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## Clinical Use of Cardiovascular Magnetic Resonance

Gerald M. Pohost, MD; Lynne Hung, MD; Mark Doyle, PhD



### Technology of Cardiovascular Magnetic Resonance

#### Overview

Whenever cardiovascular magnetic resonance (CMR) is applicable, it usually provides the standard for diagnostic evaluation. With a state-of-the-art CMR system, it is possible to acquire technically superior images with great diagnostic value. CMR is entering the early majority user phase of technology adoption.<sup>1</sup>

A period of rapid growth is anticipated as users understand and acquire the technology. Thus, a modality conceived in the last quarter of the 20th century should flourish in the 21st century. The most recent systems include shorter bore 1.5 Tesla magnets. However, CMR is on the brink of a change in magnetic field strength to 3.0T. This will decrease the imaging time, improve image quality, and detect ischemia directly using spectroscopy.

It has frequently been claimed that CMR can provide virtually all of the information needed to assess heart disease. However, such claims become a liability without full realization in a reasonable period of time. CMR is now at the stage where it should be routinely applied clinically (see Table 1 for definitions of some common CMR terminology).

### Magnetic Resonance Hardware

Magnetic resonance systems consist of 3 major components (Figure 1):

- (1) The magnet: Uses niobium-titanium wire that conducts with zero resistance when cooled to the temperature of liquid helium.
- (2) The radiofrequency (RF) coils: Generate radio waves at a frequency determined by the field strength of the magnet and by the atomic nucleus (ie, hydrogen) to be imaged. The RF coil has 2 functions: (a) to transmit signal into the body and induce resonance, and (b) to receive the signal emitted from the body, analogous to echocardiographic transducers.
- (3) The gradient coil: Produces small magnetic fields that vary in a programmed way. Magnetic gradients create a range of resonance signals that vary in a controlled manner across the field of view.

New hardware trends for CMR scanner systems include:

- (1) Using multiple RF amplifiers to receive the MR signal. Each amplifier is dedicated to an individual element of a phased array receiver coil; when more coils and RF amplifiers are used, higher signal-to-noise ratios leading to better image resolution are possible.<sup>2</sup>

- (2) As the miniaturization trend in computer technology continues, CMR scanners have evolved from centrally controlled to highly distributed systems. This will increase the flexibility and speed with which data processing tasks are performed.
- (3) Many of the successes that CMR has enjoyed have resulted from the reduction in scan times for cine and other imaging sequences. In large part, this was made possible by increases in the imaging gradient strength and speed (known in the industry as slew-rates). When gradients become too strong, they can lead to stimulation of skeletal muscle. However, reducing the region over which the gradient is applied while maintaining strength can control gradient-skeletal muscle interactions.
- (4) Early in the development of clinical magnetic resonance imaging (MRI), magnetic field strength was relatively low, eg, 0.1T. The field strength of imaging systems capable of performing CMR has increased to 1.5T. Magnets at 3.0T for whole-body imaging are now being applied to CMR. Higher fields lead to improved image quality, greater acquisition speed, and increased ability to evaluate nuclei, such as phosphorus-31, in addition to hydrogen.

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**TABLE 1. CMR Terminology**

CMR Terminology	Definition	Common Terms
Black blood imaging	Produces bright signals for muscle but a signal void from moving blood.	Spin-echo (the basic sequence); fast spin-echo; single and double inversion recovery spin-echo
Bright blood imaging	Produces bright signal for blood and darker signal for myocardium. Use in cine images.	FFE (fast field echo); GRASS (gradient recalled acquisition in the steady state); FLASH (fast low angle shot)
Steady state free precession (SSFP)	Signal produced by rapidly applying balanced gradients and RF pulses. Use to maximize the overall signal.	FIESTA (fast imaging employing steady state acquisition); balanced FFE (fast field echo); true FISP (fast imaging with steady precession)
Rapid cine imaging	Groups signals within each cardiac cycle to reduce scan time (eg, to 20 seconds).	Segmentation; FASTCARD (fast cardiac imaging); turbo
Parallel imaging	Uses multiple receivers to reduce scan time and/or increase resolution.	ASSET (array spatial sensitivity encoding technique); SENSE (sensitivity encoding scheme); SMASH (simultaneous acquisition of spatial harmonic)

Further CMR terminology can be found in a MRI textbook.<sup>29</sup>

### Imaging Sequences

Acquisition time for CMR imaging has decreased dramatically. Rather than using a gated approach that requires acquisition during several minutes of cardiac cycles, studies are now routinely performed during a 20-second breath-hold. Once this threshold was surpassed, sharper detail was made possible in cardiac cine scans. Cine and static scan quality have continued to improve, and very high quality images are routine.

An older pulse sequence known as steady state free precession (SSFP) has been applied to cardiac cine studies, leading to greater contrast between ven-

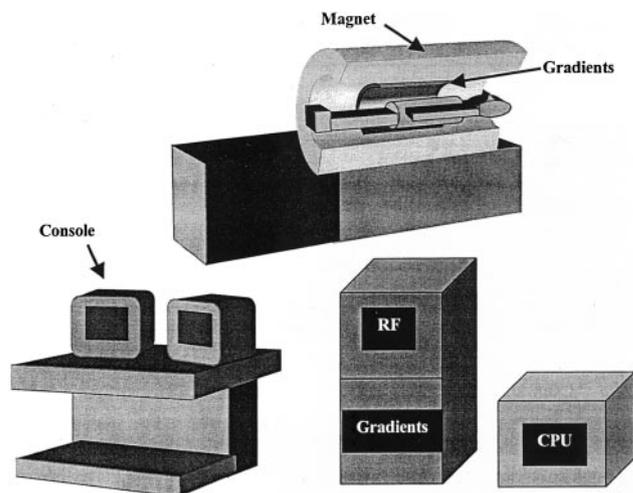
tricular myocardium and blood pool. With this technique, data are acquired continuously throughout the cardiac cycle.<sup>3</sup> Formerly, in cine scans, blood motion (or flow) was the greatest source of contrast. However, in patients with poor ventricular function, where blood motion is reduced, it becomes difficult to differentiate between blood pool and myocardium. Current class SSFP approaches have eliminated the problem of reduced contrast between blood pool and myocardium even in the face of low blood flow because contrast is independent of blood motion properties.<sup>4</sup>

Evolution of "delayed enhancement" has placed CMR as the major

contender for assessing myocardial viability, and it is now potentially superior to the present "gold standard," positron emission tomography.<sup>5</sup> Delayed enhancement has similarities to thallium redistribution single photon emission computed tomography (SPECT) imaging. A major difference is that in CMR, delayed enhancement is observed within minutes (10 to 15) rather than hours (3 to 48) after the initial pass of the agent. Further, gadolinium accumulates in nonviable myocardium, whereas thallium accumulates in viable myocardium. Thus, myocardium that does not enhance on delayed images would be assumed to be viable.

As CMR imaging improves, its applicability to real-time studies, such as stress testing, will continue to increase. RF-tagged myocardial imaging coupled with rapid analysis will provide a means to quantitate parameters of myocardial function, such as regional wall thickening, circumferential strain, and torsion.

It is probably premature to announce that the era of coronary artery imaging by CMR is here, but certainly it is far closer than it was a few years ago.<sup>6</sup> In approximately 15 minutes, sufficient data can be acquired to visualize the coronary arteries with a resolution in the submillimeter range. The ability of CMR to image arterial walls holds promise to go beyond visualization of the lumen and provide direct assessment of not just the calcium but



**Figure 1.** A schematic representation of a CMR system, featuring the control console and the cylindrical superconducting magnet represented as a cut-away structure to show the position of the gradient coils (dark and shaded) surrounding the patient. In the foreground, the power and control units to drive the gradients, radiofrequency (RF), and computer system (CPU) are depicted.

**TABLE 2. Selected Uses of CMR in Assessment of Cardiovascular Disorders With Rating of Clinical Utility for Selected Applications**

Indications	Class
Rest RV/LV function/ejection fraction	I
Assessment of myocardial viability	IIa
Detection of myocardial ischemia	
Dobutamine stress	IIa
Myocardial perfusion	IIb
Phosphorus-31 myocardial spectroscopy	research
Diagnosis of hypertrophic cardiomyopathy	
ARVD	IIa
HCM	I
DCM	I
Evaluation of valvular heart disease	IIa
Congenital heart disease	
Shunts	IIa
Pericardial disease	
Differentiate constrictive and restrictive pericarditis	I
Coronary arteries	IIb
Aortic Dissection	I

Class I indicates usually appropriate and considered useful; class II, acceptable but usefulness less well established; class IIa, weight of evidence in favor of usefulness; class IIb, helpful but not well established by evidence; class III, generally appropriate; ARVD, arrhythmogenic right ventricular dysplasia; HCM, hypertrophic cardiomyopathy; and DCM, dilated cardiomyopathy.

Adapted from Ritchie JL, Bateman TM, Bonow RO, et al. Guidelines for clinical use of cardiac radionuclide imaging: report of the American College of Cardiology/American Heart Association Task Force on Assessment of Diagnostic and Therapeutic Cardiovascular Procedures (Committee on Radionuclide Imaging), developed in collaboration with the American Society of Nuclear Cardiology. *J Am Coll Cardiol.* 1995;25:521-547.

also of important features of the atherosclerotic plaque.<sup>7</sup> Undoubtedly, further technical advances will reduce the scan time and improve data quality, making coronary angiography by CMR a routine clinical tool.

## Clinical Applications

### Congenital Heart Disease

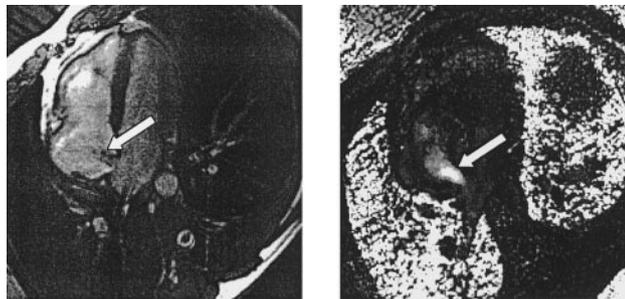
CMR is a technology that is complementary to echocardiography for detailed evaluation of simple and complex congenital heart disease (Table 2). For example, in coarctation of the aorta, the narrowed segment is best visualized on transverse images and measured using thin oblique sagittal slices in the plane of the aortic arch. Phase-velocity mapping can be used to estimate the pressure across the coarctation and quantify collateral flow. Sensitivity and specificity of CMR are 90% for identifying atrial septal de-

fects<sup>8</sup> (Figure 2). Phase-velocity mapping at the level of the shunt allows calculation of shunt size (ie, the pulmonary to systemic flow ratio or QP/QS), even with small shunts such as foramen ovale. For example, the signal from the blood on the left side of the atrial septum can be nulled, creating

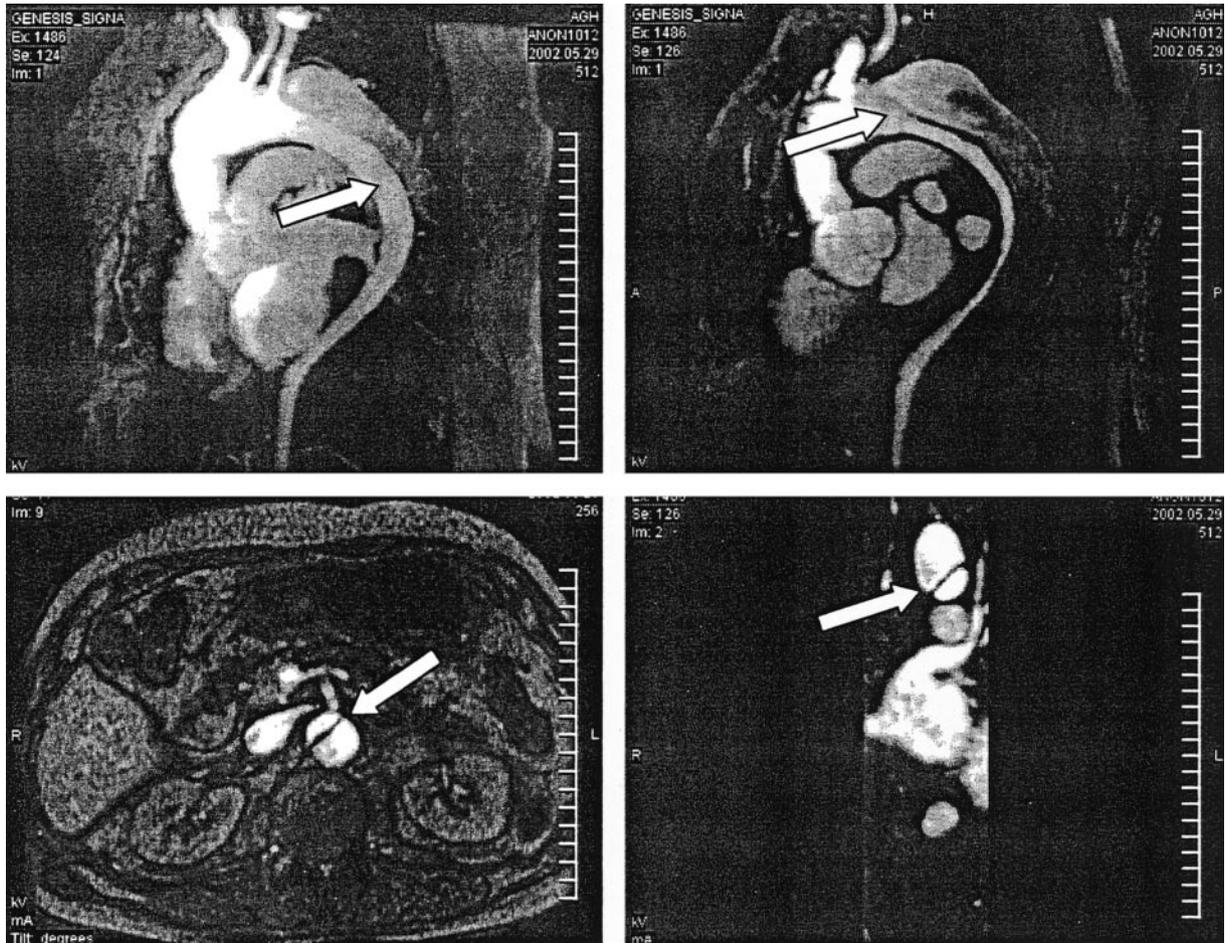
black blood. A small shunt in the atrial septum can be readily detected when the black blood from the left atrium enters the white blood of the right atrium. Similarly, ventricular septal defects are easily detected and quantitated.

Using imaging planes aligned with the cardiac chambers, lesions such as transposition, double outlet left ventricle (LV), double outlet right ventricle (RV), and truncus arteriosus can be clearly diagnosed. In complete transposition of the great vessels, transverse images can show the aorta arising from the RV and the pulmonary artery from the LV. Because consecutive transaxial images can be used to follow the aorta to its arch and the pulmonary artery to its bifurcation, it is the best approach to identify tetralogy of Fallot (TOF), pulmonary atresia, and pulmonary artery stenosis. In TOF, CMR can image narrowing of the RV infundibulum, an enlarged anteriorly displaced overriding aorta, a membranous ventricular septal defect, and hypertrophy of the RV. Accordingly, CMR also can be applied to follow the effects and complications associated with corrective surgery.

CMR is also useful for the diagnosis of anomalies of the systemic venous system, such as persistent left superior vena cava, atretic right superior vena cava with persistent left superior vena cava draining through an enlarged coronary sinus, or interruption of the inferior vena cava with azygos continuation.



**Figure 2.** A steady state free precession, long-axis view of an ostium secundum atrial septal defect (left panel, white arrow), visible as a characteristic flow jet with reduced signal (left-to-right shunt). A velocity-encoded image demonstrates the jet with higher contrast (right panel). Images were provided by Robert W.W. Biederman, MD, Allegheny General Hospital, Pittsburgh, Pa, and were acquired using a GE CV/I system.



**Figure 3.** Four views of an aortic dissection. The angiographic extent of the true lumen (white arrow) is demonstrated in the left oblique view (upper left panel), whereas a multi-planar volume reformatted image demonstrates the only communication between the true lumen and false lumen (white arrow, upper right panel). The dissection can be viewed in cross section using a cine image demonstrating that the true lumen supplies the celiac artery flow (white arrow, lower left panel). The left renal artery (not shown) arises from the false lumen. A 3-dimensional angiographic data set (lower right panel) shows the dissection (white arrow) arising just distal to the left subclavian artery. Images were provided by Robert W.W. Biederman, MD, Allegheny General Hospital, Pittsburgh, Pa, and were acquired using a GE CV/I system.

### Valvular Heart Disease

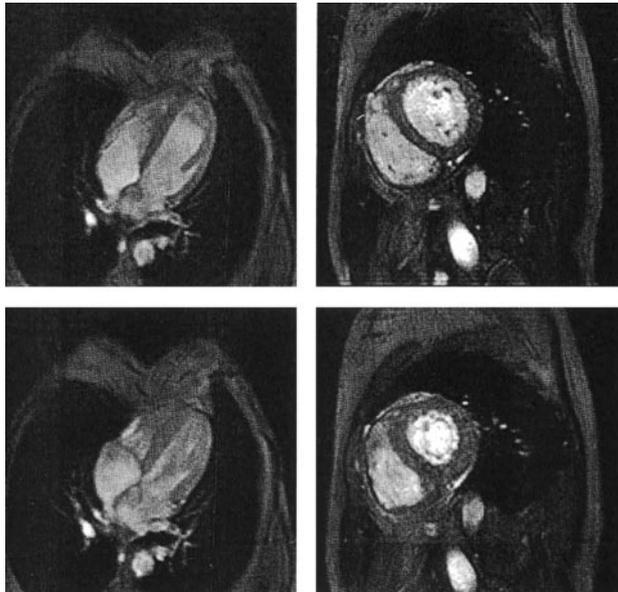
Valvular stenosis or regurgitation appears as dark jets into the bright blood-containing chambers. The turbulent flow disturbs rephasing of the CMR signal. The jet appears as a sharply demarcated area of diminished or absent signal persisting for most of systole or diastole. The duration or the extent of the signal void on MR images correlates with the severity of the aortic stenosis, and the total area of signal loss correlates with severity of mitral regurgitation as determined by echocardiogram or x-ray contrast ventriculography. CMR has a sensitivity of 98%, a specificity of 95%, and a diagnostic accuracy of 97% for identi-

fication of aortic and mitral regurgitation.<sup>9</sup>

### Pericardial Disease

The pericardium can be visualized with either gated spin-echo or gradient echo technique. The normal pericardium can be visualized on spin-echo CMR images as a line of low signal intensity located between the high signals of pericardial and epicardial fat. Visibility of this pericardial band can vary depending on the amount of epicardial and pericardial fat. Normal pericardial thickness is 2 mm, although values of up to 4 mm do not necessarily represent pathology. CMR is a

definitive approach for the diagnosis of constrictive pericarditis. In patients with constrictive pericarditis, pericardial thickening is usually >4 mm as shown by CMR. Differentiating between the causes of pericardial thickening is difficult. Thickening associated with an inflammatory process is usually greater than that due to fibrosis. Depending on severity, constrictive pericarditis can lead to dilatation of the inferior vena cava, hepatic veins, and right atrium, whereas the RV may be normal or distorted (eg, compressed or elongated). Coronal and axial spin-echo CMR imaging has a sensitivity of 88%, specificity of



**Figure 4.** The upper and lower rows of 2 images show the heart during end-diastole and end-systole, respectively, in both long-axis view (left column) and short-axis view (right column). The images were acquired using the sensitivity encoding scheme pulse sequence on a Philips CMR system. Regional and global contractile function can be readily assessed. Reprinted with permission from Pruessmann KP, Weiger M, Boesiger P. Sensitivity encoded cardiac MRI. *J Cardiovasc Magn Reson.* 2001;3:4–5.

100%, and diagnostic accuracy of 93% in the diagnosis of constrictive pericarditis.<sup>10</sup> In chronic constriction, the thickened pericardium is lower in intensity than in acute pericarditis.

CMR is sensitive for identifying generalized or localized pericardial effusions. Moderate effusions are often associated with a pericardial space anterior to the RV >5 mm. Cine CMR can detect cardiac tamponade in patients showing diastolic collapse of the right-sided (and even left-sided) cardiac chambers.

### Cardiac and Pericardial Masses

CMR is an accurate means for detecting pericardial cysts. Generally, as the echo time is increased, there is a progressive increase in signal intensity of the fluid within the cyst. Metastasis and primary tumors of the pericardium and intracardiac tumors, such as myxomas, lipomas, or teratomas, are easily delineated.

### Aortic Dissection

CMR is sensitive and specific for detecting and evaluating the extent of aortic dissection (sensitivity 98%,

specificity 98%). It is more accurate than computed tomography (sensitivity 94%, specificity 87%) and transesophageal echocardiography (sensitivity 98%, specificity 77%).<sup>11</sup> CMR can show the extension of the dissection into the aortic arch, as well as associated aortic insufficiency and intrapericardial hemorrhage. Oblique sagittal spin-echo views display the aorta in an optimal plane to image the extent of dissection and, frequently, the entry and exit locations of the intimal flap (Figure 3).

### Coronary Arteries

In patients with left main or 3-vessel coronary artery disease, CMR has a sensitivity of 100%, a specificity of 85%, and an overall accuracy of 87% for diagnosis of coronary artery stenosis.<sup>12</sup> Compared with conventional coronary angiography, the sensitivity and specificity of CMR for detecting significant coronary stenosis vary from 63% to 90% and 71% to 92%, respectively.<sup>13,14</sup> Although CMR can image the proximal vessels in most subjects, it cannot substitute for conventional

coronary angiography for identifying small, distal branch vessels.

CMR is excellent for detecting anomalous origin of the coronary arteries and coronary arteriovenous fistulas. In 2 studies involving 35 patients with anomalous aortic origin of the coronary arteries,<sup>15,16</sup> CMR detected the course in 97% of the cases.

Unlike native coronary arteries, saphenous vein and internal mammary artery bypass grafts are larger in size and easier to image on CMR. With advances in CMR technology, the predictive accuracy for assessing the patency of the coronary arteries has improved, with sensitivity and specificity in the 90% range.<sup>17</sup> However, CMR is limited for evaluation of graft patency distal to the first coronary anastomosis or of nonoccluding stenosis within the graft. Metallic hemostatic clips, sternal wires, and graft markers may create local image artifacts. CMR is useful in detecting aneurysms of saphenous vein bypass grafts that need subsequent surgical repair.<sup>18</sup>

### Ventricular Function

CMR can measure ventricular ejection fraction and end-diastolic and end-systolic volumes noninvasively and in 3 dimensions without contrast agents. By applying Simpson's rule, LV volumes and ejection fraction can be accurately determined.<sup>19</sup> Summation of the cross-sectional volumes from each of the short axis tomographic cuts provides accurate end-diastolic and end-systolic volumes. In contrast to echocardiography, cine CMR provides 3-dimensional images of the heart from base to apex, with sequential images throughout the cardiac cycle (Figure 4). Such a direct approach to the measurement of cardiac volumes and mass is dimensionally accurate and reproducible. In applying a 3-dimensional approach to the calculation of ventricular volumes and mass, the basal and apical slices must be completely included. In 1 study, both biplane long-axis and serial short-axis were used to compute LV volumes, and ejection fractions were similar by both methods in patients with global and regional LV dysfunction.<sup>20</sup>



**Figure 5.** Dobutamine stress CMR. The top rows are at rest, the middle row is during  $20 \mu\text{g} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$  of dobutamine, and the bottom row is at the maximum stress dobutamine dose. The CMR study clearly revealed apical-septal wall motion abnormalities. Reprinted with permission from Nagel E, Lorenz C, Baer F, et al. Stress cardiovascular magnetic resonance: consensus panel report. *J Cardiovasc Magn Reson*. 2001;3:273.

Although CMR volume and mass calculations are more accurate than catheter x-ray contrast ventriculography and radionuclide cineangiography, the correlations between CMR and these imaging modalities are good.<sup>21,22</sup>

### Myocardial Ischemia and Infarction

CMR detects myocardial ischemia by observing wall motion abnormalities induced by stress (Figure 5). Unlike transthoracic echocardiography and radionuclide methods, CMR is a 3-dimensional modality, has no problems with imaging windows, has high resolution, and has no ionizing radiation. When dobutamine-stimulated CMR was compared with dobutamine-stimulated echocardiography, the sensitivity was 86% versus 74% ( $P < 0.01$ ), and specificity was 86% versus 70% ( $P < 0.01$ ), respectively, for detection of wall motion abnormalities in regions supplied by significantly stenosed coronary arteries.<sup>23</sup>

CMR is a valuable tool for assessing myocardial viability. When a paramag-

netic contrast agent, such as a gadolinium chelate, is administered intravenously, perfusion is assessed on the first pass of the agent, whereas viability is assessed on later images (10 minutes or later). A defect or a hypoenhanced region on the initial scan represents either hypoperfused viable myocardium or infarction. Delayed enhancement occurs in nonviable tissue or in scars.<sup>24</sup> CMR has positive and negative predictive power similar to positron emission tomography imaging for detection of viability. The sensitivity and specificity of CMR hyperenhancement in assessing transmural defects is 86% and 94%, respectively, and in nontransmural defects with subendocardial defect, the sensitivity and specificity decrease to 83% and 88%, respectively.<sup>5</sup>

CMR uses phosphorus-31 spectroscopy to detect ischemia. A copper coil is placed on the chest wall, and the anterior LV wall is interrogated. A spectrum depicting adenosine triphosphate (ATP), phosphocreatine (PCr), and inorganic phosphate is generated.

In nonischemic myocardium, the PCr peak is 1.3 to 1.7 times higher than 1 of the 3 ATP peaks. When the anterior wall becomes ischemic, PCr decreases to or below the level of ATP. Thus, the PCr/ATP ratio will decrease from a range of 1.3 to 1.7 down to 1 or less with myocardial ischemia.<sup>25</sup> Interestingly, 20% of women presenting with a syndrome X picture demonstrate a significant decrease in PCr/ATP with handgrip stress in the absence of epicardial coronary artery disease, suggesting microvascular dysfunction.<sup>26</sup>

### Cardiomyopathy

One of the most difficult of the cardiomyopathic syndromes to define is arrhythmogenic right ventricular dysplasia (ARVD). ARVD is characterized by total replacement of a portion of the free wall of the right ventricular myocardium with fat and/or fibrosis with thinning. Using CMR, these changes can be identified in 95% of patients with ARVD.<sup>27</sup>

CMR also can be used to differentiate between subtypes of hypertrophic cardiomyopathy depicting whether the hypertrophy is in the upper, mid, or lower septum, is diffuse within the LV myocardium, or is localized to the apex.<sup>28</sup> LV mass, volume, wall motion, and ejection fraction associated with hypertrophic, restrictive, or dilated cardiomyopathies are easily determined. CMR is the ideal approach for differentiation between constrictive pericarditis and restrictive cardiomyopathy.

### Conclusions

CMR is the newest and most complex of the cardiovascular imaging technologies, with diverse clinical applications spanning nearly every aspect of disease affecting the heart and blood vessels. The advantages of CMR are its 3-dimensional imaging capability, high resolution, and ability to depict soft tissues. Contrast agents without nephrotoxic or other toxic effects can be used to expand the clinical utility of CMR to improve visualization of the blood vessels, including the coronary arteries, to assess myocardial perfu-

sion, and to identify nonviable myocardium and scar. CMR is entering a particularly important phase of its evolution, with anticipated rapid growth in existing applications and development of new clinical applications.

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