Journal of the American College of Cardiology
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Published by Elsevier Inc.

Vol. 44, No. 6, 2004
ISSN 0735-1097/04/$30.00
doi:10.1016/j.jacc.2004.06.033

STATE-OF-THE-ART PAPER

Cardiovascular Magnetic Resonance Imaging: Current and Emerging Applications

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Magnetic resonance (MR) imaging is gaining importance in cardiology as the newest, most complex, and rapidly emerging noninvasive test of choice for patients with a multitude of cardiovascular problems. It has long been recognized to provide an accurate and reliable means of assessing the function and anatomy of the heart and great vessels, but its emerging role as one of the dominant imaging modalities in other aspects of cardiology such as perfusion imaging, atherosclerosis imaging, and coronary artery imaging cannot be understated. As MR technology evolves, newer therapeutic applications are also being developed, including specific MR-compatible catheters for electrophysiology studies/ablation as well as interventional cardiology related procedures, which may alter the way we practice cardiology in the future. Also, MR is entering an important phase in its evolution, with an anticipated exponential growth in its current applications and through the development of newer molecular imaging applications. It is anticipated that such developments will be coupled to the utilization of molecular markers to index biologic processes to allow for their in vivo visualization. This combination of biochemical markers and imaging methodology will also usher in an era of molecular imaging during which much progress in the diagnosis and treatment of cardiovascular disease is anticipated. (J Am Coll Cardiol 2004;44:1164–71)

Magnetic resonance imaging (MRI) is of increasing importance in cardiovascular medicine. It is widely recognized to provide an accurate and reliable means of assessing function and anatomy of the heart and great vessels. Previously, however, the means to obtain magnetic resonance (MR) images of the cardiovascular system had been compromised by extremely long examination times and specialized equipment that was available only at specialized centers. With the recent development of cardiovascular MR scanners, the applications of this technique have become more widely used on a routine basis. The advantages and disadvantages of this technology are listed in Table 1. In this review, we briefly discuss the different clinical and emerging applications of cardiovascular MRI (Table 2).

ASSESSMENT OF VENTRICULAR FUNCTION

Magnetic resonance imaging, a highly accurate and reproducible non-invasive technique for measuring ejection fraction and ventricular volumes, is now considered a "gold standard" (1). Usually bright blood gradient echo sequences, obtained during a 15- to 20-s breath-hold, are used to cover the entire left ventricle (LV) with short-axis views from the mitral plane and slice thickness not exceeding 10 mm. Magnetic resonance imaging is the method of choice for longitudinal follow-up of patients undergoing therapeutic interventions (2). Also, the sample size needed to detect LV parameter changes in a clinical trial is far less than other imaging modalities, which markedly reduces the time and cost of patient care and clinical trials (3).

Regional myocardial function is best assessed using a unique MR technique called myocardial tagging (4), commonly acquired by special modulation of magnetization (5). Special modulation of magnetization is obtained by applying a radiofrequency pre-pulse perpendicular to the imaging plane. This pre-pulse induces local changes in saturation within their planes that label the heart muscle with a dark grid and enables three-dimensional analysis of cardiac rotation, strain (in the subendocardial, midwall, and subepicardial layers), displacement, and deformation of different myocardial layers during the cardiac cycle (6). The tags can be applied immediately after the R-wave on the electrocardiogram to image systolic function or in late systole to image diastolic function. Use of MR tagging methods has enabled us to demonstrate reduced intramural myocardial contraction in pressure-overload hypertrophy with preserved LV ejection fraction. In coronary artery disease, the application of MR tagging has enabled us to discern regional heterogeneity of myocardial function in the setting of ischemia, infarction, stunning, hibernation, and post-infarct remodeling (6). The use of MR tagging in cardiomyopathies is briefly discussed next.

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Manuscript received February 11, 2004; revised manuscript received May 6, 2004, accepted June 7, 2004.

Abbreviations and Acronyms

DHE = delayed hyperenhancement
HCM = hypertrophic cardiomyopathy
LV = left ventricle/ventricular
LVOT = left ventricular outflow tract
MR = magnetic resonance
MRI = magnetic resonance imaging
RV = right ventricle/ventricular

ASSESSMENT OF MYOCARDIAL VIABILITY

Contrast-enhanced MRI is rapidly evolving as a means of accurately predicting myocardial viability. On first-pass perfusion images, an area of hypoenhancement within the infarcted region, correlating with microvascular obstruction, related to "no reflow" inside the infarct zone has been described (7,8). The second enhancement pattern is noticed at 10 to 30 min after contrast injection (delayed hyperenhancement [DHE]) (Fig. 1) and can be depicted with a breath hold inversion-recovery gradient echo sequence. The DHE can be used to detect changes after acute and chronic myocardial infarction. After an acute infarct, the presence of DHE reflects myocardial necrosis and abnormal contrast molecule kinetics (9–11) within infarcts, whereas in chronic infarction, it reflects increased concentration of gadolinium non-viable, infarcted scar tissue (12). In patients with a chronic myocardial infarction, DHE can accurately locate and determine the extent and transmurality of the infarct and denote its non-viability (13,14). Further development of necrosis-specific contrast agents and refinement of MR spectroscopy to assess regional chemistry and metabolism will enhance the utility of MRI.

ASSESSMENT OF DIFFERENT CARDIOMYOPATHIES

Magnetic resonance imaging has a high degree of accuracy and reproducibility in the visualization of LV and right ventricular (RV) morphology and function (15) and is fast becoming the gold standard for in vivo identification of the phenotype of cardiomyopathies (1).

Dilated cardiomyopathy. In dilated cardiomyopathy, using gradient echo sequence, we can analyze wall thickening (16), impaired fiber shortening (17), and end-systolic wall stress (which is a very sensitive parameter of a change in LV systolic function) (18). Magnetic resonance spectroscopy has also revealed a change in phosphate metabolism in dilated cardiomyopathy (19). A ratio of phosphocreatine to adenosine triphosphate is shown to have prognostic value in dilated cardiomyopathy as it correlated with the clinical severity of heart failure and may improve during clinical recompensation (19). Contrast-enhanced T1-weighted images are also helpful in detecting changes of acute myocar-

Table 1. Advantages and Disadvantages of Magnetic Resonance Imaging

Advantages
Unparalleled resolution
Three-dimensional imaging capacity
Non-invasive
Non-toxic contrast agents
Ability to depict soft tissues
Disadvantages
Long scan times
Artifacts including motion, respiratory, cardiac motion
Incompatibility with pacemakers, defibrillators, and aneurysm clips

Table 2. Applications of Magnetic Resonance Imaging in Cardiovascular Medicine

Current clinical applications
Assessment of right and left ventricular function, volumes, and mass
Assessment of myocardial viability
Assessment of different cardiomyopathies
Dilated cardiomyopathy
Hypertrophic cardiomyopathy
Arrhythmogenic right ventricular dysplasia
Restrictive cardiomyopathy
Sarcoidosis
Amyloidosis
Hemochromatosis
Endomyocardial fibrosis
Evaluation of pericardial diseases
Evaluation of cardiac and paracardiac masses
Benign
Malignant
Evaluation of congenital heart disease including shunts
Evaluation of valvular heart diseases
Evaluation of aortic diseases
Aortic dissection
Aortic aneurysm
Congenital disorders (coarctation of aorta and Marfan's syndrome)
Evaluation of pulmonary veins
Emerging applications
Assessment of myocardial perfusion and ischemia
Atherosclerotic plaque imaging
Coronary artery angiography and vessel wall imaging
Therapeutic magnetic resonance imaging for electrophysiology and interventional procedures

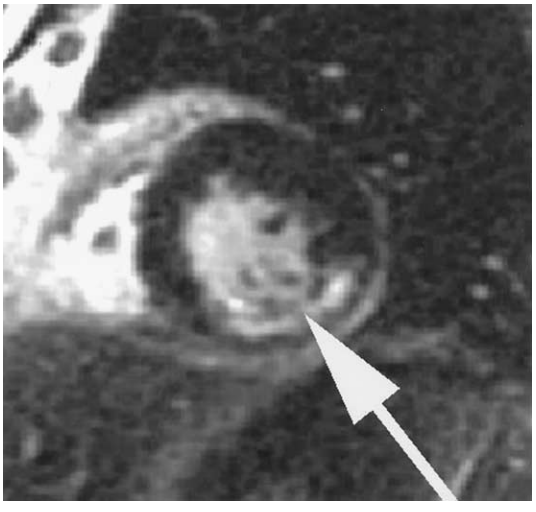

Figure 1. Short-axis image of the heart obtained 10 min after contrast injection revealing a hyperenhanced area **(arrow)** in the inferolateral left ventricular wall consistent with non-viable infarcted myocardium.

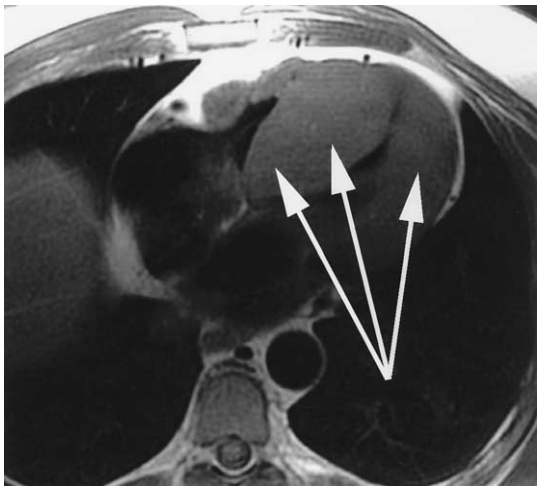

Figure 2. Long-axis view of the heart (black blood images) revealing grossly hypertrophic left ventricular wall caused by hypertrophic cardiomyopathy **(arrows).**

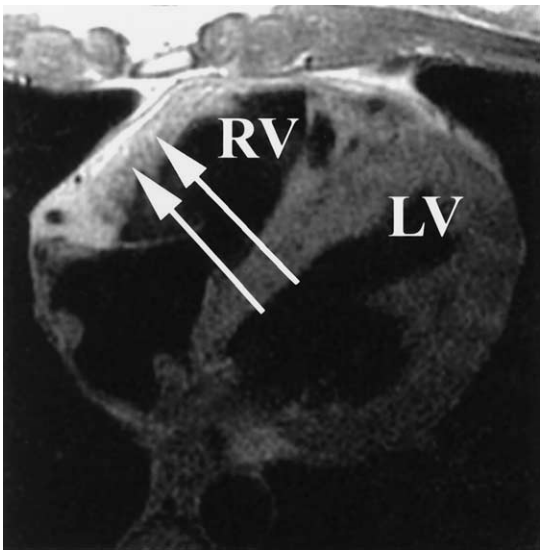

Figure 3. Black blood images of the heart showing bright signals in the right ventricular (RV) free wall **(arrow)** consistent with fatty deposits suggestive of arrhythmogenic RV dysplasia. LV = left ventricle.

ditis (20) (increased gadolinium accumulation thought to be the result of slow wash-in wash-out kinetics and diffusion into necrotic cells [9]) as well as increasing the sensitivity of endomyocardial biopsy by visualization of inflamed areas that would aid in determining a biopsy site (21). Magnetic resonance tagging reveals that depressed LV function is caused by depressed fiber and cross-fiber strain, the severity of which parallels depressed LV function, but the transmural gradients in these strains are preserved (6).

Hypertrophic cardiomyopathy. Magnetic resonance imaging can assess LV mass, regional hypertrophy patterns, and different phenotypes of the disease (e.g., apical hypertrophic cardiomyopathy [HCM] [22], degree of left ventricular outflow tract [LVOT] obstruction, systolic anterior motion of the mitral valve [23]) and can monitor postmyomectomy changes in HCM (24) (Fig. 2). Magnetic resonance spectroscopy reveals changes in the phosphate metabolism (25), whereas analysis of coronary sinus blood flow helps in determining the alterations in coronary flow reserve (26). Magnetic resonance planimetry can measure the effective LVOT area during systole and can overcome the problem of interstudy variability of the LVOT gradient, because of its independence from the hemodynamic status (27). Myocardial tagging can accurately detect a reduction in posterior rotation, reduced radial displacement of the inferoseptal myocardium, and reduced three-dimensional myocardial shortening. It can also detect the heterogeneity of regional diastolic function in the septum (related to myocardial fiber disarray) in different types of HCM, including asymmetric septal, symmetrical, and apical HCM (20). Magnetic resonance can be used to monitor patients after surgical and pharmacologic interventions (23) or alcoholic septal artery ablation (28).

Arrhythmogenic RV dysplasia. Magnetic resonance imaging is the diagnostic technique of choice for arrhythmogenic RV dysplasia (Fig. 3). Axial and short-axis views of T1-weighted spin echo images reveal fatty infiltration, thinned walls, and dysplastic trabecular structures (20). Standard gradient echo images reveal characteristic regional wall motion changes, localized early diastolic bulging, wall thinning, and saccular aneurysmal out-pouchings (29,30).

Restrictive cardiomyopathy. Primary infiltration of the myocardium by fibrosis or other tissues leads to restrictive cardiomyopathy, characterized by normal LV size and systolic function, severe diastolic dysfunction, and biatrial enlargement. The following different restrictive diseases can be effectively assessed (20).

SARCOIDOSIS. Sarcoid lesions lead to different signal intensities resulting from different stages of the disease. Some instances have reported high intensity areas in T2-weighted images, whereas other instances have reported a central low intensity area on T1- and T2-weighted imaging surrounded by a high signal ring (31). Gadolinium has also been reported to accumulate in the sarcoid lesions and is thought to be due to fibrotic non-active granulomatous nodules with inflammatory response of the surrounding tissue (32). Thus, T2-weighted followed by T1-weighted spin echo techniques in short and long axis with and without gadolinium could be useful to detect and/or exclude sarcoid granulomas.

HEMOCHROMATOSIS. Magnetic resonance imaging reveals extensive signal loss in native T1- and T2-weighted images (33) as a result of the very strong paramagnetic properties of iron. The pattern of focal signal loss in a dysfunctional myocardium associated with an abnormally "dark" liver might be sufficient to confirm the diagnosis of systemic hemochromatosis.

AMYLOIDOSIS. Magnetic resonance imaging can be useful in the detection of amyloidosis and its differentiation from HCM. A thickness of the atrial septum or the right atrial posterior wall >6 mm is fairly specific for amyloid infiltration (34). Tissue characterization in cardiac amyloidosis has not been well studied, and few data are available. In one study, there was a

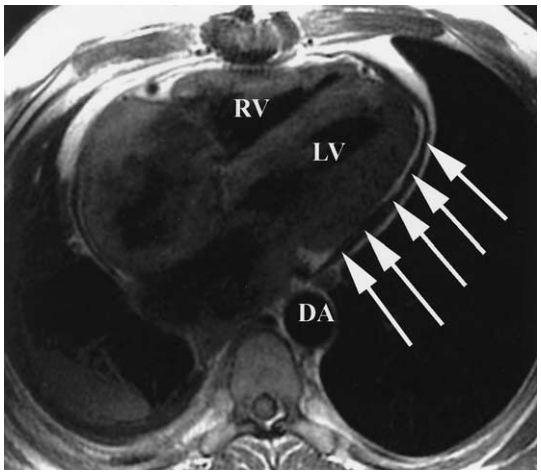

Figure 4. Black blood images of the heart in long axis revealing thickened pericardium **(arrows).** DA = descending aorta; LV = left ventricle; RV = right ventricle.

decrease in signal intensity of the amyloid infiltrated myocardium in comparison to the reference tissue (34).

ENDOMYOCARDIAL FIBROSIS. Endomyocardial fibrosis (also termed Loeffler's endocarditis) is characterized by extensive subendocardial fibrosis, apical thrombus formation, and progressive diastolic dysfunction (20). The morphologic and functional features can be well quantified by MRI. The fibrosis may be visible as a dark apical rim in bright blood prepared gradient echo sequences (35).

ASSESSMENT OF PERICARDIAL DISEASE

The T1-weighted spin echo imaging demonstrates normal pericardium as a thin band (<2 mm) of low signal, bordered by epicardial and pericardial fat, which has a high signal. A thickness of >4 mm is considered abnormal and suggestive of fibrous pericarditis (36) (Fig. 4). The use of contrast-enhanced MRI may help better delineate the pericardium in cases of effusive-constrictive pericarditis (37). Breath-hold or real-time cine gradient echo images of the ventricles and phase velocity mapping of the cardiac valves may be helpful in assessing the significance of pericardial pathology.

EVALUATION OF CARDIAC AND PARACARDIAC MASSES

Axial black blood bright blood cine MRI is excellent for delineating the morphologic details of a mass (including extent, origin, hemorrhage, vascularity, calcification, and effects on adjacent structures). Benign myxomas (the most common cardiac tumor) appear brighter on T2 weighting than myocardium, and cine images may reveal the characteristic mobility of the pedunculated tumor. Lipomas appear brighter on spin echo T1-weighted images, and the diagnosis is verified by a decrease in signal intensity using a fat pre-saturation technique. An acute thrombus appears brighter than myocardium on T1-weighted images because of an alteration in paramagnetic properties (38).

EVALUATION OF CONGENITAL HEART DISEASE

Magnetic resonance imaging plays an important role in diagnosing and serially following patients with various congenital heart diseases, complementary to echocardiography. It identifies atrial and ventricular septal defects, and phase velocity mapping at the level of the shunt allows calculation of shunt fraction (Qp/Qs ratio) (39). Using different imaging sequences including MR angiography, lesions such as anomalous pulmonary venous return, transposition of great vessels, aortic rings, truncus arteriosus, double outlet RV, tetralogy of Fallot, pulmonary atresia, and pulmonary artery stenosis can be diagnosed (40). Magnetic resonance imaging can also be used to follow up patients for effects and complications after corrective surgery (40). Magnetic resonance angiography can also be useful to diagnose venous anomalies such as persistent superior vena cava or interruption of the inferior vena cava with azygous continuation (40).

EVALUATION OF VALVULAR DISEASES

Echocardiography with color Doppler is usually the first-line imaging modality for diagnosing valvular diseases. Magnetic resonance imaging is generally reserved for use when other modalities fail or provide suboptimal information (38). Semiquantitative assessment of valvular stenosis or regurgitation can be obtained by measuring the area of signal void on gradient echo images. The duration or extent of the signal void correlates with the severity of aortic stenosis, and the total area of signal loss correlates with the severity of mitral regurgitation (41). Magnetic resonance imaging has a very high sensitivity (98%), specificity (95%), and accuracy (97%) for diagnosing aortic and mitral regurgitation (40). Phase contrast MR allows assessment of the severity of valvular stenosis (measures peak jet velocity) by calculating the valve orifice area and the transvalvular pressure gradient (38).

EVALUATION OF AORTIC DISEASES

Three-dimensional MR angiography, using a T1-weighted pulse sequence after a bolus intravenous injection of gadolinium chelate, is an accurate non-invasive imaging modality for assessment of the aorta (42) (Fig. 5). Contrast-enhanced MRI has higher sensitivity and specificity (98% and 98%, respectively) compared with computed tomography (94% and 87%, respectively) and transesophageal echocardiography (98% and 77%, respectively) in the diagnosis of aortic dissection (40). It is useful to evaluate the extent and localization of the intimal flap, associated aortic insufficiency, evidence of intrapericardial hemorrhage, relationship with branched vessels, and separation of true and false lumen (40). In cases where aortic dissection occurs without an intimal flap (intramural hematoma or as a result of aortitis), an additional delayed T1-weighted image after contrast

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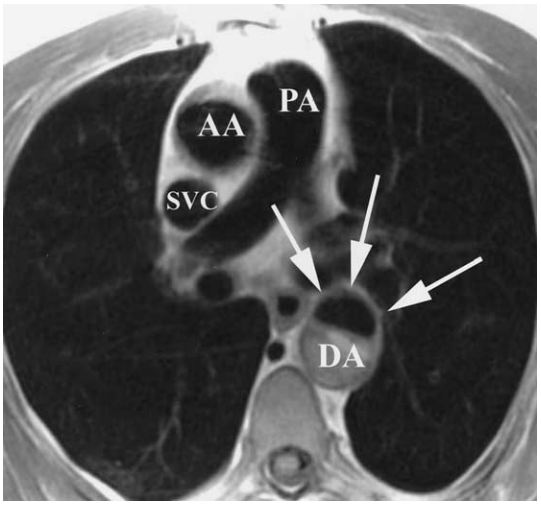

Figure 5. Black blood axial images of the chest showing a dissection **(arrow)** in the descending aorta (DA). The false lumen has a higher signal intensity owing to organized thrombus. AA = ascending aorta; PA = pulmonary artery; SVC = superior vena cava.

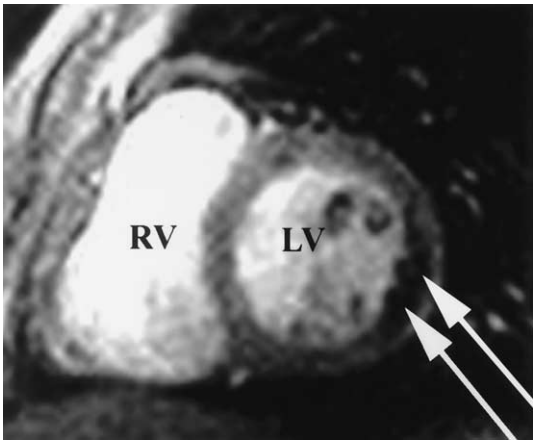

Figure 6. First-pass short-axis image of the heart obtained after injection of contrast agent revealing a hypoenhanced area in the lateral wall **(arrow)** consistent with myocardial ischemia. LV = left ventricle; RV = right ventricle.

administration is recommended. This reveals concentric thickening of the aortic wall with increased intramural signal intensity (intramural hematoma) and enhancement of the aortic wall and surrounding structures (aortitis) (41).

Magnetic resonance imaging can also be very useful in the assessment of thoracic aneurysms by demonstrating its length, site, morphology, relationship to branch vessels, and presence of a thrombus or penetrating ulcer. It can aid in the initial assessment and longitudinal follow-up (both pre- and postoperatively) of congenital aortic disorders such as Marfan syndrome and coarctation of the aorta.

EVALUATION OF THE PULMONARY VEINS

Contrast-enhanced MRI has a clinical role in evaluating pulmonary veins, to determine anomalous pulmonary venous return, and particularly as an adjunct to the radiofrequency ablation of the pulmonary vein pathways causing atrial fibrillation. Magnetic resonance imaging is useful to identify and size the pulmonary veins at baseline, and serial imaging and assessment of the size of these veins is very useful in detecting pulmonary vein stenosis, a frequent complication of the ablation procedure (43).

EVALUATION OF MYOCARDIAL PERFUSION AND ISCHEMIA

Magnetic resonance imaging is emerging as a reliable and useful tool in the assessment of regional LV perfusion (Fig. 6). After a rapid intravenous contrast injection, there is a marked signal enhancement first in the RV cavity, LV cavity, and then in the LV myocardium. Gradient echo sequences have been used for single-slice (midcavity, short-axis) perfusion MRI in humans (44,45). Recently, echo planar techniques have been employed for ultrafast multislice MRI (46,47). The peak signal intensity is related to the concentration of the contrast agent in the local tissue and is directly proportional to the coronary blood flow. Perfusion MR at rest and after infusion of pharmacologic agents (adenosine and persantine) have been compared with standard methods (angiography or radionuclide scintigraphy) and demonstrated reasonable sensitivity (67% to 83%) and specificity (75% to 100%) (48,49). Additionally, combined wall motion assessment further improved the performance of MRI to detect ischemia.

Dobutamine stress MR has also been studied as a stress testing modality. Stress induced wall motion abnormality is an early and reliable sign of myocardial ischemia. Quantitative assessment of systolic wall thickening provides better results than does the visual assessment of response to dobutamine (sensitivity of up to 91%, specificity of approximately 80%) (50,51). For high-dose dobutamine stress tests, fast techniques (echo planar imaging, turbo-gradient echo sequences, or real-time imaging) should be used in preference to conventional MR sequences as this significantly reduces scan time, improves image quality, and enables rapid detection of wall motion abnormalities (52). Because high-dose dobutamine stress MR is highly accurate and can be performed in less than 30 min, it has the potential to replace dobutamine stress echocardiography in patients with non-diagnostic or suboptimal echocardiographic image quality (52).

During stress examination using vasodilators or dobutamine, monitoring of the patient is mandatory. Continuous monitoring of heart rate, rhythm, blood pressure, pulse oximetry, and symptoms is necessary. Assessment for wall motion abnormalities is done after every dose increment of dobutamine and at peak stress after administration of adenosine/persantine (52). Currently, stress MRI precludes analysis of ST-segment, real-time display of wall motion, and it requires repeated breath holds (~15 to 16 s) throughout the study (50). This may impede communication with the patient and, if symptoms

were to arise, interfere with image acquisition (53). Finally, along with the contraindications that are identical to those for stress echocardiography or myocardial perfusion scintigraphy, specific contraindications for MR, such as pacemakers, defibrillators, and cerebral clips need to be taken into consideration.

CORONARY ARTERY IMAGING

Imaging of the coronary arteries using MR is a challenging proposition (because of the small caliber of the coronaries, tortuosity, constant cardiac/respiratory motion, and being surrounded by epicardial fat that appears bright on MRI); hence, this modality is predominantly used in research centers. In a multicenter trial evaluating coronary MR angiography, MR had a sensitivity of 100%, specificity of 85%, and accuracy of 87% for the diagnosis of coronary artery disease in patients with left main or three-vessel disease (54). With the development of more sophisticated sequences and better contrast agents, routine non-invasive MR coronary angiography might soon become a reality.

However, the role of MRI in assessing for the anomalous origin and course of coronary artery is well established. Indeed, MR techniques have shown excellent results in the definition and identification (93% to 100% of cases) of anomalous coronary arteries. Also, MRI can aid in classifying cases that were not classified or were misclassified by conventional angiography (55,56).

Unlike native coronary arteries, MR has a definite current role in the assessment of saphenous vein and internal mammary bypass grafts with a sensitivity, specificity, and accuracy in the 90% range. It is also useful in detecting saphenous vein graft aneurysms that require surgical repair. However, metallic clips, graft markers, and sternal wires may cause local artifacts (57).

MRI OF THE ATHEROSCLEROTIC PLAQUE

Magnetic resonance imaging has been used to assess the regression and tissue characterization of atherosclerotic plaques in different vascular territories, including aorta, carotid arteries, and now, coronary arteries. Atherosclerotic plaque in the aorta can be assessed volumetrically and characterized using double inversion-recovery fast echo sequences to suppress the signal from flowing blood (58,59). Studies have also been performed using transesophageal MRI to improve the signal intensity (58). Similarly, carotid arteries have been imaged, and attempts at plaque characterization have been performed (60). More recently, coronary vessel wall imaging has been attempted using black blood MRI (61). This will serve as an important tool to assess regression of the coronary plaque in the future, particularly with the advent of sophisticated pulse sequences and 3-T MR systems.

NEWER APPLICATIONS AND MOLECULAR IMAGING

As MR technology evolves, newer therapeutic applications are being developed. Preliminary work is already underway in developing newer intravascular MR contrast agents, contrast agents specific to image atherosclerotic plaque components, specific MR-compatible catheters for electrophysiology studies/ablation as well as interventional cardiology related procedures, which might alter the way we will practice cardiology in the future. It is anticipated that such developments will be coupled to the utilization of molecular markers to index biologic processes to, and allow for, their in vivo visualization. This combination of biochemical markers and imaging methodology ushers an era of molecular imaging during which much progress in the diagnosis and treatment of cardiovascular disease is anticipated.

CONCLUSIONS

Magnetic resonance imaging is the newest, most complex and rapidly emerging non-invasive test of choice for patients with a multitude of cardiovascular problems. Its emerging role as one of the dominant imaging modalities in most facets of clinical cardiology cannot be understated. It has entered an important phase in its evolution, with an anticipated exponential growth in its current applications and through the development of newer molecular imaging applications.

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REFERENCES

1. Task Force of the European Society of Cardiology, in collaboration with the Association of European Paediatric Cardiologists. The clinical role of magnetic resonance in cardiovascular disease. Eur Heart J 1998;19:19–39.
2. Doherty NE 3rd, Seelos KC, Suzuki J, et al. Application of cine nuclear magnetic resonance imaging for sequential evaluation of response to angiotensin-converting enzyme inhibitor therapy in dilated cardiomyopathy. J Am Coll Cardiol 1992;19:1294–302.
3. Semelka RC, Tomei E, Wagner S, et al. Normal left ventricular dimensions and function: interstudy reproducibility of measurements with cine MR imaging. Radiology 1990;174:763–8.
4. Zerhouni EA, Parish DM, Rogers WJ, Yang A, Shapiro EP. Human heart: tagging with MR imaging—a method for noninvasive assessment of myocardial motion. Radiology 1988;169:59–63.
5. Axel L, Dougherty L. MR imaging of motion with spatial modulation of magnetization. Radiology 1989;171:841–5.
6. Reichek N. MRI myocardial tagging. J Magn Reson Imaging 1999; 10:609–16.
7. Wu KC, Zerhouni EA, Judd RM, et al. Prognostic significance of microvascular obstruction by magnetic resonance imaging in patients with acute myocardial infarction. Circulation 1998;97:765–72.
8. Wu KC, Kim RJ, Bluemke DA, et al. Quantification and time course of microvascular obstruction by contrast-enhanced echocardiography and magnetic resonance imaging following acute myocardial infarction and reperfusion. J Am Coll Cardiol 1998;32:1756–64.
9. Lima JA, Judd RM, Bazille A, Schulman SP, Atalar E, Zerhouni EA. Regional heterogeneity of human myocardial infarcts demonstrated by

contrast-enhanced MRI: potential mechanisms. Circulation 1995;92:1117–25.
10. Judd RM, Lugo-Olivieri CH, Arai M, et al. Physiological basis of myocardial contrast enhancement in fast magnetic resonance images of 2-day-old reperfused canine infarcts. Circulation 1995;92:1902–10.
11. Kim RJ, Chen EL, Lima JA, Judd RM. Myocardial Gd-DTPA kinetics determine MRI contrast enhancement and reflect the extent and severity of myocardial injury after acute reperfused infarction. Circulation 1996;94:3318–26.
12. Rehwald WG, Fieno DS, Chen EL, Kim RJ, Judd RM. Myocardial magnetic resonance imaging contrast agent concentrations after reversible and irreversible ischemic injury. Circulation 2002;105:224–9.
13. Rochitte CE, Lima JA, Bluemke DA, et al. Magnitude and time course of microvascular obstruction and tissue injury after acute myocardial infarction. Circulation 1998;98:1006–14.
14. Kim RJ, Wu E, Rafael A, et al. The use of contrast-enhanced magnetic resonance imaging to identify reversible myocardial dysfunction. N Engl J Med 2000;343:1445–53.
15. Benjelloun H, Cranney GB, Kirk KA, Blackwell GG, Lotan CS, Pohost GM. Interstudy reproducibility of biplane cine nuclear magnetic resonance measurements of left ventricular function. Am J Cardiol 1991;67:1413–20.
16. Kasper EK, Agema WR, Hutchins GM, Deckers JW, Hare JM, Baughman KL. The causes of dilated cardiomyopathy: a clinicopathologic review of 673 consecutive patients. J Am Coll Cardiol 1994;23:586–90.
17. MacGowan GA, Shapiro EP, Azhari H, et al. Noninvasive measurement of shortening in the fiber and cross-fiber directions in the normal human left ventricle and in idiopathic dilated cardiomyopathy. Circulation 1997;96:535–41.
18. Fujita N, Duerinekx AJ, Higgins CB. Variation in left ventricular regional wall stress with cine magnetic resonance imaging: normal subjects versus dilated cardiomyopathy. Am Heart J 1993;125:1337–45.
19. Neubauer S, Krahe T, Schindler R, et al. ^{31}P magnetic resonance spectroscopy in dilated cardiomyopathy and coronary artery disease: altered cardiac high-energy phosphate metabolism in heart failure. Circulation 1992;86:1810–8.
20. Friedrich MG. Magnetic resonance imaging in cardiomyopathies. J Cardiovasc Magn Reson 2000;2:67–82.
21. Bellotti G, Bocchi EA, de Moraes AV, et al. In vivo detection of *Trypanosoma cruzi* antigens in hearts of patients with chronic Chagas' heart disease. Am Heart J 1996;131:301–7.
22. Bottini PB, Carr AA, Prisant LM, Flickinger FW, Allison JD, Gottdiener JS. Magnetic resonance imaging compared to echocardiography to assess left ventricular mass in the hypertensive patient. Am J Hypertens 1995;8:221–8.
23. White RD, Obuchowski NA, Gunawardena S, et al. Left ventricular outflow tract obstruction in hypertrophic cardiomyopathy: presurgical and postsurgical evaluation by computed tomography magnetic resonance imaging. Am J Card Imaging 1996;10:1–13.
24. Franke A, Schondube FA, Kuhl HP, et al. Quantitative assessment of the operative results after extended myectomy and surgical reconstruction of the subvalvular mitral apparatus in hypertrophic obstructive cardiomyopathy using dynamic three-dimensional transesophageal echocardiography. J Am Coll Cardiol 1998;31:1641–9.
25. Jung WI, Sieverding L, Breuer J, et al. ^{31}P NMR spectroscopy detects metabolic abnormalities in asymptomatic patients with hypertrophic cardiomyopathy. Circulation 1998;97:2536–42.
26. Kawada N, Sakuma H, Yamakado T, et al. Hypertrophic cardiomyopathy: MR measurement of coronary blood flow and vasodilator flow reserve in patients and healthy subjects. Radiology 1999;211:129–35.
27. Schulz-Menger J, Strohm O, Waigand J, Uhlich F, Dietz R, Friedrich MG. The value of magnetic resonance imaging of the left ventricular outflow tract in patients with hypertrophic obstructive cardiomyopathy after septal artery embolization. Circulation 2000;101:1764–6.
28. Suzuki J, Shimamoto R, Nishikawa J, et al. Morphological onset and early diagnosis in apical hypertrophic cardiomyopathy: a long term analysis with nuclear magnetic resonance imaging. J Am Coll Cardiol 1999;33:146–51.
29. Blake LM, Scheinman MM, Higgins CB. MR features of arrhythmogenic right ventricular dysplasia. AJR Am J Roentgenol 1994;162:809–12.
30. Ricci C, Longo R, Pagnan L, et al. Magnetic resonance imaging in right ventricular dysplasia. Am J Cardiol 1992;70:1589–95.
31. Otake S, Banno T, Ohba S, Noda M, Yamamoto M. Muscular sarcoidosis: findings at MR imaging. Radiology 1990;176:145–8.
32. Seltzer S, Mark AS, Atlas SW. CNS sarcoidosis: evaluation with contrast-enhanced MR imaging. AJNR Am J Neuroradiol 1991;12:1227–33.
33. Siegelman ES, Mitchell DG, Semelka RC. Abdominal iron deposition: metabolism, MR findings, and clinical importance. Radiology 1996;199:13–22.
34. Fattori R, Rocchi G, Celletti F, Bertaccini P, Rapezzi C, Gavelli G. Contribution of magnetic resonance imaging in the differential diagnosis of cardiac amyloidosis and symmetric hypertrophic cardiomyopathy. Am Heart J 1998;136:824–30.
35. Huong DL, Wechsler B, Papo T, et al. Endomyocardial fibrosis in Behcet's disease. Ann Rheum Dis 1997;56:205–8.
36. Masui T, Finck S, Higgins CB. Constrictive pericarditis and restrictive cardiomyopathy: evaluation with MR imaging. Radiology 1992;182:369–73.
37. Watanabe A, Hara Y, Hamada M, et al. A case of effusive-constructive pericarditis: an efficacy of GD-DTPA enhanced magnetic resonance imaging to detect a pericardial thickening. Magn Reson Imaging 1998;16:347–50.
38. Castillo E, Bluemke DA. Cardiac MR imaging. Radiol Clin North Am 2003;41:17–28.
39. Mohiaddin RH, Pennell DJ. MR blood flow measurement: clinical application in the heart and circulation. Cardiol Clin 1998;16:161–87.
40. Pohost GM, Hung L, Doyle M. Clinical use of cardiovascular magnetic resonance. Circulation 2003;108:647–53.
41. de Roos A, Reichek N, Axel L, Kressel HY. Cine MR imaging in aortic stenosis. J Comput Assist Tomogr 1989;13:421–5.
42. Vogt FM, Goyen M, Debatin JF. MR angiography of the chest. Radiol Clin North Am 2003;41:29–41.
43. Dill T, Neumann T, Ekinci O, et al. Pulmonary vein diameter reduction after radiofrequency catheter ablation for paroxysmal atrial fibrillation evaluated by contrast-enhanced three-dimensional magnetic resonance imaging. Circulation 2003;107:845–50.
44. Atkinson DJ, Burstein D, Edelman RR. First-pass cardiac perfusion: evaluation with ultrafast MR imaging. Radiology 1990;174:757–62.
45. Manning WJ, Atkinson DJ, Grossman W, Paulin S, Edelman RR. First-pass nuclear magnetic resonance imaging studies using gadolinium-DTPA in patients with coronary artery disease. J Am Coll Cardiol 1991;18:959–65.
46. Edelman RR, Li W. Contrast-enhanced echo-planar MR imaging of myocardial perfusion: preliminary study in humans. Radiology 1994;190:771–7.
47. Wendland MF, Saeed M, Masui T, Derugin N, Moseley ME, Higgins CB. Echo-planar MR imaging of normal and ischemic myocardium with gadodiamide injection. Radiology 1993;186:535–42.
48. Eichenberger AC, Schuiki E, Kochli VD, Amann FW, McKinnon GC, von Schulthess GK. Ischemic heart disease: assessment with gadolinium-enhanced ultrafast MR imaging and dipyridamole stress. J Magn Reson Imaging 1994;4:425–31.
49. Klein MA, Collier BD, Hellman RS, Bamrah VS. Detection of chronic coronary artery disease: value of pharmacologically stressed, dynamically enhanced turbo-fast low-angle shot MR images. AJR Am J Roentgenol 1993;161:257–63.
50. Nagel E, Lehmkuhl HB, Bocksch W, et al. Noninvasive diagnosis of ischemia-induced wall motion abnormalities with the use of high-dose dobutamine stress MRI: comparison with dobutamine stress echocardiography. Circulation 1999;99:763–70.
51. Pennell DJ, Underwood SR, Manzara CC, et al. Magnetic resonance imaging during dobutamine stress in coronary artery disease. Am J Cardiol 1992;70:34–40.
52. Nagel E, Lorenz C, Baer F, et al. Stress cardiovascular magnetic resonance: consensus panel report. J Cardiovasc Magn Reson 2001;3:267–81.
53. Zoghbi WA, Barasch E. Dobutamine MRI: a serious contender in pharmacological stress imaging? Circulation 1999;99:730–2.
54. Kim WY, Danias PG, Stuber M, et al. Coronary magnetic resonance

angiography for the detection of coronary stenoses. N Engl J Med 2001;345:1863–9.
55. McConnell MV, Ganz P, Selwyn AP, Li W, Edelman RR, Manning WJ. Identification of anomalous coronary arteries and their anatomic course by magnetic resonance coronary angiography. Circulation 1995;92:3158–62.
56. Post JC, van Rossum AC, Bronzwaer JG, et al. Magnetic resonance angiography of anomalous coronary arteries: a new gold standard for delineating the proximal course? Circulation 1995;92:3163–71.
57. van Rossum AC, Bedaux WL, Hofman MB. Morphologic and functional evaluation of coronary artery bypass conduits. J Magn Reson Imaging 1999;10:734–40.
58. Corti R, Fuster V, Fayad ZA, et al. Lipid lowering by simvastatin induces regression of human atherosclerotic lesions: two years' follow-up by high-resolution noninvasive magnetic resonance imaging. Circulation 2002;106:2884–7.
59. Shunk KA, Garot J, Atalar E, Lima JA. Transesophageal magnetic resonance imaging of the aortic arch and descending thoracic aorta in patients with aortic atherosclerosis. J Am Coll Cardiol 2001;37: 2031–5.
60. Yuan C, Beach KW, Smith LH Jr., Hatsukami TS. Measurement of atherosclerotic carotid plaque size in vivo using high resolution magnetic resonance imaging. Circulation 1998;98:2666–71.
61. Kim WY, Stuber M, Bornert P, Kissinger KV, Manning WJ, Botnar RM. Three-dimensional black-blood cardiac magnetic resonance coronary vessel wall imaging detects positive arterial remodeling in patients with nonsignificant coronary artery disease. Circulation 2002; 106:296–9.