REVIEW

CME CREDIT

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MRI of the heart: Promises fulfilled?

ABSTRACT

Cardiac magnetic resonance imaging (MRI) has established itself as an important noninvasive method of evaluating a wide array of cardiovascular diseases. Despite these successes, questions remain about whether cardiac MRI is the best way to evaluate patients with complex cardiac conditions in whom more traditional diagnostic techniques have been inconclusive. We review the most important current applications of MRI in heart failure, ischemic heart disease, and myocardial disease.

KEY POINTS

Cardiac MRI provides quantitative assessment of ventricular function, myocardial perfusion, viability, and shunt flow; measures valvular velocities and gradients; and assesses the pulmonary and systemic vasculature.

In patients with heart failure, cardiac MRI is now used to evaluate ventricular function, identify the cause of heart failure, and visualize ventricular thrombi.

MRI stress studies are more sensitive and specific for coronary artery disease than are traditional nuclear techniques, and they also allow for the evaluation of ventricular function, morphology, and viability.

IMPROVEMENTS IN CARDIAC magnetic resonance imaging (MRI) in the last decade have led to more sophisticated clinical applications, helping cardiac MRI fulfill its promise as a useful tool in the noninvasive assessment of cardiovascular disease.

In addition to high-resolution anatomic images, cardiac MRI provides quantitative assessment of ventricular function, myocardial perfusion, viability, shunt flow, and valvular velocities and gradients.[1,2] The pulmonary and systemic vasculature can also be assessed with contrast-enhanced magnetic resonance angiography (MRA), avoiding the use of ionizing radiation or contrast agents that are toxic to the kidney.

Yet despite these advantages, questions remain about whether cardiac MRI is the best way to evaluate patients with complex cardiac conditions in whom more traditional diagnostic techniques have been inconclusive. In this article we review the current roles and limitations of MRI in the evaluation of cardiovascular disease.

TECHNICAL ADVANCES LEAD TO NEW APPLICATIONS

How MRI works

In the strong magnetic field of an MRI scanner, some of the protons within the body align themselves with the magnetic field, much like the needle of a compass aligns with the magnetic field of the earth. MRI uses targeted radiofrequency energy, similar to that transmitted by radio broadcast towers, in certain patterns to stimulate protons within the body. As these protons relax, they emit signals that can then be measured and used to construct clinically useful images.

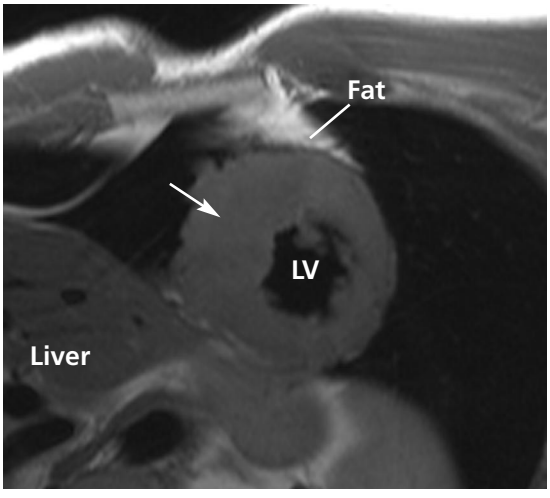

FIGURE 1. Short-axis spin-echo image in a patient with hypertrophic obstructive cardiomyopathy. Moving blood is black, whereas myocardium and fat have intermediate and high signal intensity, respectively. Note the prominent interventricular septum (arrow). The right ventricle is not well seen on this image. LV, left ventricle.

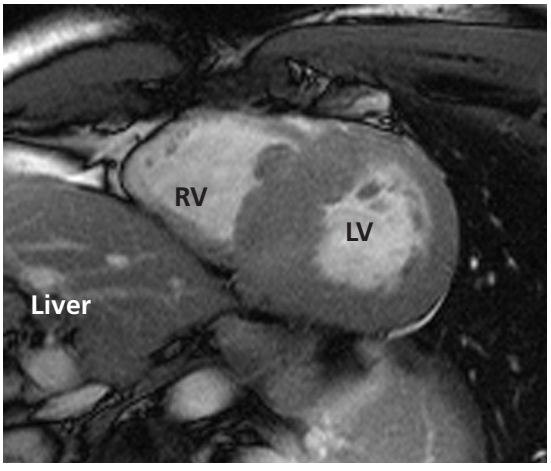

FIGURE 2. Still frame from a gradient-echo short-axis cine loop of the same patient as in FIGURE 1. Note the bright appearance of the blood pool within the left and right ventricular cavities. RV, right ventricle; LV, left ventricle.

Minimizing motion artifact

Early attempts to image the heart using MRI were hampered by motion artifact from the normal cardiac cycle and from respiration. Advances in hardware design and image acquisition have largely overcome these limitations, allowing high-resolution, detailed images of the heart in any plane.

MRI applied to angiography can be done with non-nephrotoxic contrast

Dark-blood and bright-blood imaging sequences

Currently, two common imaging sequences are used in cardiac MRI: dark-blood or "spin-echo" sequences, and bright-blood or "gradient-echo" sequences. Spin-echo sequences provide relatively high spatial resolution and are useful in the evaluation of cardiac anatomy, although images are limited to still frames (FIGURE 1). Blood within the cardiac chambers and vessels appears black, hence the name dark-blood sequences.

Gradient-echo images, in which blood appears white, are acquired faster than spin-echo sequences and provide multiple images that can displayed in a cine or movie-type format (FIGURE 2). Gradient-echo sequences are commonly used to evaluate cardiac function and blood flow.

How sequences are used

Many of the imaging sequences used in cardiac MRI are variations of these basic spin-echo and gradient-echo sequences. Various imaging sequences are often combined in one procedure to answer a particular clinical question (TABLE 1). Some common applications of these sequences for cardiovascular imaging include:

MRA, ie, MRI with a non-nephrotoxic gadolinium-based contrast agent, is useful in the evaluation of cardiovascular anatomy. This contrast agent has a very low incidence of adverse events compared with the contrast dyes used in x-ray angiography or computed tomography (CT). In cardiac imaging, MRA is often used alongside images with no contrast enhancement ("non-contrast-enhanced images") to evaluate the great vessels and to look for aortic dissection and vasculitis. MRA is the MRI technique of choice in the evaluation of renal artery stenosis and peripheral vascular disease.

Perfusion imaging: Stress perfusion MRI, similar to that done in nuclear medicine or stress echocardiography, can be used to evaluate for myocardial ischemia in patients with suspected coronary artery disease.

Delayed hyperenhancement: In areas where the myocardium is infarcted or fibrotic,

TABLE 1

Common indications for cardiac MRI

CONDITION	INDICATION
Heart failure	Evaluate ventricular function in patients in whom echocardiography is inadequate Differentiate ischemic from nonischemic cardiomyopathy Assess myocardial viability prior to revascularization Identify patients with hypertrophic or restrictive cardiomyopathy
Ischemic heart disease	Evaluate myocardial stress perfusion and viability
Aortic disease	Evaluate aneurysmal dilatation, dissection, or vasculitis of the aorta
Pericardial disease	Evaluate for constrictive pericarditis in patients with right-sided heart failure Evaluate the pericardium and myocardium in patients with suspected pericarditis or perimyocarditis
Cardiac tumors	Distinguish tumor from thrombus Make the diagnosis and facilitate planning of surgical therapy
Congenital heart disease	Evaluate valvular and ventricular function Measure shunt flow Evaluate the pulmonary and systemic vasculature Identify residue or sequelae of surgically palliated congenital heart disease

"wash-in" and "wash-out" of MRI contrast agents are delayed. Such damaged areas show up as bright or "hyperenhanced" areas of myocardium when "delayed" images are taken, ie, typically 10 to 20 minutes after injection of gadolinium contrast (FIGURE 3). Patterns of hyperenhancement can indicate myocardial scarring or fibrosis due to ischemic heart disease, hypertrophic cardiomyopathy, and infiltrative disorders.

HEART FAILURE

While the diagnosis of heart failure due to systolic dysfunction can be easily made with transthoracic echocardiography, MRI can provide a comprehensive evaluation of cardiac function, myocardial perfusion under conditions of stress, and myocardial viability. MRI has been shown to reliably discriminate between ischemic and nonischemic causes of cardiomyopathy, and it remains the gold standard technique for the evaluation of left and right ventricular volumes, mass, ejection fraction, and viability.[3,4] Evaluation of ventricular function, identification of the cause of heart failure, and visualization of ventricular thrombi are common reasons for referring patients with heart failure for cardiac MRI (FIGURE 4).

In heart failure, MRI evaluates cardiac function and myocardial perfusion and viability

EVALUATION OF MYOCARDIAL DISEASE

Intrinsic disorders of the myocardium can lead to hypertrophic or restrictive cardiomyopathies that can often be diagnosed by cardiac MRI.

Hypertrophic cardiomyopathy

Hypertrophic cardiomyopathy is marked by significant myocardial hypertrophy without an identifiable cause, often with an associated obstruction of the left ventricular outflow tract. Although hypertrophic cardiomyopathy can usually be diagnosed by echocardiography, cardiac MRI has been shown to identify this condition when it is missed by echocardiography, due to MRI's superior ability to quantify regional left ventricular wall thickness.[5]

Standard spin-echo and cine gradient-echo sequences can show asymmetric left ventricular systolic wall-thickening, subaortic poststenotic flow abnormality due to systolic anterior motion of the anterior mitral leaflet, related mitral regurgitation, and postsurgical

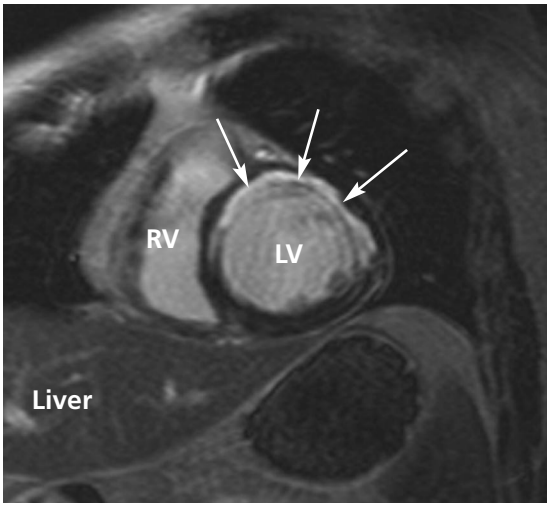

FIGURE 3. Delayed hyperenhancement short-axis image in a patient with coronary artery disease. Note the bright, hyperenhanced areas along the anterior and anterolateral walls (arrows) of the left ventricle, which represent scar. RV, right ventricle; LV, left ventricle.

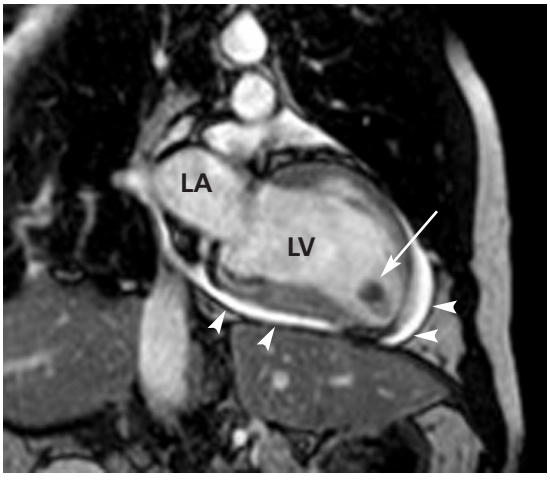

FIGURE 4. Two-chamber gradient-echo image of a patient with a prior anterior myocardial infarction. Cine images show severely reduced left ventricular systolic function and anterior hypokinesis. Note the presence of an apical thrombus (arrow) and a small pericardial effusion (white arrowheads).

changes after myectomy. In addition, delayed hyperenhancement images show a distinct pattern of hyperenhancement that spares the subendocardium in about 80% of patients, typically in the hypertrophied regions of the left ventricle. Patients with these findings have an increased risk of sudden cardiac death and may benefit from placement of a defibrillator. Such findings help to distinguish hypertrophic cardiomyopathy from other more benign conditions such as the physiologic hypertrophy of athletic heart.

Areas of hyperenhancement on delayed imaging can indicate myocardial scarring or fibrosis

Infiltrative disorders

Infiltrative disorders such as amyloidosis and sarcoidosis, although uncommon, lead to restrictive cardiomyopathy and are associated with significant morbidity and mortality. Cardiac MRI, particularly delayed hyperenhancement imaging, offers a useful and noninvasive means of evaluating patients who may have these conditions.

In amyloidosis, deposition of the amyloid protein leads to thickening of the left and right ventricular myocardium, with occasional involvement of the atrial walls and atrioventricular valves. Systolic function is usually preserved or mildly impaired, although abnormal diastolic relaxation is evident. Delayed hyperenhancement images show a distinct pattern of hyperenhancement involving most of the left and occasionally the right ventricular myocardium (FIGURE 5). Such hyperenhancement may be predominantly subendocardial, but the diffuse pattern of myocardial hyperenhancement distinguishes amyloidosis from myocardial infarction.

In comparison, patients with sarcoidosis have focal, patchy, bright areas in a noncoronary distribution on delayed hyperenhancement images. These areas correspond with foci of noncaseating granulomas that are the typical histologic findings of sarcoidosis. Cine MRI images in patients with cardiac sarcoidosis may show normal or impaired left ventricular systolic function, often with regional wall-motion abnormalities, depending on the degree of sarcoid involvement of the heart.

Arrhythmogenic right ventricular dysplasia

Arrhythmogenic right ventricular dysplasia is an uncommon but serious disorder marked by fibrosis and fatty replacement of the right ventricle, progressive right ventricular failure and enlargement, and an increased risk of sudden cardiac death due to ventricular tachycardia. Cardiac MRI has been used to

support the diagnosis by showing right ventricular enlargement or decreased right ventricular dysfunction or both, often with thinning or bulging of the right ventricular free wall.[6] Delayed hyperenhancement images show abnormal enhancement of the right ventricular free wall, indicating fibro-fatty replacement in those regions.[7] Cardiac MRI can also be used as a screening tool to identify preclinical disease in family members of patients with this condition.

Viability assessment

In patients with ischemic cardiomyopathy, the ability of cardiac MRI to distinguish viable from nonviable myocardium can help determine if the patient should undergo revascularization: patients with viable myocardium are more likely to have an increased left ventricular ejection fraction and improved survival after revascularization.[8] The extent of transmural hyperenhancement on delayed hyperenhancement images predicts improvement in both myocardial contractility and survival after coronary revascularization in patients with ischemic cardiomyopathy. In such patients, a larger degree of left ventricular hyperenhancement suggests a greater burden of nonviable myocardium.[9,10]

OTHER APPLICATIONS OF CARDIAC MRI

MRI stress testing

MRI stress testing is a way to evaluate for myocardial ischemia in patients with suspected coronary artery disease. A bolus of contrast agent is injected, and MRI follows the first pass of the contrast agent through the myocardium and provides a map of myocardial blood-flow patterns, including areas of ischemia. The test is done with the patient at rest and under chemical stress.

Dobutamine stress MRI can also be performed and is evaluated in a manner similar to that of stress echocardiography.

MRI stress studies are more sensitive and specific for coronary artery disease than traditional nuclear techniques such as single-photon emission CT, and they also allow for the evaluation of ventricular function, morphology, and viability.[11]

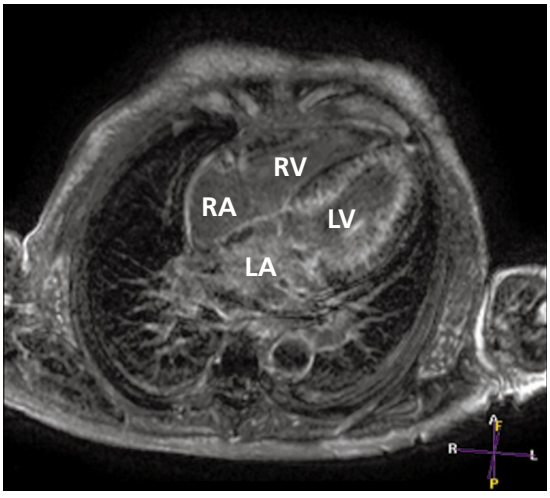

FIGURE 5. Four-chamber delayed hyperenhancement image in a patient with amyloidosis. The diffuse pattern of hyperenhancement in the left ventricle is characteristic of amyloidosis and distinguishes this condition from other causes of hyperenhancement, such as ischemic heart disease, hypertrophic cardiomyopathy, and sarcoidosis. RA, right atrium; RV, right ventricle; LA, left atrium; LV, left ventricle.

Evaluation of pericardial disease

Increased pericardial thickness, pericardial effusions, and abnormal hyperenhancement of the pericardium can be seen in patients with constrictive or inflammatory pericarditis. Characteristic MRI findings that are more specific for constrictive pericarditis include a diastolic bounce of the interventricular septum; tubular or cone-shaped narrowing of one or both ventricles, with or without enlargement of the atria; systemic venous enlargement; pleural effusions; and tethering of the pericardium to the epicardial surface.[12]

Evaluation of the aorta

Like CT, MRI permits visualization of the entire thoracic and abdominal aorta, including major branch vessels. Both techniques are useful for preoperative planning and postoperative follow-up of patients with dissections or aneurysms of the thoracic or abdominal aorta.

Whereas CT is preferred to MRI in the urgent evaluation of patients with suspected aortic dissection, MRI is better suited for long-term follow-up in some patients because

MRI stress testing is more sensitive and specific for CAD than are nuclear techniques

TABLE 2

Contraindications to magnetic resonance imaging

CONTRAINDICATIONS	CONCERNS
Absolute contraindications	
Cerebral aneurysm clip	May become displaced by the strong external magnetic field of the scanner, causing severe local injury. Aneurysm clips that are nonferromagnetic or weakly ferromagnetic are safe to image
Implanted device: neural stimulator, cochlear implant, insulin or other drug pump	Most implantable devices employ a strong internal magnet or use electronic circuitry that can be damaged by the strong external magnetic field of the scanner
Cardiac pacemaker, defibrillator	Pacemakers and defibrillators can malfunction as a result of MRI. Small studies suggest that some patients who are considered not "pacer-dependent" can undergo MRI, although the device must be checked and may have to be reprogrammed. MRI-compatible devices are in development
Foreign body: ocular foreign body, metal shrapnel, bullet fragment	Metallic foreign objects within the body can become displaced by the strong external magnetic field, causing severe local tissue injury
Temporary pacemaker wires, pulmonary artery catheters	Contain metallic clips that may become heated during MRI, causing local tissue damage
Relative contraindications	
Hearing aids	Same concerns as for cochlear implants; must be removed before patient enters the scanner
Pregnancy	Considerable evidence suggests that exposure to MRI is safe. However, exposure should be avoided during the first trimester, particularly when contrast agents are used
Claustrophobia	Some patients may experience claustrophobia while in the confines of the MRI scanner Oral anxiolytics such as alprazolam may help

it does not use ionizing radiation or nephrotoxic contrast agents.

Compared with transesophageal echocardiography, MRI and CT have a similar sensitivity for detection (98%–100%), but MRI has a superior specificity (98%–100% vs 77%–90%) for the diagnosis of aortic dissection. Inflammatory diseases of the aorta, such as Takayasu arteritis, can be diagnosed with MRI by the appearance of increased smooth thickening of the aortic wall, with an associated increase in signal on T2-weighted images suggestive of localized edema and inflammation.

Evaluation of thrombi and masses

Like CT, MRI plays an important role in the evaluation of patients with masses in the cardiovascular system, not only in making the primary diagnosis, but also in planning surgical therapy.[13] MRI provides excellent contrast resolution of soft tissues, permitting better depiction of the morphologic details of a mass, including its extent, site of origin, and secondary effects on adjacent structures. MRI's wide field of view enables it to identify involvement of the paracardiac regions of the lung and mediastinum—an important distinction in differentiating between benign and malignant tumors. Finally, perfusion with MRI contrast agents can define the vascularity of a mass and distinguish tumors from cardiac thrombi.

Congenital heart disease

Although echocardiography remains the primary tool for evaluation of congenital heart disease in children and adults, it has significant limitations if the patient's anatomy provides poor acoustic windows, hindering the evaluation of the pulmonary and systemic vasculature. In these patients, MRI is an excellent option to quantify ventricular size and

function, to evaluate valvular regurgitation, to quantify the left-to-right shunting, and evaluate the extracardiac vasculature.[14]

Complications or sequelae of surgically palliated congenital heart disease, such as recoarctation in surgically corrected coarctation of the aorta, can be easily evaluated using a combination of MRI and MRA.

LIMITATIONS OF CARDIAC MRI

Despite proving itself versatile and effective, cardiac MRI has important limitations.

The electromagnetic forces created by the MRI scanner can induce significant thermal and nonthermal effects, and a number of absolute contraindications (**TABLE 2**) must be identified and resolved before the patient enters the scanner.

Nonferromagnetic metallic devices such as mechanical heart valves, sternal wires, and retained pacing wires after cardiac surgery are safe to image, although they often cause image artifact. Internal orthopedic prostheses (eg, artificial hip joints) are also safe to image.

Critical to the success of cardiac MRI is the ability of the patient to remain still during the procedure: movement during image acquisition creates artifacts that degrade the quality of the images. Patients unable to remain still may require oral or intravenous sedation. Also, multiple breath-holds of 10 to 15 seconds are often called for in adults to limit cardiac motion due to respiration. Children and adult patients who are unable to hold their breath can still be imaged successfully, although acquisition times are often increased to preserve image quality. Arrhythmias cause image degradation and make quantification of flow unreliable.

Direct input by the interpreting physician is often required during image acquisition for complicated disease conditions such as cardiac masses or congenital heart disease.

MRI scanners are not portable, so patients must be stable enough to get to or be transported to the MRI facility. Also, acquisition times can vary between 15 and 60 minutes, making imaging of unstable patients difficult.

Limitations to the widespread use of cardiac MRI include limited availability of the MRI equipment and of the technical expertise to operate it. This will become less of an issue as opportunities increase for physicians to acquire specialized training in cardiac MRI.

EMERGING APPLICATIONS

Several exciting applications of cardiac MRI are in development, including coronary MRA and imaging of atherosclerotic plaque, and contrast agents are being developed for use in specific diseases.[15,16] Recent advances in scanner technology and acquisition techniques allow more detailed and accurate assessment of the coronary arteries—without the use of ionizing radiation or nephrotoxic contrast agents, as is the case with cardiac CT. Newer therapeutic applications are also being developed that include MRI-compatible catheters for electrophysiology studies and ablation, and interventional cardiology procedures, which may change the way interventional cardiology is practiced in the future.

MRI is contraindicated in patients with pacemakers, aneurysm clips, insulin pumps

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