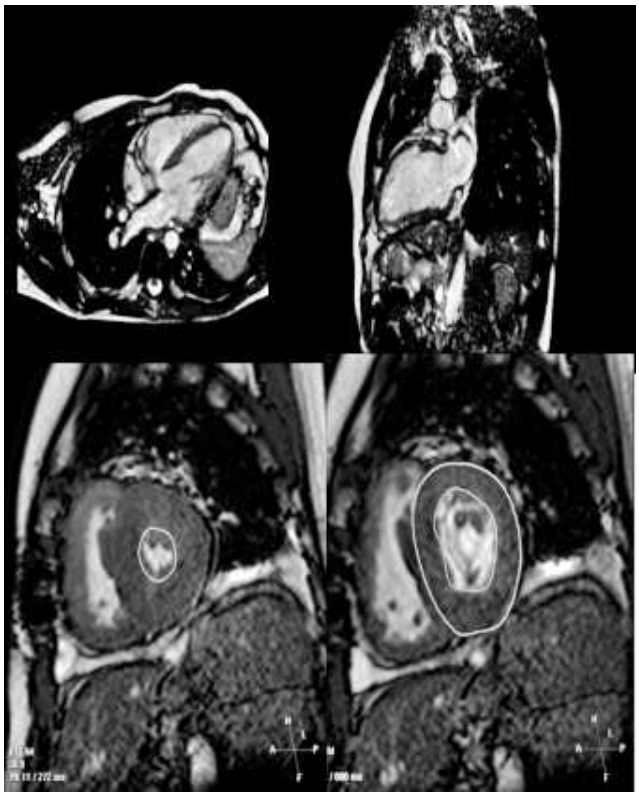

Figure 3. Case: 72-year-old cachectic male with chronic obstructive pulmonary disease and shortness of breath. Echocardiogram was nondiagnostic secondary to poor acoustic window. Cardiac magnetic resonance imaging: Cine images created by steady state free precession. Diagnosis: Ejection fraction, 67.4%; stroke volume of 95.2 cc; end diastolic volume of 141.1 cc; end systolic volume, 45.9 cc; left ventricular mass, 196 g.

preciseness allows both intra- and interobserver variability to be less than 2%.[3] Cardiac MRI is currently the only imaging modality reliably used to assess right ventricular volumes and function. In contrast to computed tomography (CT) and cardiac catheterization, cMRI does not require an intravenous line or contrast. Also, because cMRI is able to characterize tissue it can differentiate blood versus muscle versus clot using the same techniques (Figures 3–5).

MYOCARDIAL PERFUSION AND STRESS TESTING

Cardiac MRI combines the capabilities of nuclear medicine and echocardiography to assess myocardial

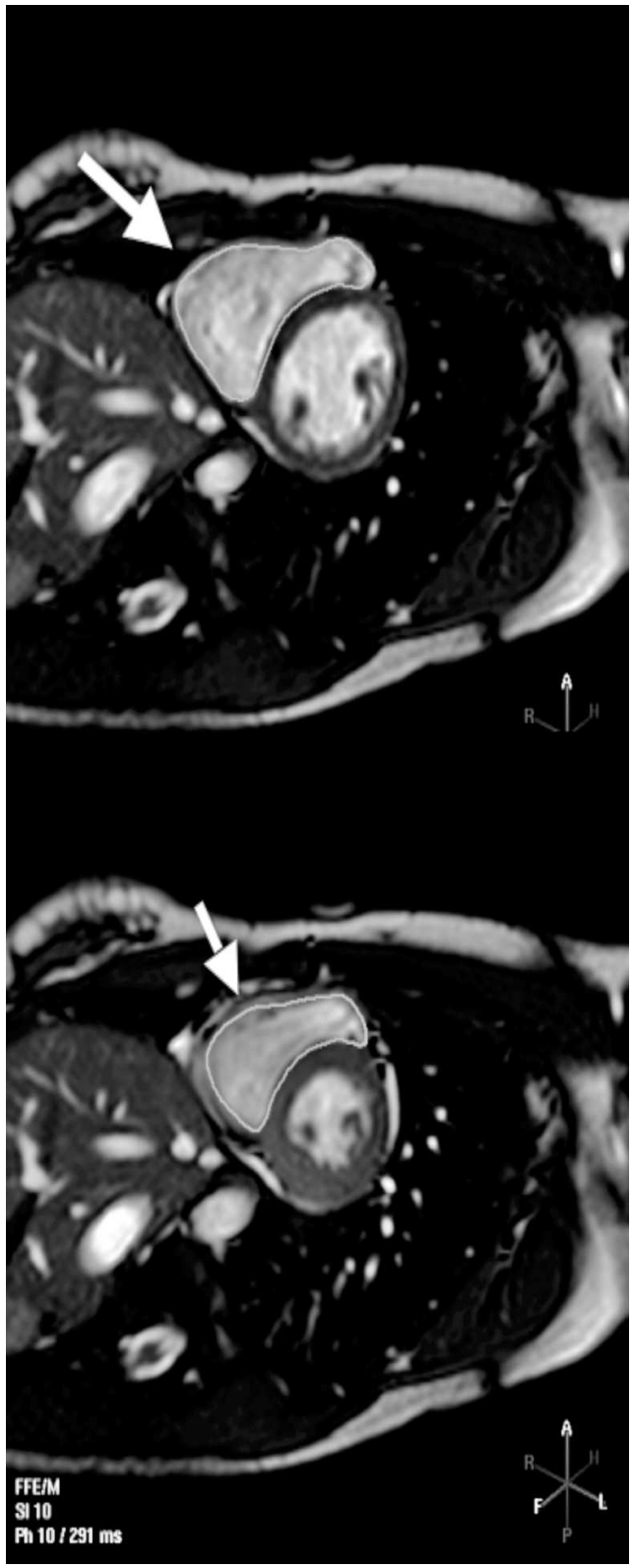

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Figure 4. Case: 16-year-old female with dyspnea on exertion. Echocardiogram shows right ventricular enlargement with reduced function. Cardiac magnetic resonance imaging: Cine images, steady state free precession. Diagnosis: Precise measurement of right ventricular (arrow) end-diastolic volume (top image) and end-systolic (bottom image) show normal right ventricular (RV) volumes and function: RV ejection fraction, 52%; RV end diastolic volume, 133 cc; RV end systolic volume: 64 cc; stroke volume: 69 cc.

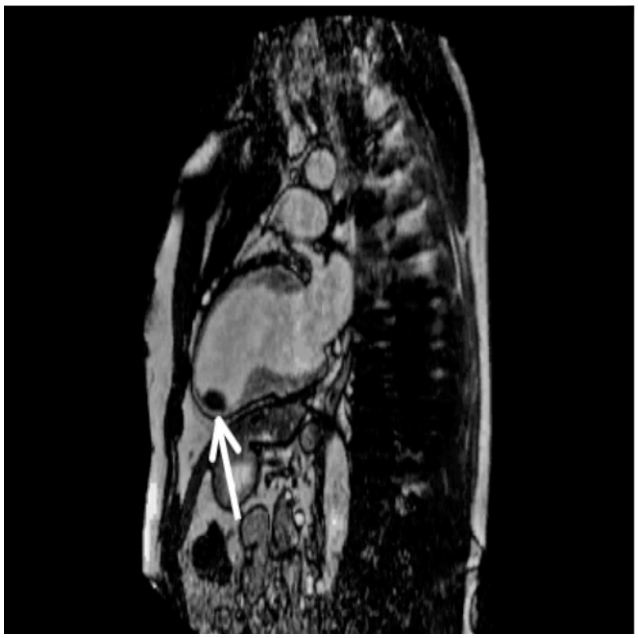

Figure 5. Case: 68-year-old male post left anterior descending infarct. Cardiac magnetic resonance imaging: Cine images, steady state free precession. Diagnosis: Akinesis and thinning of the mid-apical anterior wall and apical inferior wall and apical thrombus (arrow).

ischemia. Stress can be accomplished either via vasodilatation (e.g., using adenosine) or through a chronotropic agent (e.g., dobutamine). Chronotropic stress requires escalating doses of dobutamine to reach target heart rates with cMRI acquisition in multiple cardiac planes at rest, stress, and recovery. Adenosine cMRI stress requires the injection of gadolinium at stress, with comparison of stress and rest images (Figure 6).[4] The two major benefits to cMRI stress imaging are that the spatial resolution of ischemia is higher than that obtained with competing modalities (especially echocardiography) and viability assessment can be obtained during the same examination. The disadvantage of cMRI is the high reliance on patient cooperation for breath-holding and inability to image during arrhythmias. Myocardial perfusion imaging with gadolinium can also be used to assess myocardial tumors to help determine if a tumor is highly vascular (Figure 7).

TISSUE CHARACTERIZATION

The most unique and, perhaps, most useful aspect of cMRI is its ability to characterize tissue. The clinically relevant aspect of cardiovascular imaging is its use to differentiate tissue edema, tissue fibrosis, and fat. Detecting differences in tissue composition, using cMRI, without the administration of exogenous contrast is largely dependent on the evaluation of proton-rich water content. This is where

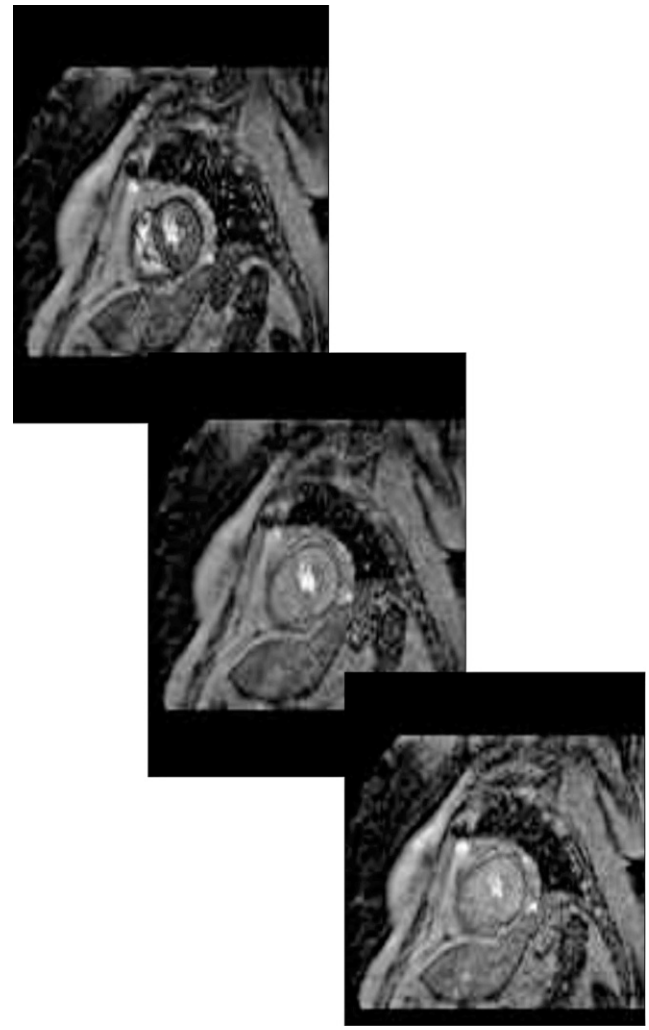

Figure 6. Case: 65-year-old male with history of recurrent lymphoma and coronary artery disease with newly depressed left ventricular function. Cardiac magnetic resonance imaging: Assessment of differential perfusion of the myocardium with gadolinium during adenosine stress. Diagnosis: Left ventricular ejection fraction, 41%. No evidence of ischemia.

the body of research on the use of cMRI is most quickly growing.

Ischemic heart disease

Ischemic heart disease is a major target for therapeutic intervention in our society. Although revascularization technology has progressed at a tremendous rate in terms of being able to provide blood flow to an ischemic or infarcted myocardium, the ability to assess viability of the tissue has historically been largely dependent on nuclear techniques. The nuclear assessment of viability suffers both from poor spatial resolution as well as radiation exposure to the patient. There are four important advantage of cMRI over other imaging methods to

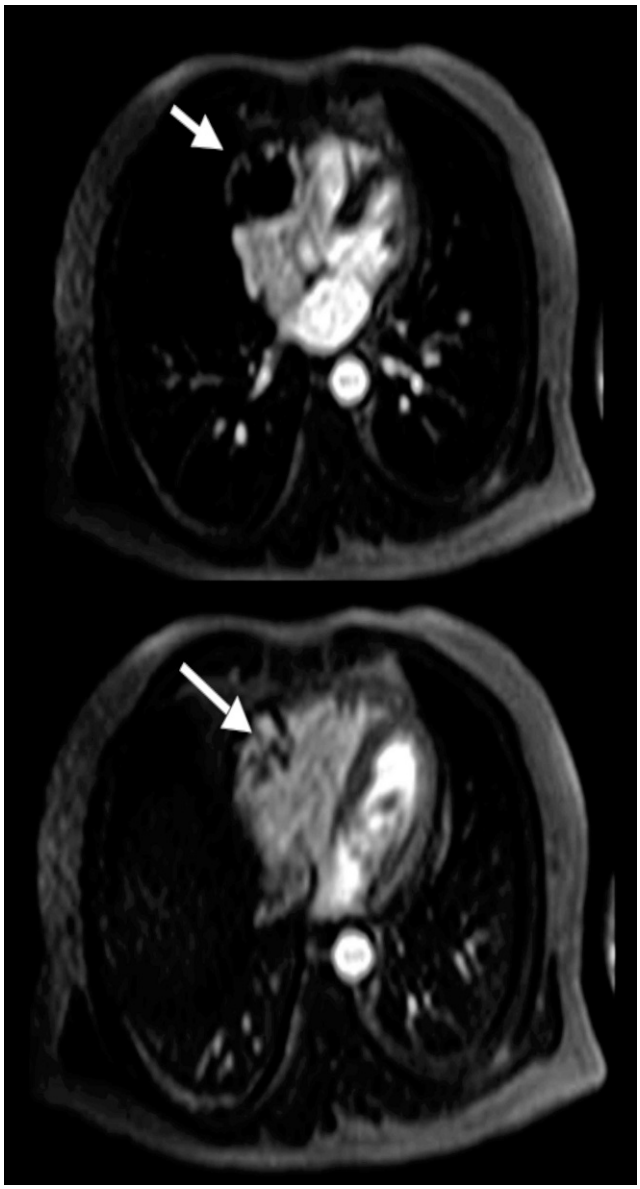

Figure 7. Case: 56-year-old male with new onset weight loss. Echocardiogram showed intracardiac mass. Cardiac magnetic resonance imaging: Without (top) and with (bottom) gadolinium. Diagnosis: Highly vascular structure with gadolinium; cardiac sarcoma (arrow).

assess myocardial viability: (1) it can show the transmural extent of nonviable myocardium; (2) it has superior spatial resolution; (3) it can assess normal myocardial wall thickness; and (4) it can show contractility reserve with dobutamine.

Administration of a gadolinium-based contrast agent is typically used to assess tissue fibrosis via cMRI technique of delayed hyperenhancement (DHE). The gadolinium is injected, and after approximately 10–15 minutes of ''wash-out'' period, the areas with fibrotic tissue appear white on DHE images due to the slower wash-out of contrast. *Thus*, *white is fibrosis or*

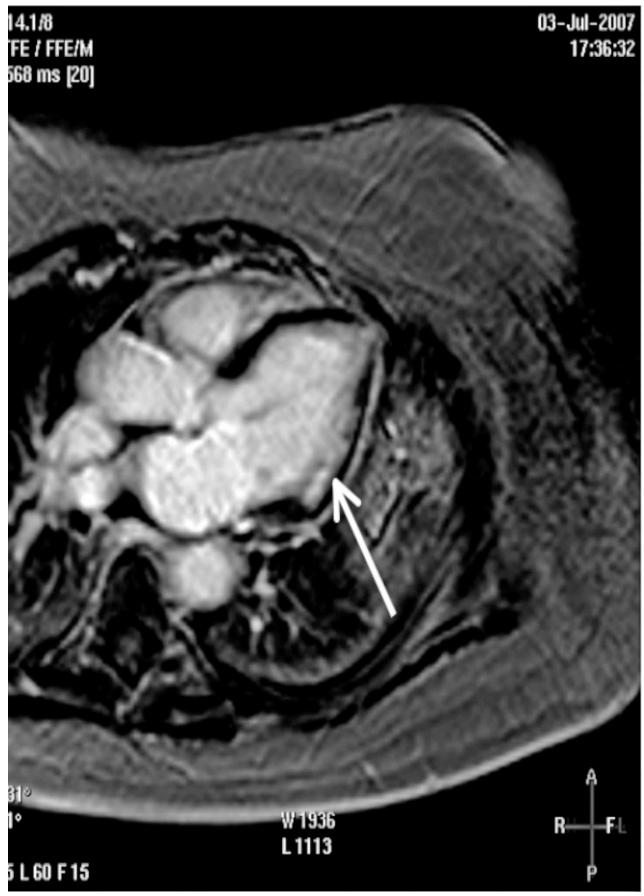

Figure 8. Case: 55-year-old female with echocardiogram ejection fraction of 45% and normal nuclear stress test. Cardiac magnetic resonance imaging: Delayed hyperenhancement. Diagnosis: Nontransmural infarct (arrow) of the mid inferolateral wall; superior spatial resolution magnetic resonance imaging defects >2 g necrosis; single photon emission computed tomography detects >10 g necrosis.

inflammation, *and black is normal tissue*. DHE has been validated with ex vivo pathology specimens in dogs who underwent infarction of a specific coronary distribution.[5] This technique was then correlated in the clinical arena in a study by Kim et al, wherein 50 patients with left ventricular dysfunction underwent pre-revascularization cMRI with gadolinium injection.[6] Notably, the degree of hyperenhancement was inversely related to the improvement in post-revascularization contractility. Seventy-eight percent of patients identified as completely viable by contrast-enhanced MRI had an improvement in contractility after revascularization. On the other hand, of the patients labeled as nonviable by cMRI, less than 8% had an improvement in contractility (Figure 8).[6]

Nonischemic cardiomyopathy

Ischemic heart disease may represent one of the most common dilemmas facing the cardiologist, but

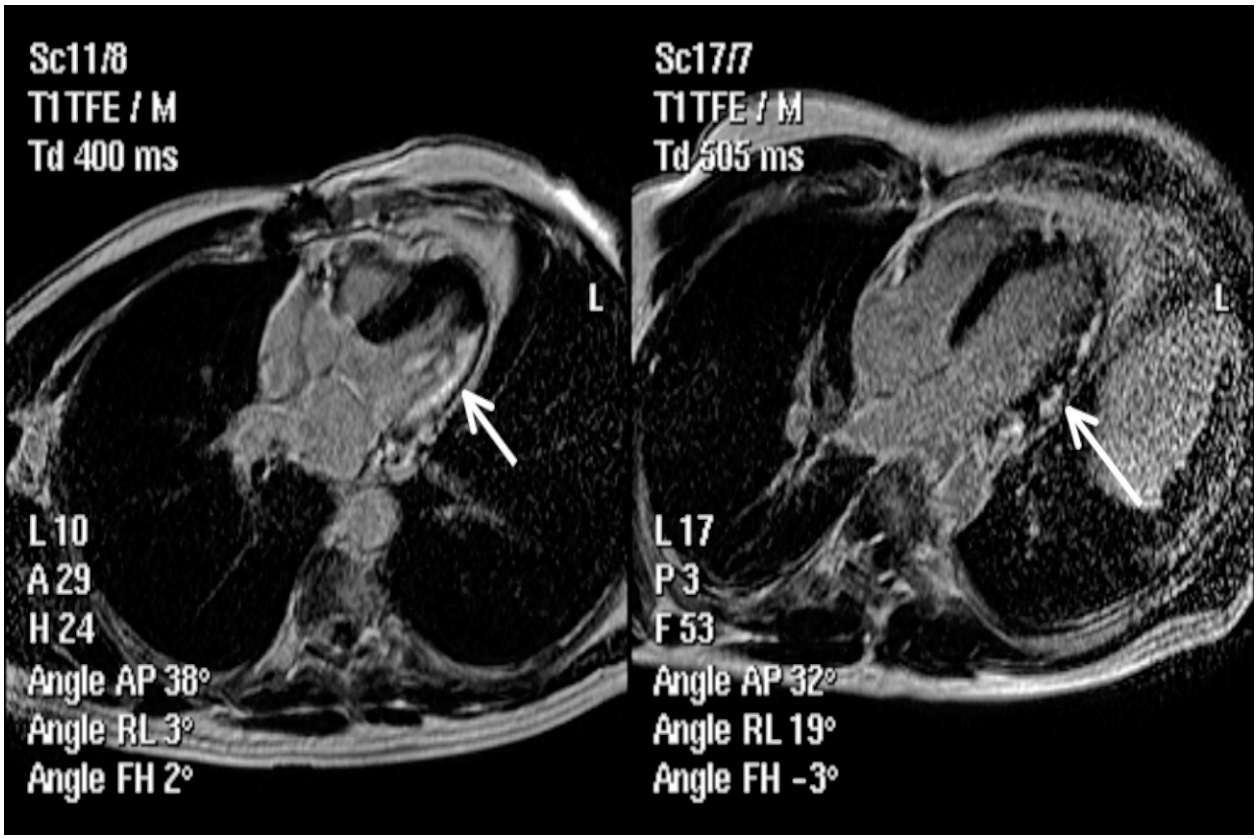

Figure 9. Case: 24-year-old male with chest pain, elevated troponin, and normal coronary arteries. Cardiac magnetic resonance imaging: delayed hyperenhancement (DHE). Diagnosis: Image on the left shows typical DHE (arrow) consistent with myocardial infarction (involving endocardium and sparing epicardium). Image on the right shows DHE (arrow) in this patient with myocarditis (involvement of epicardium only).

nonischemic cardiomyopathy represents one of the most frustrating. Though certain forms of nonischemic cardiomyopathy are readily diagnosed by echocardiography, many other forms have required biopsy or autopsy tissue diagnosis to determine their etiology. Cardiac MRI is unique in offering a noninvasive evaluation of tissue composition and, thus, the opportunity to determine the etiology of many less common forms of cardiomyopathy without endomyocardial biopsy. Identification of a patient's cause of cardiomyopathy carries with it important differences in therapy and prognosis. The specific pattern of DHE and/or the presence of fatty infiltration of the myocardium is used in the diagnosis of cardiomyopathies, such as myocarditis, hypertrophic cardiomyopathy, amyloidosis, and arrhythmogenic right ventricular dysplasia.[7]

Myocarditis

Myocarditis represents another area in which cMRI offers a significant improvement in diagnostic imaging options. Traditionally, myocarditis is diagnosed via its clinical manifestations: typically a viral syndrome, another infectious, or autoimmune etiology associated with the development of chest pain, heart failure, or arrhythmia.[8] Autopsy studies have demonstrated myocarditis in up to 12% of young patients presenting with sudden cardiac death, emphasizing the importance of appropriate diagnosis and treatment.[9] Endomyocardial biopsy has previously been the gold standard for diagnosis, but it is not only invasive but also highly insensitive, with only 10–25% of patients with clinically diagnosed myocarditis demonstrating histological findings of the disease.[10] Some of this discrepancy is undoubtedly related to clinical misdiagnosis, but the *epicardial* distribution of inflammatory cells (tissue unobtainable by intracardiac biopsy) may account for a significant proportion of false-negative biopsies. Myocarditis on cMRI shows a very characteristic DHE of the epicardium, most prominently of the lateral wall (Figure 9).[11] Given the importance of appropriate diagnosis and of ruling out other etiologies, such as acute ischemic events, that present with similar symptoms and laboratory findings, cMRI offers a unique and as yet underutilized imaging modality for confirming this diagnosis. In a study of patients presenting with chest pain, elevated troponin values, and normal coronary angiography

who underwent subsequent cMRI, more than 30% demonstrated findings consistent with myocarditis, emphasizing the probability that this disease is likely under diagnosed because of the lack of sensitive modalities capable of providing antemortem diagnosis.[12]

Amyloidosis

Cardiac amyloidosis, an infiltrative cardiomyopathy, carries an extremely poor prognosis, with a median survival of 13 months. Confirmatory diagnosis has historically been obtained through endomyocardial biopsy, which carries a sensitivity of 55%.[13] Several studies have reported a characteristic diffuse hyperenhancement pattern on cMRI, typically more prominent in the subendocardium. When compared to endomyocardial biopsy performed in patients with restrictive cardiomyopathy, cMRI had a positive predictive valve of 92% and a negative predictive valve of 85%.[14] In addition, cMRI provides prognostic data on patients with amyloidosis. Patients with diffuse DHE of the myocardium have a significantly worse outcome compared to those with amyloidosis without DHE. The difference in median survival was 144 days with DHE vs. 600 days for those with no evidence of hyperenhancement (Figure 10).[15]

Hypertrophic Cardiomyopathy (HCM)

For the assessment of hypertrophic cardiomyopathy, cMRI determines the involved area and degree of myocardial hypertrophy, as well as the extent of myocardial fibrosis with DHE. A characteristic pattern of DHE is observed in the mid-myocardium at the junction of the interventricular septum and right ventricular free wall. This pattern of DHE has been correlated with pathologic specimens and has now been shown to correlate with increased incidence of ventricular arrhythmias. These findings are clinically important, as the amount/location of hypertrophy and presence of DHE has been associated with an increased risk of sudden cardiac death.[16]

Arrhythmogenic Right Ventricular Dysplasia (ARVD)

The diagnosis of ARVD is based on the presence of major and minor criteria encompassing structural, histological, electrocardiographic, arrhythmic, and genetic factors proposed by the ARVD Task Force in 1994.[10] Abnormalities in the right ventricular structure and function constitute some of the diagnostic criteria for ARVD: fatty infiltration of the myocardium, free wall aneurysms, right ventricular enlargement, and DHE. Cardiac MRI allows multiplanar evaluation of the right ventricle, enabling accurate morphologic and functional assessment

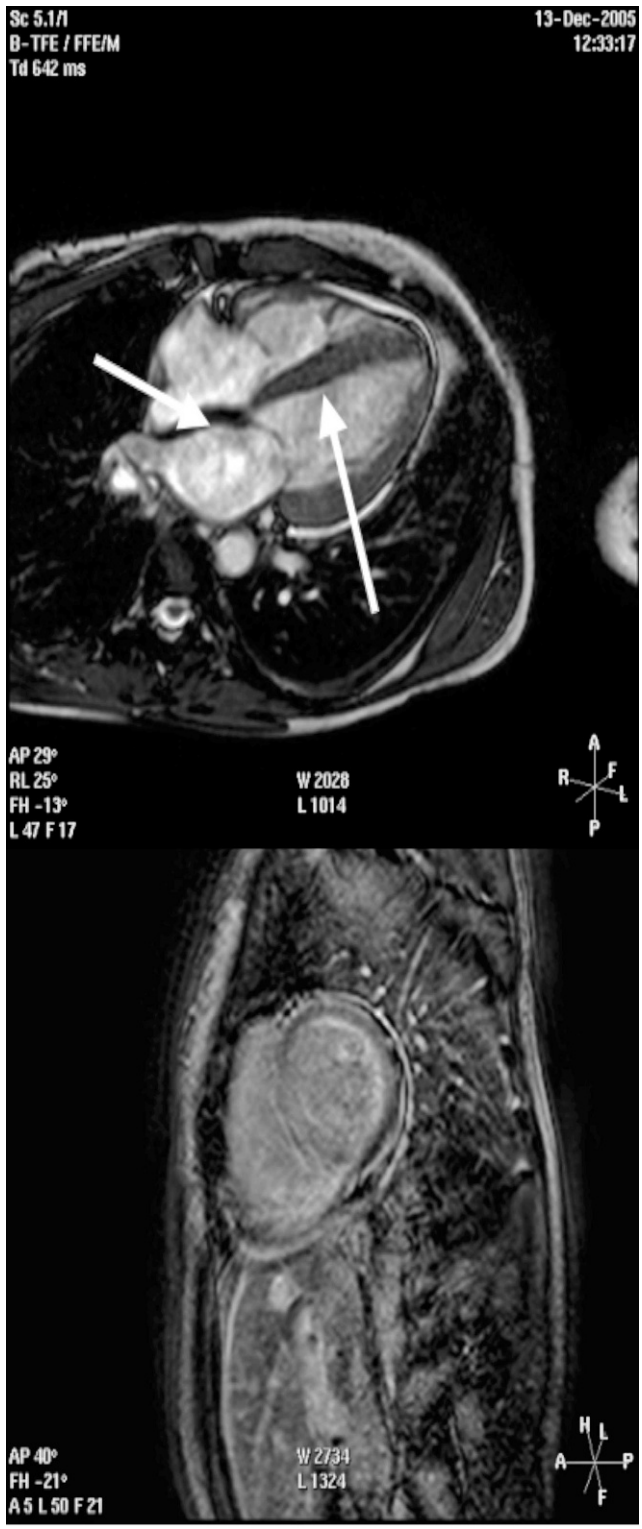

Figure 10. Case: 45-year-old female with rapidly progressing heart failure. Cardiac magnetic resonance imaging: Cine images, steady state free precession (top) and delayed hyperenhancement (bottom). Diagnosis: Amyloidosis—ventricular hypertrophy (top image, right arrow), thickened intra-atrial septum (top image, left arrow), and diffuse delayed hyperenhancement (bottom image).

without any geometric assumptions. Intramyocardial fat accumulation is a pathologic hallmark of ARVD, and cMRI has excellent tissue characterization capability, particularly for fatty tissue. The ability to provide tissue characterization as well as to visualize right ventricular function makes MRI suitable for diagnosis of this disease.[17]

Cardiac Tumors

The diagnosis of intracardiac tumors can be challenging in the absence of autopsy or intraoperative tissue. Cardiac MRI offers several advantages over echocardiography in better classifying the nature of an intracardiac mass. Through a series of imaging algorithms, cMRI can not only define the location of a mass with the high degree of spatial resolution, but also demonstrate perfusion characteristics, enhancement patterns, mobility, hemodynamic effects, and the tissue composition. Previously, we illustrated the utility of black blood and perfusion imaging by cMRI in evaluating cardiac tumors (Figure 7). The black blood images help delineate the location of the tumor and potential pericardial and extra-pericardial extension. Perfusion imaging establishes the structure's vascularity. A technique known as fat suppression provides additional insight into tissue composition (Figure 11).[18]

Valvular Heart Disease

Echocardiography is the primary modality for the assessment and follow-up of valvular heart disease. However, cMRI can provide similar information: defining valvular anatomy and quantifying regurgitation volumes, peak gradients, chamber volumes, and ejection fraction. The pulse sequence primarily used involves cine images by steady state free precession and velocity encoding contrast (VENC) imaging. The cine images define the valve anatomy, visualize the regurgitation or stenotic jet, and quantify the ventricular volumes and function. The VENC pulse sequence is used to measure the velocity and volume of blood flow. This technology has been instrumental in the evaluation of chronic aortic, mitral, and tricuspid regurgitation (Figures 12).[19] These techniques give great insight into the optimum timing of mitral valve repair or replacement as it is able to accurately and reproducibly quantitate the regurgitation fraction, the ejection fraction, and the ventricular volumes.

Congenital Heart Disease

After echocardiography, cMRI is the primary imaging modality used in the evaluation of congenital heart disease, as it does not expose children and young adults to radiation and can provide both anatomic and physiological information in preoperative and postoperative periods. It provides comprehensive evaluation of ventricular function, valvular disease, postoperative grafts, and angiography of arterial and venous structures with gadolinium. The

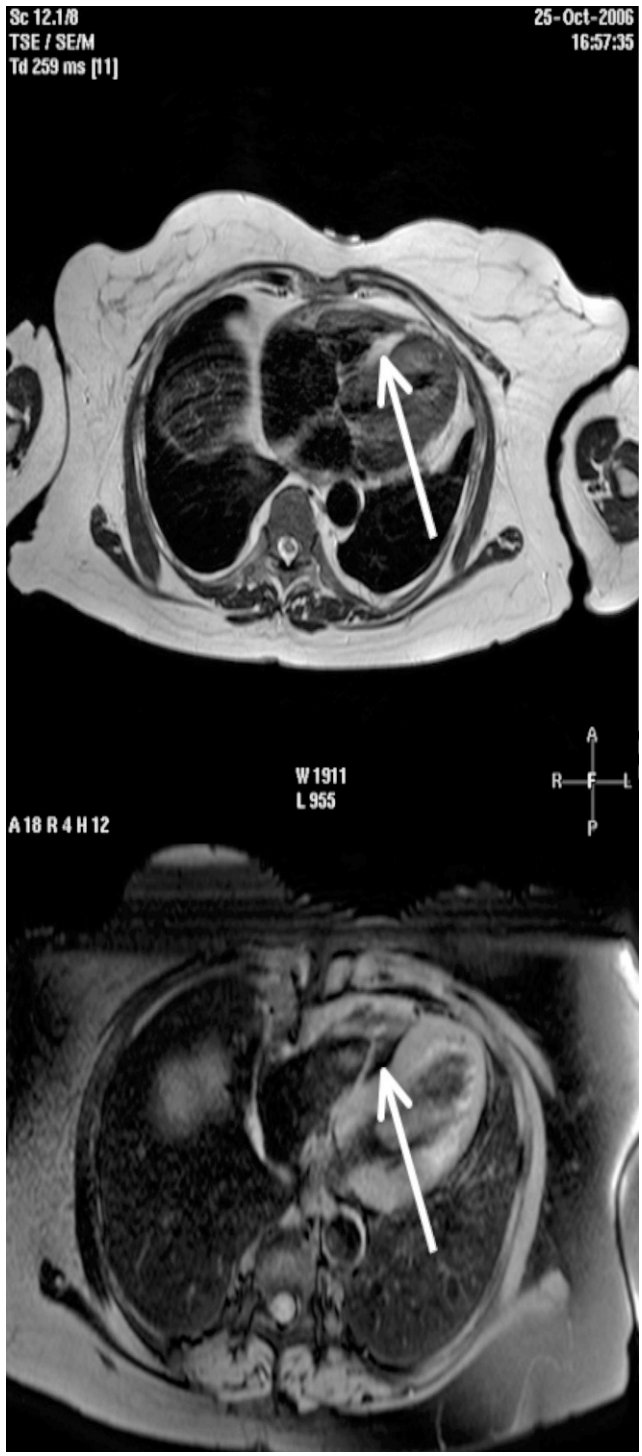

Figure 11. Case: 75-year-old female with a bright mass seen in the intraventricular septal on echocardiogram. Cardiac magnetic resonance imaging: Black blood imaging (top) and fat suppression (bottom). Diagnosis: Benign cardiac lipoma (arrows); mass disappears with fat suppression.

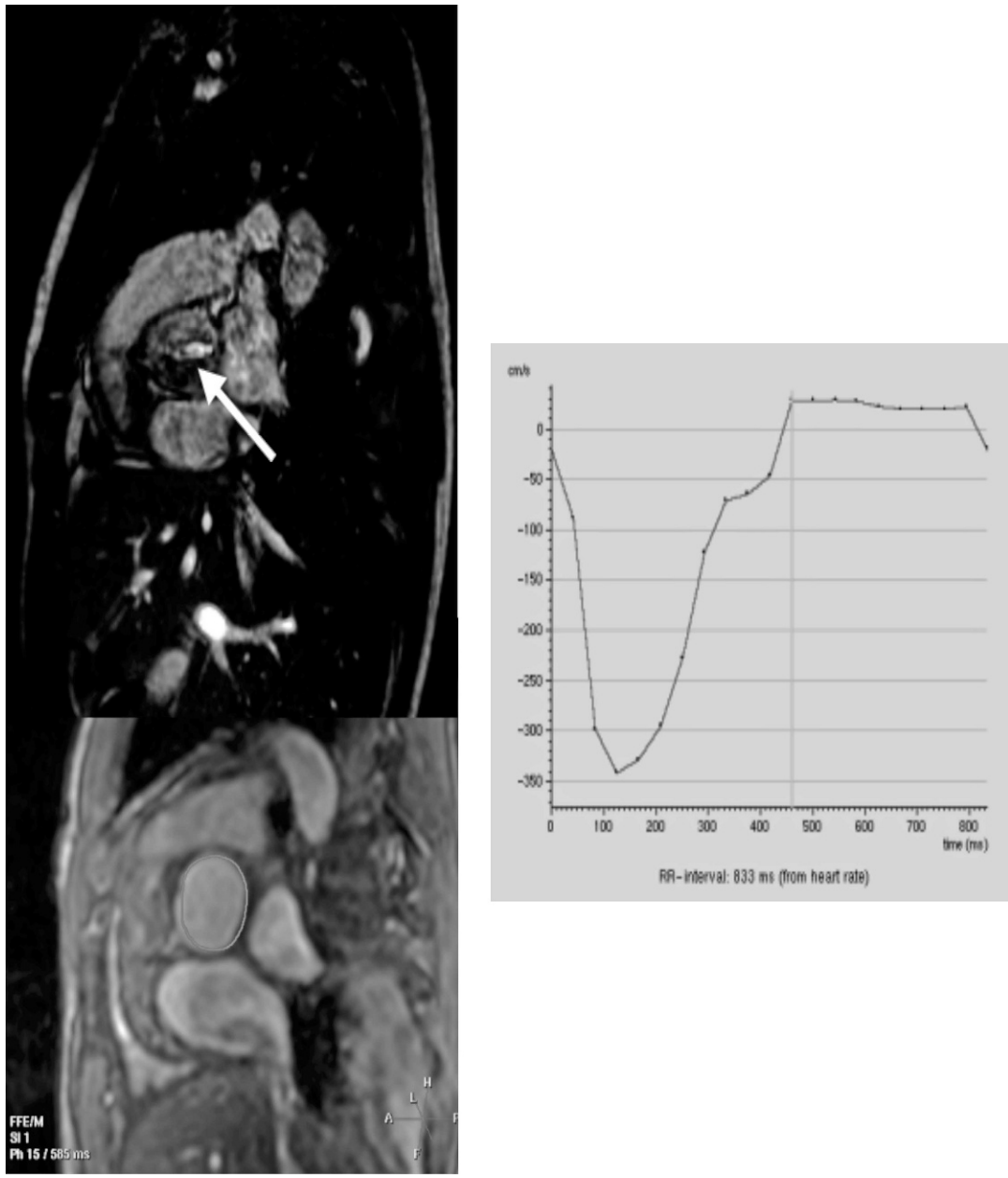

Figure 12. Case: 19-year-old male with bicuspid aortic valve (AV). Cardiac magnetic resonance imaging: Cine image (top image with arrow on bicuspid AV) and velocity encoding contrast imaging (bottom). Graph depicts flow through the valve in systole and diastole. Diagnosis: Bicuspid AV with peak gradient of 40 mmHg and aortic insufficiency with regurgitation fraction of 21%.

evaluation of congenital heart disease not only relies on the above evaluation, but also calculation of cardiac shunts. MRI relies on the use of VENC imaging to calculate Qp:Qs and saturation pulses to allow for visualization of the shunt. The calculation of shunt fraction by MRI has been validated with angiography.[20] Cardiac MRI is also used to evaluate for anomalous origin of coronary arteries by allowing visualization of the proximal coronary arteries without gadolinium (Figures 13).

SAFETY AND CONTRAINDICATIONS

One of the greatest advantages of cMRI is its safety, with no reported short- or long-term ill effects from the magnet.[21] As opposed to CT, which relies on x-ray frequency radiation, cMRI relies on the application of radiofrequency (RF) pulses within a strong magnetic field. Because no high-energy radiation is involved, no genetic effects or carcinogenic potential are known.[22] Cardiac MRI thus shares with ultrasound

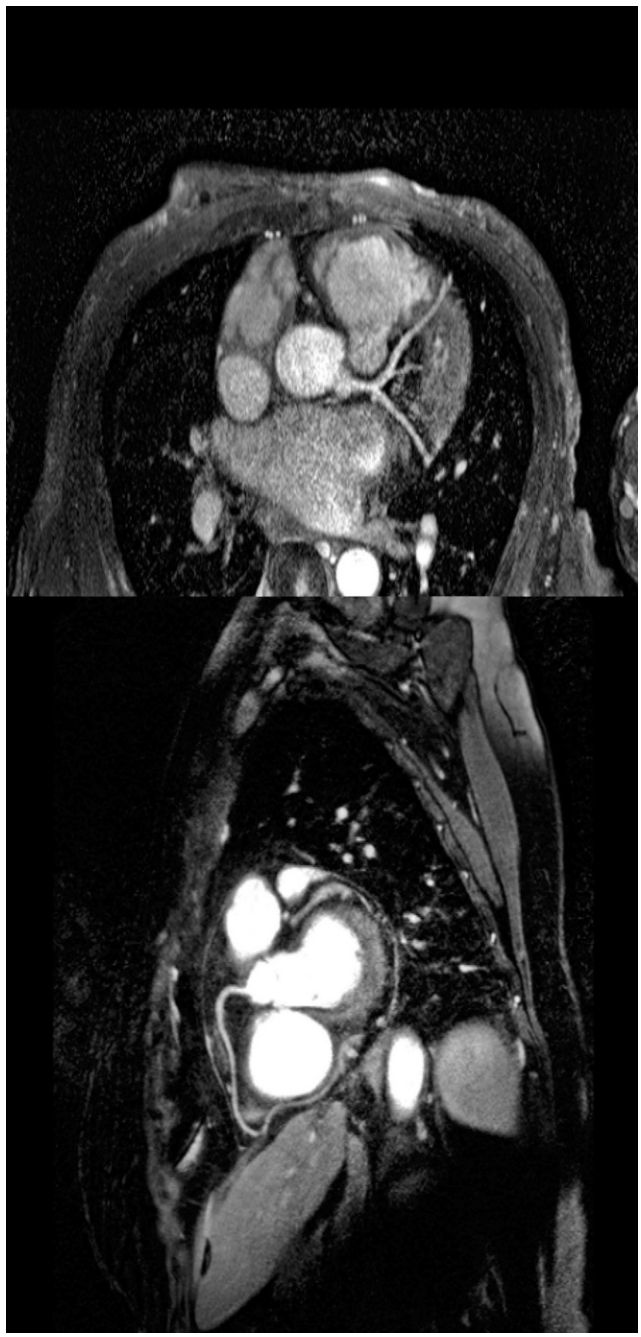

Figure 13. Case: 25-year-old female with chest pains. Cardiac magnetic resonance imaging: Bright blood images with navigation pulse. Diagnosis: Normal take-off of the left main (top) and right coronary artery (bottom).

an inherent safety advantage over x-ray techniques. The corollary is that iodine-based agents are not used for imaging and, thus, are not a concern for patients undergoing cMRI scanning. However, there are two concerns a physician must be aware of when ordering a cMRI. First, the magnetic field interacts with ferromagnetic materials (potential for movement) and electronic circuits (dysfunction or damage), and the RF may produce the theoretical heating of ferrous material.[22] Second, there is a very rare, but possible reaction to gadolinium know as nephrogenic systemic fibrosis in selected patients. These phenomena require special attention in cMRI.

Ferromagnetism does not strictly refer to iron but to any metal with magnetic properties. As a general rule, the strength of the magnetic field, the degree of ferromagnetism of the object, the mass, the location, and the presence of retentive tissues such as fibrosis, skin, sutures, or bone all contribute to the feasibility of cMRI.[21,22] For example, a hip prosthesis and a neurovascular clip may be made of similar material, but MRI with a hip implant is safe and with a cranial neurovascular clip is contra-indicated. Information about the safety of any device can be found on www.MRIsafety.com.

The safety of cMRI in patients with pacemakers (PPMs) or implantable cardiac defibrillators (ICDs) is in a period of flux. Currently, both are listed as a strong relative contraindication to cMRI scanning for multiple reasons. First, the device itself could move in the pocket and battery life could decrease. Second, the RF energy may cause inappropriate signaling to the device, which could lead to inappropriate inhibition or stimulation of the device, and the RF energy may cause heating of the tips of the lead. *A recent scientific statement by Levine et al gives an algorithmic recommendation for patients with PPMs/ICDs being evaluated for cMRI*.[23] Cardiac MRI in these patients should only be considered when a strong clinical indication is present and the benefits clearly outweigh the risks. The examination should only be performed at extremely experienced centers by physicians highly knowledgeable in MR physics and ICD/PPM technology. Full informed consent should be obtained. The patient can not be PPM-dependent, as both PPM and ICD must be turned off. The device should be interrogated prior to and after examination. Also, defibrillation threshold testing of ICDs is recommended after the study is complete. There is strong *absolute* contraindication to cMRI scanning in patients with leads unattached at either end, as this could theoretically cause a lethal laceration to a vascular structure.[23]

Another common concern for practicing physicians wishing to utilize cMRI is the presence of coronary stents, septal occluder devices, and peripheral stents. These, with the exception of the Zenith Iliac Branch Device made by Cook Medical (Bloomington, IN), are safe for patients undergoing cMRI scanning. Cardiac MRI imaging can safely be performed within hours of cardiac stent placement.[23]

Although MRI contrast agents are unrelated to the potentially nephrotoxic iodinated contrast agents of

Table. Advantages of Cardiac Magnetic Resonance Imaging

• Excellent spatial resolution.
• Quantification of pathology.
• Reproducible serial assessment of pathology.
• No acoustic window limitation.
• No ionizing radiation.

CT and fluoroscopy, gadolinium-based contrast is not without its own set of limitations. First described in 1997, nephrogenic systemic fibrosis (NSF), formerly known as nephrogenic fibrosing dermopathy, is now a known hazard for chronic kidney disease patients. As of May 2008, 215 cases have been described in a U.S. registry.[24] NSF has been observed only in patients either with acute or chronic severe renal insufficiency with glomerular filtration rate [GFR] <30 mL/min/1.73 m^2, with acute kidney injury (AKI) of any severity due to the hepatorenal syndrome, or with recent liver transplantation. Nephrogenic systemic fibrosis is characterized by skin indurations preferentially affecting the extremities, but involvement of internal organs is reported, which ultimately leads to death. A confident diagnosis can usually be reached through the combination of a clinical history, a physical examination, and the histopathologic assessment of a biopsy specimen of involved skin. The predominant mechanistic hypothesis for NSF involves the liberation of free gadolinium from its binding molecule, which is thought to trigger an inflammatory response.[24]

The data on the epidemiology of this disease are primarily limited to retrospective case series with relatively small patient populations. Nonetheless, a practice pattern of prescan screening forms and GFR calculation is pervasive in the community. For patients with a GFR <30 mL/min/1.73 m^2 who are being evaluated for cMRI, certain recommendations should be remembered. Cardiac MRI scanning with contrast administration should only be performed if the information cannot be gathered via alternative testing and the information gathered is essential to the treatment of the patient. For Stage 5 (on hemodialysis) and AKI (GFR < 30) patients, hemodialysis no later than 2 hours after gadolinium exposure should be ensured. Hemodialysis for 2 subsequent days, which can remove up to 93% of the body's gadolinium, should be entertained. For Stage 4 patients, no data support hemodialysis. Of note, there is no conclusive treatment for NSF.[24]

CONCLUSION

In conclusion, cMRI provides a tremendous amount of information through a single study (Table). It provides both anatomic and physiological information that is not available by any other single imaging modality. It has superb spatial resolution, allowing for precise quantification where approximation has been the traditional standard of care. It also provides tissue characterization vital for diagnosis and treatment. For these reasons, its role in providing enhanced diagnostic and procedural information continues to grow. Ongoing research continues to demonstrate novel clinical applications for cMRI withing branches of cardiology, including pulmonary hypertension, heart transplant, and pacemaker implantation. Given the rapid acceleration of improvement in imaging quality and the tremendous enthusiasm of the research community for bringing this tool to its full clinical potential, cMRI will undoubtedly continue to play a prominent role in providing optimal care for an increasingly broad spectrum of cardiovascular disease.

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