Review Article

Clinical Applications of Cardiovascular Magnetic Resonance Methods

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Abstract

The application of magnetic resonance to diagnostic medical imaging stands as one of the great scientific achievements in the past 50 years. Magnetic resonance techniques are easily applied to organs which remain stationary during the imaging procedure, such as the brain and musculoskeletal system. Imaging of moving heart structures and circulating blood is considerably more difficult. Clinical application of magnetic resonance to the cardiovascular system remains challenging but continuing technological innovations have enabled cardiovascular specialists to more effectively utilize magnetic resonance in clinical practice as well as for innovative research. Cardiovascular magnetic resonance imaging (MRI) and magnetic resonance angiography (MRA) are now being used with increasing frequency for the assessment of patients with cardiovascular disease. This paper will introduce clinicians to the current applications of these flexible and robust tools. A brief introduction will be given to the physics of MRI, the instrumentation and the imaging strategies. The main focus of the article, however, is to review how these techniques are being applied by clinicians in routine daily care.

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Introduction

Terminology can be a stumbling block for clinicians being introduced to the study of magnetic resonance methods. In conventional parlance, the term cardiovascular MRI is used to describe imaging of the heart and blood vessels which is accomplished without using contrast agents. The term cardiovascular magnetic resonance angiography (MRA) is most commonly used when blood vessel imaging is accomplished with the use of intravenous contrast agents. MRA techniques increase the conspicuity of blood vessels and aid in defining vascular pathology (Figure 1).

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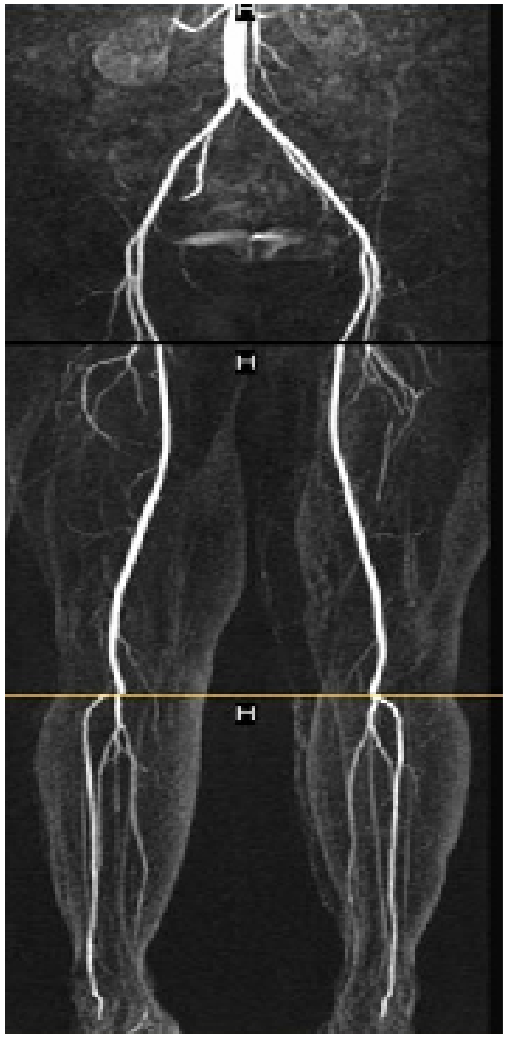

Figure 1. Magnetic resonance angiography (MRA) of the abdominal aorta, iliac arteries and lower extremities in a normal patient. This image was acquired following the intravenous administration of gadolinium contrast

The term contrast enhanced magnetic resonance imaging (CE-MRI) is used to describe imaging of the myocardium and soft tissues, as opposed to blood vessels, following contrast agent infusion. CE-MRI is most commonly used to assess myocardial viability, myocardial perfusion or to aid in soft tissue characterization (e.g. assessment of cardiac masses or thrombi).

The physics of magnetic resonance can be daunting but, a relatively simple working knowledge of how images are formed using magnetic resonance is all that is required to facilitate informed clinical application. Recall that most clinical cardiologists are not expert in the physics of ultrasound, nuclear pharmacy or X-rays yet can quite ably apply echocardiography, nuclear stress imaging and cardiac catheterization techniques within their practice. In an analogous fashion, armed with basic principles, the clinician can also apply magnetic resonance methods within their practice.

Basic Principles

Magnetism arises as a result of the motion of charged particles.[1] Many materials exhibit magnetic properties but, in medicine we exploit the hydrogen nucleus to generate images. The hydrogen nucleus, which is abundantly distributed throughout the body primarily in the form of water molecules, both spins and possesses an electric charge. Accordingly, the hydrogen nucleus creates magnetism. When the human body is placed in the external magnetic field of a commercial magnetic resonance instrument a small net magnetic force is produced by the hydrogen nuclei. This net magnetic force can be manipulated and localized in space forming an image which represents the distribution of the aforementioned nuclei. When one looks at a typical magnetic resonance image, one is simply looking at a map of hydrogen nuclei, primarily in the form of water, in the area being interrogated.

A crucial point in magnetic resonance methods is to understand that the magnetic behavior of hydrogen nuclei is highly dependent on the local environment in which they are concentrated. The human body, with its complex latticework of tissues and organs, has a variable distribution and concentration of hydrogen nuclei in solid organs and in the vasculature. Each tissue has 2 unique signatures which describes how the hydrogen nuclei behave in a magnetic field after they have been perturbed by a radiofrequency pulse of appropriate energy. The magnetic behavior within the overall lattice that the nuclei are located is referred to as T1 relaxation (spin-lattice relaxation). The magnetic behavior between adjacent hydrogen nuclei is referred to as T2 relaxation (spin-spin relaxation). T1 and T2 values for typical tissues are well established. The signal produced by hydrogen nuclei and detected by magnetic resonance instruments can be made to be dependent on T1 and T2 characteristics of the area interrogated. With this background, it can now be appreciated that image appearance in MRI is dependent on hydrogen nuclei density, T1 characteristics, T2 characteristics and motion (including blood flow). Although complex, it is just this complexity which can be manipulated by magnetic resonance methods, with and without contrast agents, to provide unparalleled insight into form and function in both normal and pathological states.

Instrumentation

The components of a commercial MR scanner include:

(1) A large superconducting magnet which is always on and provides a continuous and stable field strength.

(2) A series of smaller magnets, referred to as gradient coils, which surround the main magnet. These gradient magnets are switched on and off quite rapidly and transiently create a "gradient" of field strengths in 3 dimensions.

(3) Radiofrequency transmission and receiver coils

(4) A computer to process the information and generate the typical image display.[2]

To acquire an image, the patient must lie still in the main bore of the magnet. The local magnetic environment is manipulated through the rapid application of the magnetic "gradients" which, as noted above, surround the main magnet. Radiofrequency energy is applied and absorbed within the imaging area of interest. The combination of gradient application and radiofrequency energy perturbation allows a 3-dimensional signature to be given to the hydrogen nuclei within the imaging plane. The timing chosen for the image field perturbation and the timing chosen for detection are software parameters programmed into the instrument (see Imaging Sequences section below). These techniques facilitate localization and image contrast which result in the generation of medical images capable of exquisite temporal and spatial resolution.

Most MR instruments in clinical use throughout the world operate at field strengths of 0.5 to 1.5 Tesla. For perspective, the earth's magnetic field is less than 1 Gauss (1 Tesla = 10,000 Gauss). The workhorse instrument for general imaging use is the 1.5 Tesla instrument. Recently, scanners have become commercially available that operate at a field strength of 3 Tesla. For the highest quality CV applications, standard bore configuration magnets are required. It should be noted that scanners are available which do not have a bore configuration (open magnets) but, these instruments are not adequate for most cardiovascular applications. Figure 2 shows the 1.5 Tesla magnet used in our laboratory.

Imaging Sequences

There are myriad ways that an MR instrument can be made to interact with tissues of interest. The set of instructions given by the computer to the gradient coils and radiofrequency coils during acquisition is referred to as an imaging sequence. The basic imaging sequences have been designed to highlight a tissue of interest. The blood pool can be made to appear either dark or bright and the acquisition can also be designed to highlight anatomic information or flow information. Spatial resolutions ranging from several millimeters to sub-millimeter can be achieved in any desired plane to highlight anatomy. Very low temporal resolutions can be achieved to highlight function. Cardiac gating is required for cine imaging and in a typical acquisition used to assess ventricular function, cine images with a temporal resolution in the range of 15-30 milliseconds are routinely obtained. Commercially available sequences can provide limited information about tissue characteristics. Further, as will be described later, clinically important information about tissue vascularity and myocardial viability can be obtained following the infusion of MRI contrast agents.

A detailed treatment of imaging sequences is a complex topic which is beyond the scope of this paper but can be found in many standard references. Suffice it to say that imaging sequences are continually being developed by software programmers and many of the new and exciting developments in cardiovascular magnetic resonance methods are being made possible by innovations in this area.

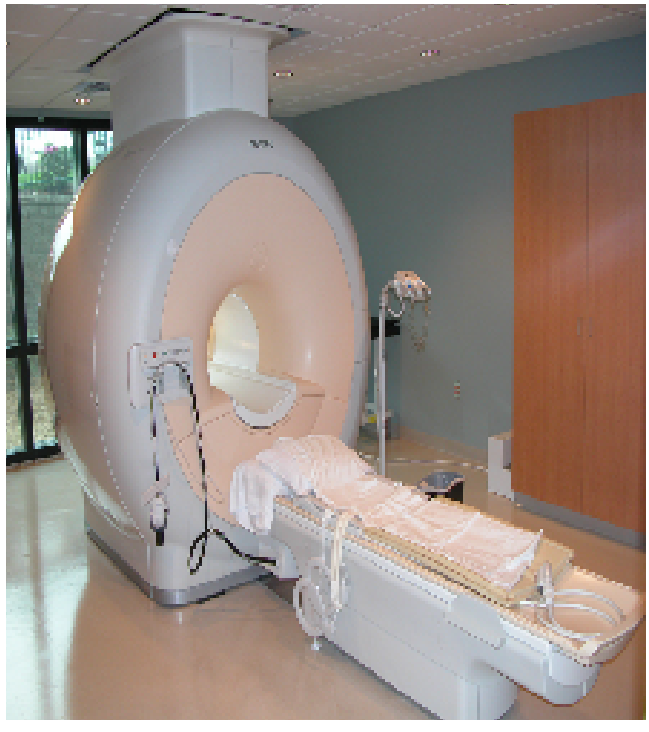

Figure 2. 1.5 Tesla MRI instrument optimized for cardiovascular applications from the authors lab

Contrast Agents

Agents have been developed which significantly alter the magnetic field behavior of hydrogen nuclei and thereby alter tissue contrast. Most currently available MR contrast agents are chelates of the rare earth metal gadolinium. Gadolinium is not imaged directly, rather the images obtained are a representation of the effect that gadolinium has on adjacent hydrogen nuclei. Gadolinium is effective because hydrogen nuclei in close proximity to gadolinium have a T1 relaxation time that is dramatically lowered when compared to hydrogen nuclei not in proximity to gadolinium. Accordingly, imaging sequences can be chosen to highlight differences in T1 relaxation and these differences can produce excellent tissue contrast. Bolus administration and early imaging, while the gadolinium chelate is still within the vasculature, is used to produce high quality angiograms (MRA). The normally used MR contrast agents diffuse rapidly into the extracellular space and images can be obtained after the infused agent has left the vascular compartment and distributed into the tissues (CE-MRI).

Gadolinium is highly toxic in its elemental state but, gadolinium chelates have been devised with remarkable safety

profiles. There have been rare but, well described, systemic side effects including anaphylactoid reactions. Serious toxic effects have also recently been reported in patients with renal failure and advanced renal failure should be regarded as a strong relative contraindication to contrast MRI. Despite the small risks associated with their use, gadolinium based agents have been used safely in patients of all ages and contrasted images have greatly improved the diagnostic power of magnetic resonance imaging. The development of improved contrast agents for clinical applications is an area of intense research in laboratories throughout the world.

Safety

A major advantage of MRI is that imaging is performed without exposing the patient to ionizing radiation or iodinated contrast material. Accordingly, as currently applied, MRI is devoid of any known destructive biophysical effects in appropriately selected patients.

There are, however, important safety considerations for MR imaging and many excellent resources are available which deal with safety.[3,4] An excellent web based resource is http://www.mrisafty.com/ Standard contraindications include cardiac pacemakers, defibrillators, ferromagnetic intracranial aneurism clips, and various implanted or magnetically activated devices. Most orthopedic hardware can be imaged safely although image degradation is likely to occur if the region of interest is in close proximity to the metallic hardware. Sternal wires, coronary stents, and artificial heart valves can be safely imaged in almost all situations. There is an increasing body of literature describing the safety of imaging some cardiac pacemaker patients in a carefully monitored protocol.[5] These preliminary results are exciting, and may expand the use of MRI but, imaging of patients with pacemakers is investigational and can not be recommended at this time.

Clinical Applications

Indications

A unique strength of magnetic resonance methods is the ability to obtain anatomic, functional and perfusion information with a single method. Vascular and nonvascular anatomy can be imaged with excellent resolution and, since MRI techniques are inherently 3 dimensional, images can be acquired in any plane. As long as the patient can cooperate with lying still and occasional breath-holding instructions (to reduce respiratory motion) high quality images can be obtained in most patients. Table 1 lists the current clinical uses for MRI. Resources are now available from international organizations which highlight clinical indications as well as appropriateness criteria.[6-8]

Table 1. Indications for cardiovascular magnetic resonance imaging assessment of right and left ventricular volumes, ejection fraction and mass

Ischemic Heart Disease
- (a) Ventricular morphology, volumes and ejection fraction
- (b) Myocardial perfusion at rest and following pharmacologic stress
- (c) Myocardial viability following contrast administration (delayed CE-MRI)
- (d) Phosphorous spectroscopy (investigational – not a current clinical tool)

Valvular Heart Disease
- (a) Serial assessment of ventricular volumes, ejection fraction and mass
- (b) Valvular morphology (echo techniques are first line)
- (c) Quantitative flow, measuring stenotic gradients and regurgitant fractions

Myocardial Disease Primarily Involving the Left Ventricle
- (a) Ventricular morphology, volumes and ejection fraction
- (b) Assessment of patterns of hypertrophy (hypertrophic cardiomyopathy)
- (c) Delayed CE-MRI as an aid in recognizing the etiology of cardiomyopathy (e.g. dilated or ischemic cardiomyopathy, myocarditis, sarcoid, amyloid)

Right Ventricular Cardiomyopathy

Pericardial Disease
- (a) Constrictive pericardial disease
- (b) Atypical pericardial effusions (echo techniques are first line)

Congenital Heart Disease
- (a) Morphology of the heart, central pulmonary arteries and aorta
- (b) Right and left ventricular morphology and function
- (c) Assessment of intracardiac shunts
- (d) Assessment of post-surgical results

Assessment of Cardiac and Paracardiac masses (echo techniques are first line)

Diseases of the Thoracic and Abdominal Aorta

Peripheral and Cerebrovascular Angiography

Coronary Artery Imaging
- (a) Assessment of anomalous coronary arteries
- (b) Kawasaki's disease

Ventricular Function

Validation of the accuracy of MR methods for assessing volume, function and mass dates back to the early days of cardiovascular MRI.[9-14] In the opinion of most authorities, MRI now represents the gold standard for assessing right

and left ventricular function. Unlike other modalities, MRI can accurately and reproducibly assess ventricular function and mass independent of geometric assumptions. In our lab, we routinely assess ventricular function using several single plane long axis images and a stack of serial short axis images proscribed to encompass the entire heart from base to apex. To acquire a 2 chamber plane (RAO equivalent), a 4 chamber plane (LAO equivalent) and an LVOT plane requires a total of 3 EKG-gated, breath-hold scans each lasting only ~5 to 10 seconds. Using these views, standard area-length ejection fraction calculations can be obtained which are quick and accurate, particularly in patients with normal regional wall motion. The serial short axis series usually requires 4 to 6 separate breath-hold scans. Accurate ejection fraction and volume calculations can be made using a Simpson's rule algorithm. Results obtained using these inherently 3 dimension data sets are reproducible and accurate even in patients with regional wall motion abnormalities. A comprehensive assessment of ventricular function can be obtained in ~10 minutes from the time the patient lies down in the scanner until the results are obtained. MRI has the added benefit of being able to measure wall thickness, wall thickening and LV mass. Patients, such as those with chronic valvular pathology, in who chamber dilatation and ejection fraction influence prognosis and the timing of surgical intervention, can be accurately followed. The benefits of MRI can also be exploited in the research community, particularly in the area of drug therapy and development. Studies can be designed that involve fewer patients and can be accomplished in a more cost effective and shorter time frame using MRI methods.

Cardiomyopathy

MRI is useful for the assessment of patients with cardiomyopathy since treatment algorithms are often based on the etiology and severity of myocardial dysfunction. Defining an ischemic etiology may lead to additional testing in the hope of identifying treatable coronary artery obstruction. Accurate assessment of ejection fraction can influence the appropriate use of device therapy in the form of biventricular pacing and/or implantable defibrillators. Facilitating proper patient selection for device therapy is an issue of clinical and economic importance.

Contrast enhanced MRI (CE-MRI) techniques have been used to accurately distinguish between ischemic and nonischemic etiologies for cardiomyopathy. Patients with prior myocardial infarction (ischemic etiology) demonstrate a characteristic endocardial to transmural pattern of contrast enhancement following gadolinium infusion (see section on Ischemic Heart Disease). In comparison, patients with a nonischemic etiology typically do not show this pattern. In ground-breaking work from the laboratory of Dr. Dudley Pennell at the Royal Bromptom Hospital in London, McCrohon et al. showed that patients with nonischemic dilated CE-MRI often demonstrate a pattern of mid-wall enhancement. Their work was the first to suggest that delayed CE-MRI may become a useful alternative to invasive coronary angiography in the work-up of patients with cardiomyopathy.[15] This is a complicated and somewhat controversial area and continued research is to be expected.[16-17]

Abnormal contrast uptake has been seen in patients with acute myocarditis using several acquisition techniques although the findings can be variable.[18-21] Ventricular function assessment, chamber morphology, valvular function, quantitative flow measurements and CE-MRI make possible a comprehensive evaluation of known or suspected hypertrophic cardiomyopathy.[22-26] Figure 3 is an example of asymmetric septal hypertrophy in a patient with hypertrophic cardiomyopathy. MRI may be uniquely useful in less common variants such as apical hypertrophic cardiomyopathy which can be missed by echocardiography.[24] MRI findings in sarcoid and amyloid heart disease have been described by MRI, although the findings can be variable and nonspecific.[27-28]

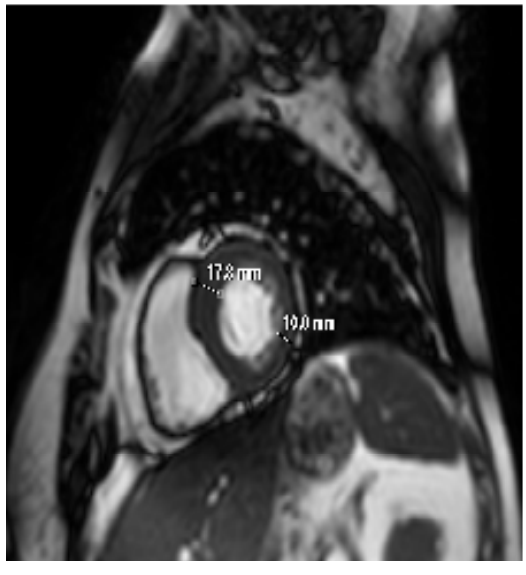

Figure 3. Basal slice from a cine MRI study demonstrating asymmetric septal hypertrophy in a patient with hypertrophic cardiomyopathy

Cardiomyopathy associated with thalassaemia can be evaluated by MRI.[29] These patients often receive multiple blood transfusions during their lifetime resulting in iron overload and cardiomyopathy with subsequent death due to arrhythmia or heart failure. There is no consistent relation between serum iron and myocardial dysfunction. Nor does liver iron consistently predict myocardial iron content. Some authors have demonstrated the usefulness of the MRI T2* studies in diagnosing such cases. It is hoped that diligent follow-up may prevent myocardial scarring and irreversible cardiomyopathy in this select population.

Right ventricular cardiomyopathy is difficult to evaluate

and requires the combination of a strong clinical suspicion and the strict application of clinical and imaging criteria. Since the right ventricle is poorly evaluated by echo, nuclear and catheterization techniques MRI has assumed an important role in the imaging criteria. Helpful parameters include right ventricular dilation, focal contractile abnormality, trabecular disarray and fat infiltration of myocardium.[30-32]

Ischemic Heart Disease

Left ventricular size and function is a major determinant of prognosis in patients with ischemic heart disease. As noted above, the accuracy of MRI for assessing both the myocardium (mass, wall motion, regional wall thickening) and the blood pool (chamber volumes and ejection fraction) is quite helpful. MRI pharmacologic stress testing can be performed using dobutamine or adenosine. The spatial resolution of MRI stress testing is superior to conventional nuclear studies but, stress testing in the MR environment can be cumbersome and therefore, is not widely used.

MRI can also be used to assess myocardial viability. The usual protocol includes assessment of cardiac anatomy and function and delayed imaging of the myocardium following the infusion of gadolinium contrast (delayed CE-MRI). The gadolinium chelates in routine clinical use are primarily extracellular agents which diffuse into the interstitial space. Normal myocytes exclude gadolinium while areas of myocardial scar, which don't contain normal myocytes, accumulate gadolinium over time. When imaged with a specialized inversion recovery sequence normal myocardial tissue is nulled and made to appear dark (black). Figure 4 is an example of a normal delayed CE-MRI study.

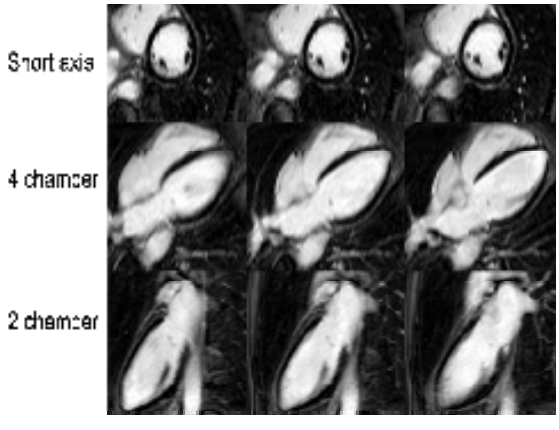

Figure 4. Delayed contrast enhanced magnetic resonance imaging (CE-MRI) demonstrating normal myocardial viability. Note the excellent nulling of the myocardium (normal myocardium appears dark) and the absence of any areas of abnormal hyperenhancement within in the myocardium

In contradistinction, abnormal areas of high gadolinium concentration are made to appear bright (white). The easily remembered adage in MR myocardial viability imaging is: "bright is dead". Figure 5 is an example of a localized myocardial infarction from our lab.

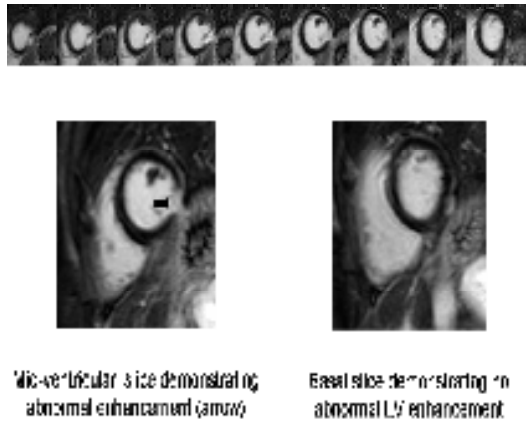

Figure 5. The top row shows a series of short axis slices from a delayed contrast enhanced magnetic resonance imaging (CE-MRI) acquisition. This patient presented with chest pain, malignant ventricular ectopy and enzyme evidence of a small myocardial infarction. The bottom left image is a magnified image from the mid-ventricle and shows a discrete transmural infarction (arrow). The bottom right image is a magnified image from the base of the heart showing normal myocardium

The spatial resolution of MRI is approximately 40-fold superior to conventional nuclear viability imaging and its accuracy has been validated in both animal and human studies. Pioneering work was done by Dr. Raymond Kim and associates and has been corroborated and expanded through the work of others.[33-40] The exquisite resolution of MRI facilitates a full thickness evaluation of myocardial infarction. Small subendocardial infarcts can be identified as well as extensive transmural infarctions.[41-42] The extent of infarction has been precisely correlated with improvement of regional myocardial function following surgical revascularization in humans.[34] Recent research is being directed at making the techniques even quicker and more patient friendly.[43] Most authorities now consider delayed CE-MRI to represent a gold standard for the clinical assessment of myocardial viability.

A combined LV function and viability study can be performed in less than 20 minutes and requires no additional equipment. In labs that combine the above with stress testing, a comprehensive physiologic evaluation of ischemic heart disease can be achieved in 30-45 minutes but, requires specialized drug infusion equipment and the presence of trained medical personnel. Combining stress perfusion imaging with an assessment of myocardial viability appears to improve clinical utility.[44-45]

Valvular Heart Disease

Transthoracic and transesophageal echocardiography are excellent techniques for assessing fine morphologic detail of

heart valves. However, MRI is complementary for assessing valve morphology and, is a superior technique for assessing the physiologic consequences of valvular pathology. Subjective assessments can be obtained using cine gradient echo techniques which highlight the disturbed flow patterns characteristic of valvular stenosis and regurgitation. Reproducible objective assessments can be obtained using quantitative flow and volumetric MR techniques. Aortic and mitral valve gradients and valve areas can be rapidly calculated in a manner analogous to echocardiography.[46-48] Regurgitant flow and volume can be reproducibly assessed in both mitral and aortic regurgitation.[49-51]

Magnetic resonance methods are uniquely helpful in identifying patients with pathology of the aortic valve and ascending aorta. It has been recognized that patients with a congenitally abnormal aortic valve (bicuspid) often have associated pathology of the aortic wall (aneurysm or coarctation). A high index of suspicion is required to tailor the diagnostic imaging strategy and guide appropriate therapy. In these patients, MRI is used to assess anatomy and ventricular function, quantitative flow methods are used to assess stenotic and/or regurgitant lesions and MRA is used to assess the entire aorta. Figure 6 is an example of a patient from our lab that was accurately diagnosed by MR methods and underwent successful surgical therapy.

Prosthetic valves can be imaged safely but, morphologic detail at valve level valve cannot be assessed due to local artifacts from the metallic components of the valves. Eccentric regurgitant jets and quantitative flow can still be assessed.

Pericardial Disease

MRI is accurate for diagnosing pericardial effusions. Echocardiography is the initial choice for assessing pericardial pathology but, MRI is complementary and is particularly useful for assessing loculated effusions. MRI can also contribute to the evaluation of suspected constrictive pericardial disease by allowing accurate measurement of pericardial thickness and assessment of the physiologic sequelae of constriction such as RV chamber distortion and RA enlargement. Calcium produces an MRI signal void and its presence can only indirectly be inferred by MRI. Computed tomography (CT) is another tool that can be used since CT very accurately assesses pericardial calcium content. A comprehensive assessment of pericardial disease often requires a multimodality approach.[52]

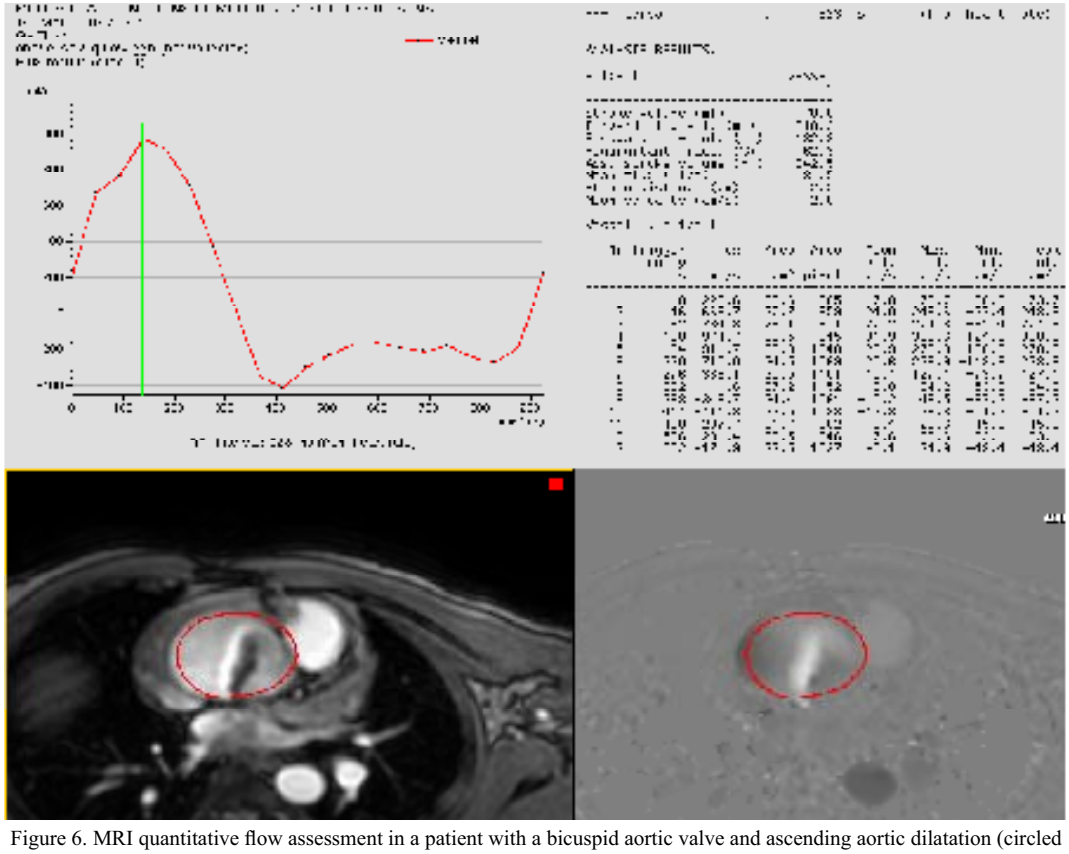

Figure 6. MRI quantitative flow assessment in a patient with a bicuspid aortic valve and ascending aortic dilatation (circled region of interest in the bottom frames). The top left frame is a graphic representation of flow across the region of interest at the level of the aortic valve. The top right frame demonstrates volumes and flow velocities in tabular form. This patient was shown to have increased velocities and severe aortic regurgitation. He underwent successful replacement of his aortic root and aortic valve

Cardiac and Paracardiac Masses

Echocardiography is the first line imaging strategy for evaluation of cardiac masses but MRI is an important complementary tool. The large field of view can precisely assess size and the relationship to cardiac and noncardiac structures. The flexibility of imaging sequences (e.g. T1-weighted, T2-weighted and fat suppression techniques) permits some insight into tissue composition. Finally, image appearance following contrast infusion facilitates assessment of vascularity. Left ventricular thrombi, even small apical thrombi, can be reliably imaged using MRI techniques (Figure 7).

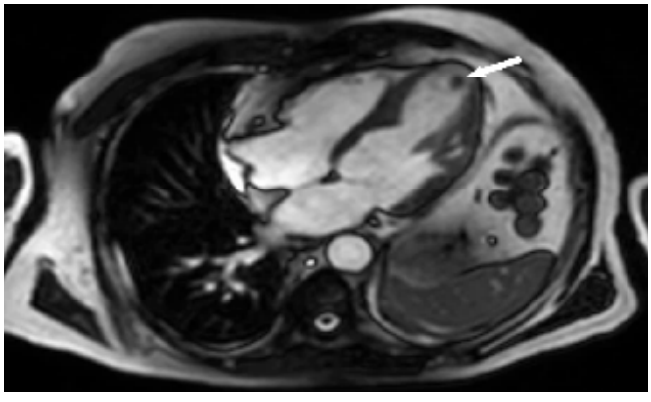

Figure 7. Cine MRI demonstrating a small apical thrombus (arrow)

Congenital Heart Diseases and Post Surgical Follow Up

Advances in medical and surgical techniques have created an increasing population of patients with congenital heart disease surviving in to adulthood. Echocardiography is an excellent tool in most young children. However, MRI is of great complementary utility in complex congenital heart anomalies in the adult. The absence of radiation or nephrotoxic iodine administration is important in the younger population. The wide field of view facilitates the systematic assessment of cardiac morphology as well as the status of venous return, the central pulmonary arteries and the thoracic aorta.[6,53,54] Quantitative flow techniques can be used to noninvasively calculate systemic and pulmonary blood flow and, thereby identify the presence of any shunt. Figure 8 is an example of an atrial septal defect with a significant left-to-right shunt identified in our lab.

In the post-surgical population, surgically created conduits can be notoriously difficult to locate and interrogate. MRI is useful to follow patients after surgery and to look for complications or residual defects. The wide field of view of MRI and the ability to perform quantitative flow assessment in any imaging plane can be helpful.

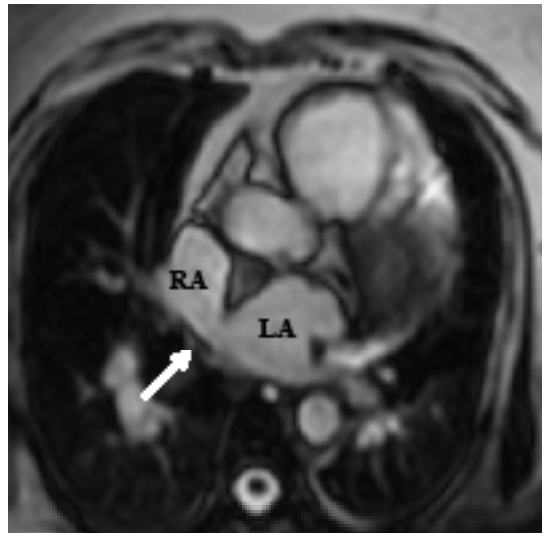

Figure 8. Cine MRI of a sinus venosus atrial septal defect (arrow). RA, Right atrium; LA, Left atrium

Coronary Artery Imaging

A significant body of research has been done on MR coronary angiography and in carefully selected patients diagnostic images can be obtained. A preliminary early report was published many years ago by Dr. Warren Manning and associates comparing MR coronary angiography with conventional angiography.[55] Figure 9 is an example of an MR coronary angiogram obtained in our lab. It must be recognized that the technical requirements are considerable and long acquisition times are required. Accordingly, MR coronary artery imaging is seldom used clinically in the detection of atherosclerotic coronary artery disease.

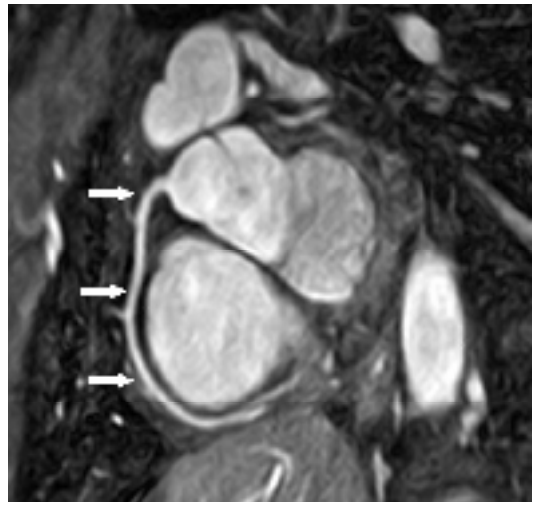

Figure 9. MR coronary angiogram of a normal right coronary artery (arrows)

A niche clinical use of MR coronary imaging is for the detection of congenital coronary anomalies involving the origin and course of the proximal vessels.[56] In young patients, where the desire to avoid radiation is of greatest relevance, MRI is often used as the first line test. Coronary artery aneurysms, such as those seen in Kawasaki's disease, can be followed-up via MRI (Figure 10). In the current state of development, CT coronary angiography is much faster, has superior spatial resolution and is the preferred noninvasive strategy for coronary imaging in most situations. Research using magnetic resonance to characterize not only the lumen of the epicardiac coronary arteries but to assess plaque morphology continues.

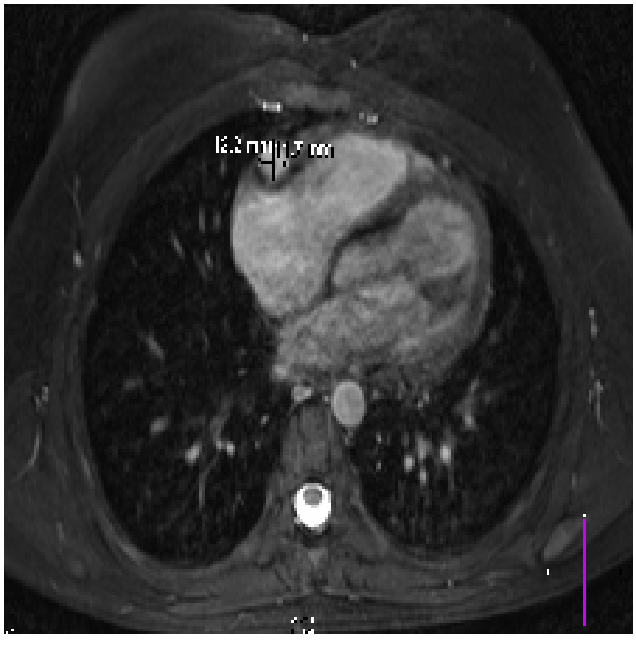

Figure 10. Magnetic resonance image of a 12.2 mm x 11.7 mm right coronary artery aneurysm in a young patient with Kawasaki's disease

Magnetic Resonance Angiography

Magnetic resonance imaging is inherently sensitive to flow and early investigators recognized the potential for noninvasive MR angiography. The earliest efforts were done by manipulating imaging sequences in order to highlight natural flow phenomena and contrast. However, it wasn't until the widespread use of MR contrast agents that MRA became sufficiently accurate and reproducible for clinical use. Magnetic resonance angiography has revolutionized the diagnostic evaluation of patients with aortic disease (Figure 11), renovascular disease (Figure 12), cerebrovascular disease, and upper and lower extremity peripheral vascular disease (Figure 13). In the past, most of these patients required invasive angiography to assess their status. Currently, in state-of-the-art labs, almost all diagnostic angiography is accomplished noninvasively with MRA or, recently, CT angiography. The invasive angiography suite remains valuable to arbitrate an equivocal or nondiagnostic noninvasive angiography study. Fortunately, the major role of the invasive angiography suite has shifted to the performance of therapeutic interventions.

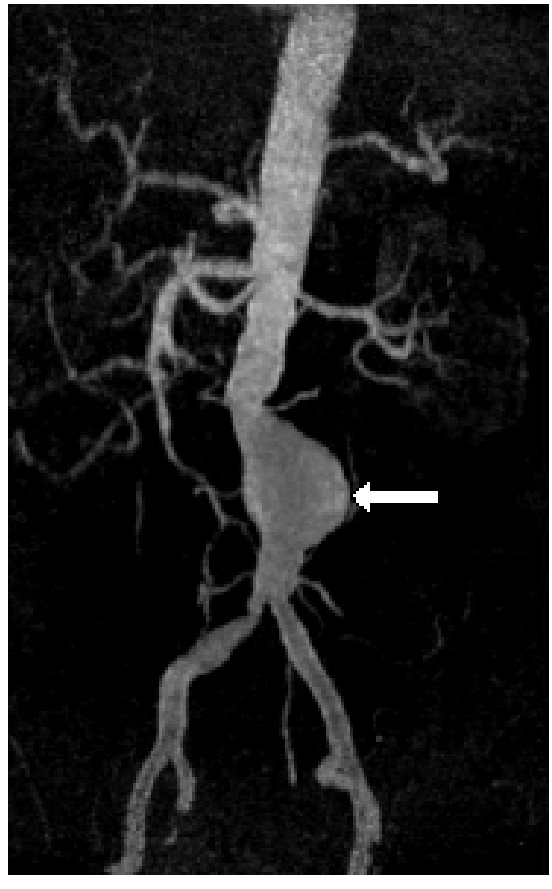

Figure 11. MR angiogram demonstrating an infrarenal abdominal aortic aneurysm (arrow)

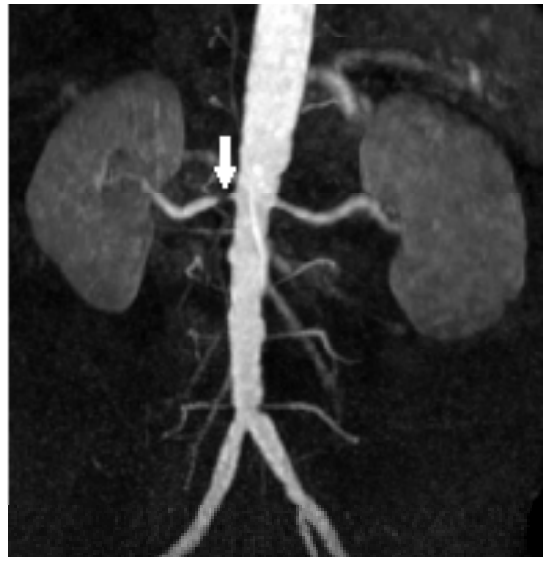

Figure 12. MRA of right renal artery stenosis (arrow)

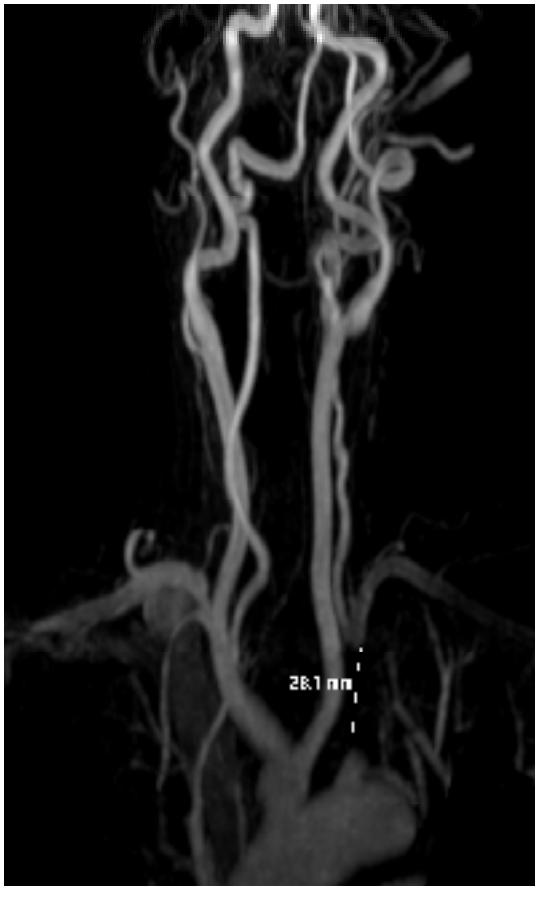

Figure 13. MRA of the aortic arch and neck arteries demonstrating 100% occlusion of the left subclavian artery

Future Considerations

The field of cardiovascular magnetic resonance is well established for the clinical applications described above. This field is far from mature and new developments are being reported regularly. Accurate definition of atherosclerotic plaque composition and burden would be of enormous clinical utility and is an area of active and promising research.[61,62] Work continues to be pursued in the area of MR coronary angiography. A potential role for MR spectroscopy has been described and is the subject of ongoing basic science investigation.[63] The disciplines of interventional MRI and high field strength (3 Tesla) MRI are also in their early stages.

Conclusions

Magnetic resonance methods are assuming an increasingly prominent role in the evaluation of patients with cardiovascular disease. The contemporary clinician should acquire a working knowledge of the technology available and how to apply these techniques in a cost effective manner. It is to be expected that the uses of cardiovascular MR will proliferate as promising new avenues of research are explored.

References

1. Saini S, Frankel RB, Stark DD, Ferrucci JT, Jr. Magnetism: a primer and review. Ajr 1988;150:735-743.
2. Pohost GM, Hung L, Doyle M. Clinical use of cardiovascular magnetic resonance. Circulation 2003;108:647-653.
3. Higgins CB, Roos Ad. MRI and CT of the cardiovascular system. 2nd ed. Philadelphia: Lippincott Williams & Wilkins;2006.
4. Shellock FG, Crues JV, 3rd. MR Safety and the American College of Radiology White Paper. Ajr 2002;178:1349-1352.
5. Martin ET, Coman JA, Shellock FG, Pulling CC, Fair R, Jenkins K. Magnetic resonance imaging and cardiac pacemaker safety at 1.5-Tesla. J Am Coll Cardiol 2004;43:1315-1324.
6. Pennell DJ, Sechtem UP, Higgins CB, Manning WJ, Pohost GM, Rademakers FE, van Rossum AC, Shaw LJ, Yucel EK. Clinical indications for cardiovascular magnetic resonance (CMR): Consensus Panel report. J Cardiovasc Magn Reson 2004;6:727-765.
7. Hendel RC, Patel MR, Kramer CM, Poon M, Hendel RC, Carr JC, Gerstad NA, Gillam LD, Hodgson JM, Kim RJ, Kramer CM, Lesser JR, Martin ET, Messer JV, Redberg RF, Rubin GD, Rumsfeld JS, Taylor AJ, Weigold WG, Woodard PK, Brindis RG, Hendel RC, Douglas PS, Peterson ED, Wolk MJ, Allen JM, Patel MR. ACCF/ACR/SCCT/SCMR/ASNC/NASCI/SCAI/SIR 2006 appropriateness criteria for cardiac computed tomography and cardiac magnetic resonance imaging: a report of the American College of Cardiology Foundation Quality Strategic Directions Committee Appropriateness Criteria Working Group, American College of Radiology, Society of Cardiovascular Computed Tomography, Society for Cardiovascular Magnetic Resonance, American Society of Nuclear Cardiology, North American Society for Cardiac Imaging, Society for Cardiovascular Angiography and Interventions, and Society of Interventional Radiology. J Am Coll Cardiol 2006;48:1475-1497.
8. Budoff MJ, Cohen MC, Garcia MJ, Hodgson JM, Hundley WG, Lima JA, Manning WJ, Pohost GM, Raggi PM, Rodgers GP, Rumberger JA, Taylor AJ, Creager MA, Hirshfeld JW, Jr., Lorell BH, Merli G, Rodgers GP, Tracy CM, Weitz HH. ACCF/AHA clinical competence statement on cardiac imaging with computed tomography and magnetic resonance: a report of the American College of Cardiology Foundation/American Heart Association/American College of Physicians Task Force on Clinical Competence and Training. J Am Coll Cardiol 2005;46:383-402.
9. Rehr RB, Malloy CR, Filipchuk NG, Peshock RM. Left ventricular volumes measured by MR imaging. Radiology 1985;156:717-719.
10. 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;67:1413-1420.
11. Dell'Italia LJ, Blackwell GG, Pearce DJ, Thorn B, Pohost GM. Assessment of ventricular volumes using cine magnetic resonance in the intact dog: a comparison of measurement methods. Invest Radiol 1994;29:162-167.
12. Lawson MA, Blackwell GG, Davis ND, Roney M, Dell'Italia LJ, Pohost GM. Accuracy of biplane long-axis left ventricular volume

determined by cine magnetic resonance imaging in patients with regional and global dysfunction. Am J Cardiol 1996;77:1098-1104.
13. Lotan CS, Cranney GB, Bouchard A, Bittner V, Pohost GM. The value of cine nuclear magnetic resonance imaging for assessing regional ventricular function. J Am Coll Cardiol 1989;14:1721-1729.
14. Cranney GB, Lotan CS, Dean L, Baxley W, Bouchard A, Pohost GM. Left ventricular volume measurement using cardiac axis nuclear magnetic resonance imaging: Validation by calibrated ventricular angiography. Circulation 1990;82:154-163.
15. McCrohon JA, Moon JC, Prasad SK, McKenna WJ, Lorenz CH, Coats AJ, Pennell DJ. Differentiation of heart failure related to dilated cardiomyopathy and coronary artery disease using gadolinium-enhanced cardiovascular magnetic resonance. Circulation 2003;108:54-59.
16. Assomull RG, Prasad SK, Lyne J, Smith G, Burman ED, Khan M, Sheppard MN, Poole-Wilson PA, Pennell DJ. Cardiovascular magnetic resonance, fibrosis, and prognosis in dilated cardiomyopathy. J Am Coll Cardiol 2006;48:1977-1985.
17. Bello D, Shah DJ, Farah GM, Di Luzio S, Parker M, Johnson MR, Cotts WG, Klocke FJ, Bonow RO, Judd RM, Gheorghiade M, Kim RJ. Gadolinium cardiovascular magnetic resonance predicts reversible myocardial dysfunction and remodeling in patients with
18. Liu PP, Yan AT. Cardiovascular magnetic resonance for the diagnosis of acute myocarditis: prospects for detecting myocardial inflammation. J Am Coll Cardiol 2005;45:1823-1825.
19. Mahrholdt H, Goedecke C, Wagner A, Meinhardt G, Athanasiadis A, Vogelsberg H, Fritz P, Klingel K, Kandolf R, Sechtem U. Cardiovascular magnetic resonance assessment of human myocarditis: a comparison to histology and molecular pathology. Circulation 2004;109:1250-1258.
20. Mahrholdt H, Wagner A, Deluigi CC, Kispert E, Hager S, Meinhardt G, Vogelsberg H, Fritz P, Dippon J, Bock CT, Klingel K, Kandolf R, Sechtem U. Presentation, patterns of myocardial damage, and clinical course of viral myocarditis. Circulation 2006;114:1581-1590.
21. Abdel-Aty H, Boye P, Zagrosek A, Wassmuth R, Kumar A, Messroghli D, Bock P, Dietz R, Friedrich MG, Schulz-Menger J. Diagnostic performance of cardiovascular magnetic resonance in patients with suspected acute myocarditis: comparison of different approaches. J Am Coll Cardiol 2005;45:1815-1822.
22. Moon JC, Reed E, Sheppard MN, Elkington AG, Ho SY, Burke M, Petrou M, Pennell DJ. The histologic basis of late gadolinium enhancement cardiovascular magnetic resonance in hypertrophic cardiomyopathy. J Am Coll Cardiol 2004;43:2260-2264.
23. Moon JC, McKenna WJ, McCrohon JA, Elliott PM, Smith GC, Pennell DJ. Toward clinical risk assessment in hypertrophic cardiomyopathy with gadolinium cardiovascular magnetic resonance. J Am Coll Cardiol 2003;41:1561-1567.
24. Moon JC, Fisher NG, McKenna WJ, Pennell DJ. Detection of apical hypertrophic cardiomyopathy by cardiovascular magnetic resonance in patients with non-diagnostic echocardiography. Heart 2004;90:645-649.
25. Moon JC, Mogensen J, Elliott PM, Smith GC, Elkington AG, Prasad SK, Pennell DJ, McKenna WJ. Myocardial late gadolinium enhancement cardiovascular magnetic resonance in hypertrophic cardiomyopathy caused by mutations in troponin I. Heart 2005;91:1036-1040.
26. Schulz-Menger J, Abdel-Aty H, Busjahn A, Wassmuth R, Pilz B, Dietz R, Friedrich MG. Left ventricular outflow tract planimetry by cardiovascular magnetic resonance differentiates obstructive from non-obstructive hypertrophic cardiomyopathy. J Cardiovasc Magn Reson 2006;8:741-746.
27. Maceira AM, Joshi J, Prasad SK, Moon JC, Perugini E, Harding I, Sheppard MN, Poole-Wilson PA, Hawkins PN, Pennell DJ. Cardiovascular magnetic resonance in cardiac amyloidosis. Circulation 2005;111:186-193.
28. Schulz-Menger J, Wassmuth R, Abdel-Aty H, Siegel I, Franke A, Dietz R, Friedrich MG. Patterns of myocardial inflammation and scarring in sarcoidosis as assessed by cardiovascular magnetic resonance. Heart 2006;92:399-400.
29. Pennell D. MRI and iron-overload cardiomyopathy in thalassaemia. Circulation 2006;113:43-44.
30. Sen-Chowdhry S, Prasad SK, Syrris P, Wage R, Ward D, Merrifield R, Smith GC, Firmin DN, Pennell DJ, McKenna WJ. Cardiovascular magnetic resonance in arrhythmogenic right ventricular cardiomyopathy revisited: comparison with task force criteria and genotype. J Am Coll Cardiol 2006;48:2132-2140.
31. Bluemke DA, Krupinski EA, Ovitt T, Gear K, Unger E, Axel L, Boxt LM, Casolo G, Ferrari VA, Funaki B, Globits S, Higgins CB, Julsrud P, Lipton M, Mawson J, Nygren A, Pennell DJ, Stillman A, White RD, Wichter T, Marcus F. MR Imaging of arrhythmogenic right ventricular cardiomyopathy: morphologic findings and interobserver reliability. Cardiology 2003;99:153-162.
32. Kumar A, Abdel-Aty H, Kriedemann I, Schulz-Menger J, Gross CM, Dietz R, Friedrich MG. Contrast-enhanced cardiovascular magnetic resonance imaging of right ventricular infarction. J Am Coll Cardiol 2006;48:1969-1976.
33. Kim RJ, Fieno DS, Parrish TB, Harris K, Chen EL, Simonetti O, Bundy J, Finn JP, Klocke FJ, Judd RM. Relationship of MRI delayed contrast enhancement to irreversible injury, infarct age, and contractile function. Circulation 1999;100:1992-2002.
34. Kim RJ, Wu E, Rafael A, Chen EL, Parker MA, Simonetti O, Klocke FJ, Bonow RO, Judd RM. The use of contrast-enhanced magnetic resonance imaging to identify reversible myocardial dysfunction. N Engl J Med 2000;343:1445-1453.
35. Yan AT, Shayne AJ, Brown KA, Gupta SN, Chan CW, Luu TM, Di Carli MF, Reynolds HG, Stevenson WG, Kwong RY. Characterization of the peri-infarct zone by contrast-enhanced cardiac magnetic resonance imaging is a powerful predictor of post-myocardial infarction mortality. Circulation 2006;114:32-39.
36. Thiele H, Kappl MJ, Conradi S, Niebauer J, Hambrecht R, Schuler G. Reproducibility of chronic and acute infarct size measurement by delayed enhancement-magnetic resonance imaging. J Am Coll Cardiol 2006;47:1641-1645.
37. Hillenbrand HB, Kim RJ, Parker MA, Fieno DS, Judd RM. Early assessment of myocardial salvage by contrast-enhanced magnetic resonance imaging. Circulation 2000;102:1678-1683.
38. 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;94:3318-3326.
39. Shan K, Constantine G, Sivananthan M, Flamm SD. Role of cardiac magnetic resonance imaging in the assessment of myocardial viability. Circulation 2004;109:1328-1334.
40. Wagner A, Mahrholdt H, Thomson L, Hager S, Meinhardt G, Rehwald W, Parker M, Shah D, Sechtem U, Kim RJ, Judd RM. Effects of time, dose, and inversion time for acute myocardial infarct size measurements based on magnetic resonance imaging-delayed contrast enhancement. J Am Coll Cardiol 2006;47:2027-2033.
41. Wagner A, Mahrholdt H, Holly TA, Elliott MD, Regenfus M, Parker M, Klocke FJ, Bonow RO, Kim RJ, Judd RM. Contrast-enhanced

MRI and routine single photon emission computed tomography (SPECT) perfusion imaging for detection of subendocardial myocardial infarcts: an imaging study. Lancet 2003;361:374-379.

42. Moon JC, De Arenaza DP, Elkington AG, Taneja AK, John AS, Wang D, Janardhanan R, Senior R, Lahiri A, Poole-Wilson PA, Pennell DJ. The pathologic basis of Q-wave and non-Q-wave myocardial infarction: a cardiovascular magnetic resonance study. J Am Coll Cardiol 2004;44:554-560.

43. Sievers B, Elliott MD, Hurwitz LM, Albert TS, Klem I, Rehwald WG, Parker MA, Judd RM, Kim RJ. Rapid detection of myocardial infarction by subsecond, free-breathing delayed contrast-enhancement cardiovascular magnetic resonance. Circulation 2007;115:236-244.

44. Klem I, Heitner JF, Shah DJ, Sketch MH, Jr., Behar V, Weinsaft J, Cawley P, Parker M, Elliott M, Judd RM, Kim RJ. Improved detection of coronary artery disease by stress perfusion cardiovascular magnetic resonance with the use of delayed enhancement infarction imaging. J Am Coll Cardiol 2006;47:1630-1638.

45. Kramer CM. When two tests are better than one: adding late gadolinium enhancement to first-pass perfusion cardiovascular magnetic resonance. J Am Coll Cardiol 2006;47:1639-1640.

46. Lin SJ, Brown PA, Watkins MP, Williams TA, Lehr KA, Liu W, Lanza GM, Wickline SA, Caruthers SD. Quantification of stenotic mitral valve area with magnetic resonance imaging and comparison with Doppler ultrasound. J Am Coll Cardiol 2004;44:133-137.

47. Kupfahl C, Honold M, Meinhardt G, Vogelsberg H, Wagner A, Mahrholdt H, Sechtem U. Evaluation of aortic stenosis by cardiovascular magnetic resonance imaging: comparison with established routine clinical techniques. Heart 2004;90:893-901.

48. Caruthers SD, Lin SJ, Brown P, Watkins MP, Williams TA, Lehr KA, Wickline SA. Practical value of cardiac magnetic resonance imaging for clinical quantification of aortic valve stenosis: comparison with echocardiography. Circulation 2003;108:2236-2243.

49. Gelfand EV, Hughes S, Hauser TH, Yeon SB, Goepfert L, Kissinger KV, Rofsky NM, Manning WJ. Severity of mitral and aortic regurgitation as assessed by cardiovascular magnetic resonance: optimizing correlation with Doppler echocardiography. J Cardiovasc Magn Reson 2006;8:503-507.

50. Kon MW, Myerson SG, Moat NE, Pennell DJ. Quantification of regurgitant fraction in mitral regurgitation by cardiovascular magnetic resonance: comparison of techniques. J Heart Valve Dis 2004;13:600-607.

51. Cranney GB, Benjelloun H, Perry GJ, Lotan CS, Blackwell JG, Coghlan CH, Pohost GM. Rapid assessment of aortic regurgitation and left ventricular function using cine nuclear magnetic resonance imaging and the proximal convergence zone. Am J Cardiol 1993;71:1074-1081.

52. Oyama N, Komuro K, Nambu T, Manning WJ, Miyasaka K. Computed tomography and magnetic resonance imaging of the pericardium: anatomy and pathology. Magn Reson Med Sci 2004;3:145-152.

53. Prasad SK, Soukias N, Hornung T, Khan M, Pennell DJ, Gatzoulis MA, Mohiaddin RH. Role of magnetic resonance angiography in the diagnosis of major aortopulmonary collateral arteries and partial anomalous pulmonary venous drainage. Circulation 2004;109:207-214.

54. Babu-Narayan SV, Goktekin O, Moon JC, Broberg CS, Pantely GA, Pennell DJ, Gatzoulis MA, Kilner PJ. Late gadolinium enhancement cardiovascular magnetic resonance of the systemic right ventricle in adults with previous atrial redirection surgery for transposition of the great arteries. Circulation 2005;111:2091-2098.

55. Manning WJ, Li W, Edelman RR. A preliminary report comparing magnetic resonance coronary angiography with conventional angiography. N Engl J Med 1993;328:828-832.

56. McConnell MV, Stuber M, Manning WJ. Clinical role of coronary magnetic resonance angiography in the diagnosis of anomalous coronary arteries. J Cardiovasc Magn Reson 2000;2:217-224.

57. Isbell DC, Meyer CH, Rogers WJ, Epstein FH, Dimaria JM, Harthun NL, Wang H, Kramer CM. Reproducibility and reliability of atherosclerotic plaque volume measurements in peripheral arterial disease with cardiovascular magnetic resonance. J Cardiovasc Magn Reson 2007;9:71-76.

58. Kim WY, Astrup AS, Stuber M, Tarnow L, Falk E, Botnar RM, Simonsen C, Pietraszek L, Hansen PR, Manning WJ, Andersen NT, Parving HH. Subclinical coronary and aortic atherosclerosis detected by magnetic resonance imaging in type 1 diabetes with and without diabetic nephropathy. Circulation 2007;115:228-235.

59. Buchthal SD, den Hollander JA, Merz CN, Rogers WJ, Pepine CJ, Reichek N, Sharaf BL, Reis S, Kelsey SF, Pohost GM. Abnormal myocardial phosphorus-31 nuclear magnetic resonance spectroscopy in women with chest pain but normal coronary angiograms. N Engl J Med 2000;342:829-835.