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Evolving cardiovascular applications for magnetic resonance imaging

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■ ABSTRACT

Improvements in magnetic resonance imaging (MRI) have increased its value in existing cardiovascular applications and opened the door to new uses. The image quality and spatial resolution of cardiovascular MRI is better than that of most other noninvasive imaging procedures. In addition, MRI can measure and map biochemical markers diminished by ischemic damage.

MRI gives information about cardiac anatomy, function, perfusion, and metabolism

MAGNETIC RESONANCE IMAGING (MRI) has improved extraordinarily over the last 10 years and is finding new applications in cardiovascular medicine. These advances will likely alter the way clinicians use MRI in the coming years. New research is showing that MRI is in some ways superior to standard imaging techniques in cardiology and that it can provide additional information not only about anatomy but also about myocardial function, perfusion, and metabolism.

■ CONVENTIONAL USES FOR CARDIOVASCULAR MRI

Current clinical applications of MRI are primarily to detect aortic disease, assess congenital heart disease, and study pericardial structure, as well as left ventricular structure and function.

Detecting aortic dissections and aneurysms

Cardiovascular MRI has been used to assess aortic aneurysms and dissections and can provide detailed, multiplanar, quantitative, anatomic information.[1]

A German study[2] of patients presenting with suspected thoracic aortic dissection compared four noninvasive imaging tests: MRI, contrast-enhanced computed tomography, transthoracic echocardiography, and transesophageal echocardiography. A subset of 47 patients underwent all four noninvasive tests. Dissection was later independently verified by surgery, autopsy, or contrast angiography.

MRI did well, with a sensitivity and specificity of 98% (TABLE 1). In addition, MRI was as sensitive as computed tomography and transesophageal echocardiography in identifying thrombus formation throughout the entire thoracic aorta. The investigators concluded that performing MRI in all hemodynamically stable patients is the optimal approach to detecting dissection in the thoracic aorta. They recommended transesophageal echocardiography for patients who are hemodynamically unstable.

Another significant advantage of MRI over several noninvasive imaging studies for detecting thoracic aortic disease is its ability to image the branch vessels. MR angiography enhances the detection of branch vessel stenosis, intimal flaps, and communications to the false lumen.[3]

Assessing left ventricular structure and function

Cardiovascular MRI is increasingly being used to assess ventricular structure and function in the clinic and in clinical trials.[4] The intrinsic three-dimensional nature of MRI obviates geometric assumptions necessary to calculate ventricular mass or ejection fraction with conventional echocardiography. This, combined with cardiovascular MRI's high spatial resolu-

tion and tissue contrast, enables the most precise measures of human myocardial mass, chamber dimensions, and ventricular function available today, even in the settings of ventricular remodeling and heart failure.[5] Cardiovascular MRI can also provide unique information about regional heart function that cannot be obtained by any other noninvasive technique. For example the use and detection of tissue "tagging" with MRI permits a unique assessment of transmural wall motion throughout the cardiac cycle.[6,7]

Assessing congenital heart disease

The ability of cardiovascular MRI to characterize the size, geometry, and relationships between cardiac chambers and major vessels has quickly made it a very powerful technique for assessing congenital heart disease and its consequences in children and adults.[8,9]

■ TECHNICAL ADVANCES IN MRI

Technical advances in MRI have increased its cardiovascular usefulness considerably. These include increased imaging speed, sophisticated respiratory and cardiac gating techniques, and phased-array detection coils.

In the mid-1980s, cardiovascular MRI primarily used spin-echo techniques that often took 7 to 15 minutes to produce a series of images. As a result, an hour's worth of scanning yielded only a limited set of images of several cardiac orientations. With the development of gradient-recalled imaging, which can be done in 15 to 30 seconds, scan times became short enough for patients to hold their breath during image acquisition and thus reduce the degradation caused by respiratory motion. Today, echo-planar imaging and several other new rapid-imaging techniques can acquire images in less than 50 ms and permit real-time acquisition and display rates approaching 15 frames per second.

Combining multiple MR detector surface coils into groups called "phased arrays" has enabled studies of larger fields of view and improved sensitivity, which has benefited both vascular and cardiac MRI. Techniques to suppress the signals from certain chemicals, such as those from lipids, have enabled and enhanced the visualization of the coronary

arteries that are normally surrounded by fat.

■ ASSESSING CORONARY ANATOMY

As a result of these and other developments, MRI can be used to noninvasively image the location, course, and caliber of the proximal coronary arteries (FIGURE 1).

Manning et al[10,11] developed some noninvasive MR approaches to study the coronary arteries and were the first to compare noninvasive MR angiography of the native coronary arteries with conventional coronary angiography. The ability to detect significant coronary stenoses by MRI varies among groups today, and thus this still rapidly evolving technique is not yet established as a routine method for detecting or quantifying coronary stenoses.[1]

Although MRI can image the proximal vessels in most subjects, its spatial resolution and ability to identify small, distal branch vessels still significantly lags behind that of conventional angiography. Coronary MR angiography is better established for defining the course of anomalous coronary arteries. MRI and MR angiography are more promising for assessing the patency of coronary grafts than for assessing native vessels because the former are larger. Studies suggest that the sensitivity and specificity of these techniques for detecting significant stenosis typically range between 75% and 98%.[1] An especially exciting area of new research is using black-blood MR (ie, in which the blood is displayed as black rather than white) to study not just the vessel lumen but the coronary wall and atherosclerotic disease.[12]

MRI may be as effective as angiography in measuring coronary flow

MRI can image the proximal coronary arteries noninvasively
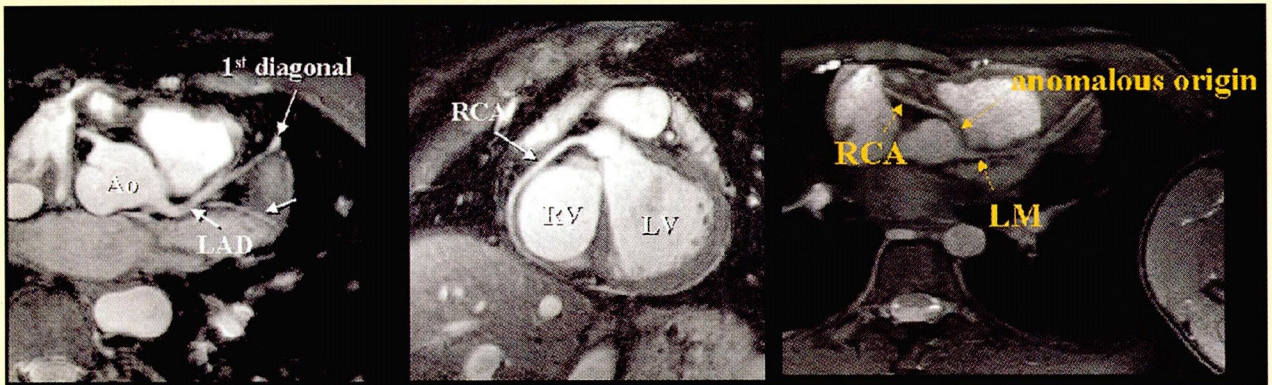
FIGURE 1. Coronary magnetic resonance imaging (MRI) showing the left (**left**) and right (**center**) coronary systems in a normal subject, as well as an anomalous origin of a right coronary artery (RCA) from the left main (LM) in another patient (**right**). AO: aorta; LAD: left anterior descending; LV: left ventricle; RV: right ventricle.

SOURCE: WARREN J. MANNING, MD, BETH ISRAEL/DEACONESS HOSPITAL AND THE HARVARD MEDICAL SCHOOL.

■ ASSESSING CARDIAC PERFUSION

Most MRI studies of perfusion are performed using intravenous gadolinium-based (Gd) contrast materials. Unlike x-ray contrast agents, these contrast agents are not nephrotoxic and are typically injected in volumes of 10 to 20 mL.

Fundamentally, there are two types of studies with contrast agents: first-pass studies and steady-state perfusion studies. In the first case, images are rapidly acquired before and during Gd contrast injection, and the signal intensity of the right ventricle, left ventricle, and myocardium sequentially increase as the contrast agent appears. Decreased perfusion from ischemic heart disease results in a delay or reduction in the increase in myocardial signal intensity shortly after contrast administration.[13]

The other approach is to collect detailed MR images at least 10 minutes after Gd injection: changes in steady-state enhancement have been related to severe perfusion abnormalities and infarction.[14] This steady-state Gd-MRI approach probably provides the best measure of infarct size in humans today.

■ ASSESSING WALL MOTION

MRI stress testing of cardiac mechanical function and metabolism can be used to assess for coronary disease.

Dobutamine MRI as a test of function is especially appealing in patients with poor-quality echocardiographic studies. Hundley et al[15] studied 153 patients in whom it was not possible to obtain a high-quality echocardiographic study—a relatively common situation. The patients underwent dobutamine-atropine MRI for the assessment of regional wall motion. The investigators developed software that allows multiple short-axis and long-axis MRI views of the heart at each stage of the test and dose of dobutamine. In this way, they were able to compare function at different doses and terminate the test when wall motion abnormalities developed. The sensitivity and specificity of MRI for identifying luminal narrowings greater than 50% by quantitative angiography was more than 83%. Among the 103 patients with negative MRI findings, the cardiovascular event-free survival rate was 97%.

■ DETECTING MYOCARDIAL ISCHEMIA WITH MR SPECTROSCOPY

The heart is one of the most metabolically active organs in the body. In looking for manifestations of ischemia, physicians typically use ST-segment changes on the electrocardiogram or contractile changes on the echocardiogram or ventriculogram. However, the pri-

MRI displays branch vessels in exquisite detail

mary pathophysiologic consequence of ischemia is altered metabolism, which in turn leads to the secondary electrical and mechanical abnormalities.

Significant progress has been made in developing techniques to evaluate the biochemistry of the human heart with clinical MR systems. With MR spectroscopy one can quantify and map several critical metabolites and ions in the heart, including adenosine triphosphate (ATP), creatine phosphate (PCr), total creatine (CR), and sodium 23.

Detecting inducible ischemia with phosphorus 31 MR spectroscopy

Phosphorus 31 (^{31}P) MR spectroscopy can noninvasively detect and quantify the naturally occurring high-energy phosphate compounds that are essential for viability and for fueling myocardial contraction. In experimental settings, one of the earliest biochemical changes of severe ischemia is a decline in the myocardial PCr/ATP ratio.

To determine whether ischemic metabolic changes can be detected by ^{31}P MR spectroscopy in people, we studied 16 patients with coronary heart disease, 9 patients with nonischemic heart disease, and 9 age-matched normal subjects using a clinical 1.5 T MR scanner before, during, and after handgrip exercise.[16] The mean PCr/ATP ratio declined significantly during exercise in subjects with coronary disease but not in normal subjects.

These results were the first to demonstrate transient, stress-induced changes in human cardiac energy metabolism indicative of ischemia and have been reproduced by others.[17] Stress-induced metabolic changes resolve after revascularization. Thus, ^{31}P MR stress-testing is a unique, novel, and potentially important method for assessing the presence, severity, and treatment of myocardial ischemia in humans.

Detecting irreversible myocardial injury with hydrogen 1 spectroscopy

Total creatine (phosphorylated plus nonphosphorylated) is important for muscle energetics and is lost from myocytes following irreversible ischemic injury.

In 1998 we described a method for measuring the total creatine content in heart muscle with hydrogen 1 (^{1}H) MR spectroscopy. We reported a significant 50% to 70% decline in cardiac creatine in nonviable infarcted regions of chronic MI patients as compared with normal subjects.[18]

The ^{1}H MR approach provides better spatial resolution than the ^{31}P MR approach. This may provide a metabolic method for detecting myocardial viability with cardiovascular MR, like PET scanning, but without injected radioactive isotopes or the costs of a PET scanner or cyclotron. These metabolic studies could be part of a cardiovascular MRI study that also evaluates cardiac function, perfusion, and coronary anatomy.

Imaging the consequences of ischemic injury with sodium 23 MRI

The sodium concentration inside cardiac cells (approximately 10–20 mM) is normally much lower than that in the serum (approximately 140 mM). However, myocardial sodium increases dramatically following severe ischemia with reperfusion.

Sodium 23 (^{23}Na) MRI can generate images of the naturally abundant sodium in tissues without injection of tracers or contrast agents. Sodium 23 MRI can be obtained on clinical 1.5 T MR scanners and can detect significant increases in cardiac sodium following infarction with reperfusion.[19]

■ INVASIVE CARDIAC MRI

A long-recognized advantage of MRI for the cardiovascular system is its noninvasive nature. However, the imaging advantages of MRI technology may someday be used to enhance some interventional procedures, while modifications of intravascular catheters may be used to generate higher-quality MRI images. Specifically, MRI is being tested as a research tool in electrophysiology procedures and may better identify catheter position and permit imaging of radiofrequency injury at the time of ablation.[20] Likewise, intravascular catheters can be modified to become MRI receiver coils and thereby provide the best images to date of vessel wall morphology and atherosclerotic plaque geometry and composition.[21,22]

MRI should help when patients cannot have stress testing or angiography

In summary, cardiovascular MRI has several current clinical applications and rapidly evolving growth in other areas critical for the assessment and management of clinical heart disease.

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