Cardiovascular imaging in the new millennium

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Magnetic resonance imaging is ideally suited for visualizing the cardiovascular system by providing images with high spatial and temporal resolution. These images are acquired in the absence of ionizing radiation, in any tomographic plane, and without interference from surrounding bone or soft tissue. Magnetic resonance imaging can be used to assess cardiac morphology, function, and valvular disease and to evaluate the anatomy of the great vessels and peripheral vasculature. Eventually, it may be possible to perform myocardial perfusion studies and to image the coronary arteries noninvasively. This review addresses the current clinical use of magnetic resonance imaging in cardiovascular medicine and briefly discusses future applications.

Cardiovascular disease remains the leading cause of mortality in the USA, accounting for 40% of all deaths. The annual cost for diagnosing and treating these diseases is staggering, with some estimates as high as $250 billion. Therefore, the health care system would benefit from an accurate means of imaging the cardiovascular system. These benefits include not only simply making a diagnosis or demonstrating the effects of treatment or preventive measures, but also determining the risk for future cardiac events, predicting survival, providing insight into physiology and pathology, and perhaps even decreasing the length of hospitalizations or minimizing the need for more expensive invasive testing.

MAGNETIC RESONANCE IMAGING

Magnetic resonance imaging (MRI), a noninvasive method that is ideally suited for visualizing the cardiovascular system, provides images that have high spatial and temporal resolution. These images are acquired in any tomographic plane, without ionizing radiation or interference from surrounding bone or soft tissue.

For routine clinical applications, image acquisition is based on observing the interaction or behavior of hydrogen nuclei, the magnetic field, and radiofrequency energy. Three basic steps are necessary for imaging. First, the patient is placed in the magnetic field, and hydrogen nuclei become aligned with the field. Second, radiofrequency energy is momentarily applied to the system to perturb the aligned nuclei. Finally, a radiofrequency signal is received as the perturbed nuclei return to equilibrium. The received signal is transformed (using Fourier methods) into image data.

Unlike ionizing radiation, magnetic fields and radiofrequency energy do not damage DNA. The imaging procedure is safe for the patient because no known harmful biologic effects have been demonstrated at field strengths of currently available commercial scanners. Nevertheless, certain
metallic objects and devices can interact with the magnetic field. Contraindications to MRI include intracranial aneurysmal or hemostatic clips, pacemakers or implantable defibrillators, pre-6000 Starr-Edwards mitral valve prostheses, Poppen-Blaylock carotid clamps, McGee stapes piston implants, or any metal located near a vital structure (for example, a metal splinter in the eye). Patients with sternal wires or stents used with percutaneous transluminal coronary angioplasty can be imaged safely.

A pulse sequence is a series of gradient and radiofrequency pulses produced by the scanner to acquire image data. The 2 primary sequences used in cardiac imaging are the spin-echo and gradient-echo sequences (Figure 1). The spin-echo, or dark blood, sequence provides excellent spatial resolution and is used to study anatomy and morphology. The gradient-echo, or bright blood, sequence samples multiple data points during the cardiac cycle. Because there is intrinsic contrast between flowing blood and static tissue, no contrast agents are required. The resulting gradient-echo images can be displayed in a continuous loop of ventricular contraction and relaxation, so-called cine-MRI, to assess regional and global ventricular function.

APPLICATIONS

Cardiac function and morphology

Magnetic resonance imaging is unique in its ability to image in multiple planes (or slices). In fact, the operator may select any oblique plane. Multiple slices in any orientation will ensure that the entire structure is examined. Common orientations used in MRI of the heart include the vertical long axis (so-called 2-chamber view), horizontal axis (so-called 4-chamber view), and short axis (see Figure 1). From these standard views, cardiac chamber sizes and volumes can be measured and calculated. Wall thickness can be measured to determine myocardial mass. Unlike other imaging modalities, MRI can provide accurate information on the right ventricle without making any geometric assumptions. Magnetic resonance imaging is invaluable in visualizing complex congenital heart disease. Venoorarterial, atrioventricular, and ventriculoarterial connections are readily identified, as are chamber morphology, position, and relation to other visceral organs and great vessels. Magnetic resonance imaging can demonstrate the location, extent, and attachment of intracardiac and paracardiac masses. Generalities regarding tissue composition can be made based on the signal intensity and homogeneity, because there are different relaxation properties between normal and diseased tissue. In a similar manner, MRI can help elucidate infiltrative processes such as hemochromatosis, amyloidosis, and fatty replacement of myocardium in right ventricular dysplasia.

Ventricular function

Global and regional ventricular function can be measured from cine-MRI. The ejection fraction is calculated from tomographically determined end-systolic and end-diastolic volumes. Abnormal regional contraction due to failure of the ventricular wall to thicken can be seen with cine-MRI. Ventricular remodeling and myocardial thinning after myocardial infarction can be appreciated easily (Figure 2).
Valvular assessment

In cine-MRI, turbulent blood flow creates an area of low signal (“signal void”) due to dephasing (asynchronous precession) of the hydrogen nuclei. Accordingly, regurgitant flow is identified by a jet of signal loss in the receiving chamber (Figure 3b and c). Likewise, turbulent flow is seen with stenotic valve (Figure 3a). A qualitative assessment of the degree of valvular disease can be made based on the size of the jet, the duration of the jet in the cardiac cycle, and the presence of a proximal convergence zone (an area of flow acceleration) on the opposite side of the valve.

After a radiofrequency pulse has been delivered, the received signal from the body has both amplitude and phase. A technique known as phase velocity mapping can determine the velocity of hydrogen atoms traveling within or through a given plane. The scanner can encode velocities as high as 5 m/s. Whereas previous figures have used amplitude data to construct anatomic images, phase images display the velocity of moving blood in much the same way as Doppler echocardiography (Figure 4). To interrogate an area of turbulent flow, the operator can draw a region of interest around turbulent flow from which peak and mean velocities can be measured and flow can be calculated. Shunts (using Qp/Qs calculation) can be evaluated by calculating the flow through the ascending aorta and main pulmonary artery.

Pericardial evaluation

Pericardial effusions can be defined, and some generalities about fluid composition can be made, based on signal intensity. The thickness of the pericardium can be measured and should be <3 to 4 mm.

Magnetic resonance angiography

Magnetic resonance angiography (MRA) has increasingly become an accepted method for visualizing both venous and arterial vessels. Most MRAs can be performed without administration of a contrast agent because there is intrinsic contrast between flowing blood and static tissue, although contrast agents may improve image quality in certain circumstances. Magnetic resonance angiography depicts normal laminar flow as bright signal, whereas turbulent, diminished, or absent flow is depicted as signal voids.

Intimal flips, true and false lumen identification, thrombus formation, origin of the tear, involvement of the brachiocephalic vessels, and the presence of aortic regurgitation or hemopericardium all can be demonstrated during an MRI examination for aortic dissection (Figure 5). Similarly, aortic aneurysms are well delineated with MRA, and 3-dimensional reconstruction of multislice transaxial images is helpful in planning surgical repair (Figure 5). Besides aortic imaging, the carotid, renal, and peripheral vasculature can be evaluated for stenoses and for suitability of distal vessels for grafting (Figure 6).

Myocardial perfusion imaging

Myocardial perfusion can be assessed either directly or indirectly using MRI. In a method similar to stress echocardiography, ischemic wall motion changes during an infusion of dobutamine can be
observed. Contrast-enhanced MRI to evaluate perfusion presently uses a first-pass technique during which a bolus of an MRI contrast agent is injected intravenously, and serial MRI images track the bolus through the cardiac chamber and finally into the myocardium. In the presence of coronary artery disease, inhomogeneities in perfusion can be induced by an infusion of dipyridamole or adenosine. Myocardium perfused by a stenotic coronary artery shows lower signal intensity as well as a delay in the appearance of contrast.

**Magnetic resonance spectroscopy**

Magnetic resonance spectroscopy (MRS) is increasingly used to assess myocardial metabolism. Other nuclei besides hydrogen that are MRI sensitive include phosphorus-31, carbon-13, fluorine-19, and sodium-23. Magnetic resonance spectroscopy acquires the spectra of a particular nuclear species in a selected region of tissue. For example, phosphocreatine and adenosine triphosphate levels can be measured and the bioenergetic profile of the myocardium investigated.

**Coronary MRA**

Imaging the coronary arteries has been one of the most important advances in the management of coronary artery disease. Estimates are that 1.4 million cardiac catheterizations are performed each year in the USA, with as many as 20% demonstrating no critical stenosis. Conventional x-ray angiography carries a small risk and involves admission to a hospital, local anesthesia and mild conscious sedation, arterial puncture, the passage of catheters within the vessels, the injection of radiopaque contrast media, and the exposure of the patient and staff to ionizing radiation. At present, there is no satisfactory alternative, and, thus, the possibility of noninvasive coronary MRA has been considered by many to be the “Holy Grail” of MRI.

Magnetic resonance angiography has challenged conventional carotid, renal, and peripheral angiography. However, coronary MRA has been hindered by a combination of obstacles. These include the small caliber of the coronary arteries, their tortuous course, and their encasement within epicardial fat (a high-signal tissue). Unlike other vessels, the coronary arteries move considerably during image acquisition from a combination of both cardiac and respiratory motion. These challenges are not insurmountable, as MRI techniques continue to improve over the years.

A technique for imaging the coronary arteries that has met success is one that employs both cardiac gating and respiratory compensation using navigator echoes. Cardiac gating ensures image acquisition of the coronary arteries during diastole when the heart is relatively still and coronary blood flow is maximal. Early attempts with breath-holding to minimize respiratory motion were disappointing because the patients often became fatigued after several breath-holding maneuvers, and each successive breath-hold became less reliable. Subsequently, a navigator echo approach using a “pencil beam” tag to track the motion of the diaphragm ensures proper alignment and position registration of the coronary arteries during quiet breathing (Figure 7a and b). A fat-suppression pulse nulls the signal from epicardial fat, and a surface coil is placed on the patient's chest to improve signal from the coronary arteries and reduce noise that would degrade image quality. A block of multiple transaxial slices is acquired (about 2-mm thick) through the chest, analogous to the slices in a loaf of bread. Because a coronary artery will transverse through multiple slices, a computer-generated reconstruction of the artery usually is performed to visualize
the artery along its course (Figure 7c).

In its current state of development, coronary MRA can evaluate only the proximal two thirds of the length of the major epicardial vessels and will not replace x-ray angiography as we know it today. Instead, MRA could be used to diagnose high-grade stenoses of the left main or proximal left anterior descending arteries (the 2 main indications for revascularization) and to screen symptomatic patients having chest pain syndromes or asymptomatic patients having multiple risk factors. Coronary MRA continues to be an area of active research to improve image quality. With the future introduction of faster imaging sequences, coronary-specific surface coils, and intravascular MRI contrast agents (administered intravenously), signal from the coronary arteries should increase and thus significantly improve the quality of the images.

Ultimately, for MRI to play a key role in the understanding and management of coronary artery disease, MRI should not be as good as conventional x-ray angiography. Rather, MRI should be better, since MRI has the potential to image the wall of the vessel rather than simply to image the lumen of the vessel. The potential of MRI to characterize plaque by measuring lipid concentration would have important prognostic and therapeutic implications.

THE “ONE-STOP SHOP”

Imagine a single, noninvasive test that assessed cardiac morphology, function, valvular disease, myocardial perfusion, and coronary arteries as well as evaluated the anatomy of the great vessels and peripheral vasculature. Magnetic resonance imaging has the potential to provide this comprehensive examination in one sitting at considerably less risk and cost to the patient. With rapid imaging techniques, it should be possible to complete a comprehensive study within an hour (perhaps costing $1500 to $2000). Although MRI and MRA may seem expensive as screening tools, they may actually be cost effective by eliminating the need for an echocardiogram ($800), nuclear perfusion imaging ($1200), and cardiac catheterization ($4000).

With so many different modalities, it is often difficult for the clinician to select the appropriate test or series of tests to evaluate the patient. For a test to be useful to the clinician, it should provide a diagnosis, effect a management strategy, and provide insight into the prognosis. The test or series of tests should not be redundant (i.e., does not add anything) but rather be confirmatory (i.e., increases understanding or confidence) or independent (i.e., provides relevant information beyond what is already known). So, when should MRI be considered? This question is best answered by asking, “When should MRI not be considered?” Magnetic resonance imaging should not be considered if there is a contraindication for imaging. Magnetic resonance imaging should not be considered in patients with arrhythmias, especially rapid atrial fibrillation. Arrhythmias degrade image quality due to irregular cardiac gating and incomplete relaxation between excitations. Magnetic resonance imaging should not be considered for the evaluation of smaller, randomly moving objects (such as thrombi and valvular vegetations) that are not well visualized with MRI. This is because image data are acquired over multiple cardiac cycles, and an imaged object must be in the identical location in each successive cardiac cycle. Although it is possible to measure heart rhythm and rate, blood pressure, and oxygen saturation while the patient is in the magnet, clinicians understandably feel uneasy with critically ill patients who are isolated from them in the bore of the magnet. Occasionally, metal objects (such as sternal wires and left internal mammary artery clips)
may obscure an area of interest due to distortion in the magnetic field caused by these objects. Otherwise, MRI and MRA would be indicated in all other forms of cardiovascular disease.

So, what has kept cardiac MRI from becoming the imaging method of choice? It is not the value of the data, the quality of the data, or the cost. Rather, it is lack of awareness, lack of imaging expertise, lack of convincing literature that compares and contrasts imaging modalities, and lack of trust in the reliability of a new technology and new consultants.

The role of cardiovascular MRI and MRA will continue to expand, as they are low-risk, cost-effective technologies. Clinicians should remain mindful of these powerful diagnostic imaging modalities.

The reader is directed to the selected review articles and textbooks listed in the general references for further readings on cardiovascular MRI.

**General references**
