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Performing cardiac MR imaging: an overview

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Cardiovascular disease is the major cause of death in the United States and many other countries. It absorbs a large portion of health-care budgets and, thus, has not only social but also economic consequences. Despite many well-established techniques for cardiac disease diagnosis, a full diagnostic work-up may require examinations with several different imaging modalities. This is both expensive and time-consuming. MR imaging of the heart has the potential to provide information often supplied by a number of modalities in a single examination. Cardiac MR imaging provides both anatomic and functional diagnosis of acquired and congenital heart disease. It is, moreover, a precise technique for quantifying ventricular dimension and function [1] and, more recently, has been used to assess myocardial viability and perfusion [2,3]. With recent technical advances in the field of cardiovascular MR imaging, there will be an increased demand for clinical cardiac MR imaging. This article provides the reader with a basic understanding of cardiac MR imaging and its practical applications.

Cardiac MR imaging techniques: general principles

Monitoring of a cardiac MR imaging examination by a physician is essential. This permits the

physician to interrogate findings further as they are demonstrated during the exam. Communication with the referring clinician, moreover, is vital. Thus, the specific reason for the performance of the examination can be determined, permitting it to be tailored to the given question. Communication with the patient is also important. First, the patient should be screened for any contraindications to the MR imaging exam. This routinely includes queries regarding the presence of pacemakers, ferromagnetic implants, or intracranial aneurysm clips. If pharmacologic myocardial stress agents such as adenosine or dobutamine are to be included in the protocol, the patient should also be queried about relative contraindications to these agents and instructed not to eat prior to the examination. In addition, patients scheduled to receive adenosine should be informed to refrain from partaking of any caffeine, chocolate, or theophylline-containing drugs during the 24-hour period prior to the MRI. They should be instructed that they may feel flushed or nauseated. Instructing all patients in breath-holding techniques prior to patient entrance into the scanner is an efficient method of improving image quality. Patients should also be informed that motion during scanning can limit the quality of the exam.

Cardiac gating and physiologic monitoring

In most instances, in order to avoid image blur, MR image acquisition must be limited to a

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constant portion of the cardiac cycle. This is accomplished through cardiac gating. Gating can be triggered to the QRS complex of the electrocardiogram (ECG) or, if that fails, to a peripheral pulse. This coordination of imaging to cardiac contraction reduces flow and motion artifacts. The most effective gating involves the use of the electrocardiographic signal (ECG gating). The objective of ECG gating is to acquire an R wave that is substantially larger than the T or S wave of the ECG. The most common configuration for placement of ECG leads for cardiac gating is shown here (Fig. 1). It is important to obtain good skin contact by shaving the skin if necessary and cleansing it, preferably with commercially available abrasive agents, and by the use of ECG electrodes with coupling gels. Even after obtaining a strong R wave prior to the examination, once the patient enters the magnet or after the MR imaging has started, additional noise caused by the magnetic field and the RF pulse may obscure the R wave. Repositioning the electrodes to obtain a better ECG signal and the use of newer fiberoptic leads to reduce interference may help to reduce some of these problems.

In addition to cardiac gating, physiologic monitoring is necessary during many types of cardiac MR examinations. This is especially true if the examination is being performed for assessment of ischemic cardiac disease, or when anesthesia or

sedation is administered for pediatric patients. MR-compatible systems are now available, permitting continuous monitoring of pulse, blood pressure, oxygenation, and heart rhythm throughout the MR examination.

Cardiac MR pulse sequences

With recent technologic advances in MR hardware and software, there are now many pulse sequences available for cardiac MR imaging. Pulse sequences currently used for cardiac imaging can be generally divided into dark-blood and bright-blood techniques. In dark-blood or black blood techniques, fast flowing blood is black or of low signal intensity. These techniques produce images for anatomic delineation of blood vessel lumen and cardiac chambers [4,5]. Examples of this technique include conventional spin echo (SE), breath-hold turbo or fast spin echo (TSE, FSE), and half-Fourier turbo spin echo sequences with double inversion recovery (IR) pulses to suppress blood signal (HASTE, double-IR TSE/FSE).

Generally speaking, for dark-blood sequences, the effective (or total) repetition time (TR) should be approximately 85% to 90% of (or 100 millisecond less than) the patient's $R-R$ interval (time between R waves). For instance, the actual TR plus any trigger delay (TD), if necessary, will be approximately 85% to 90% of the $R-R$ interval.

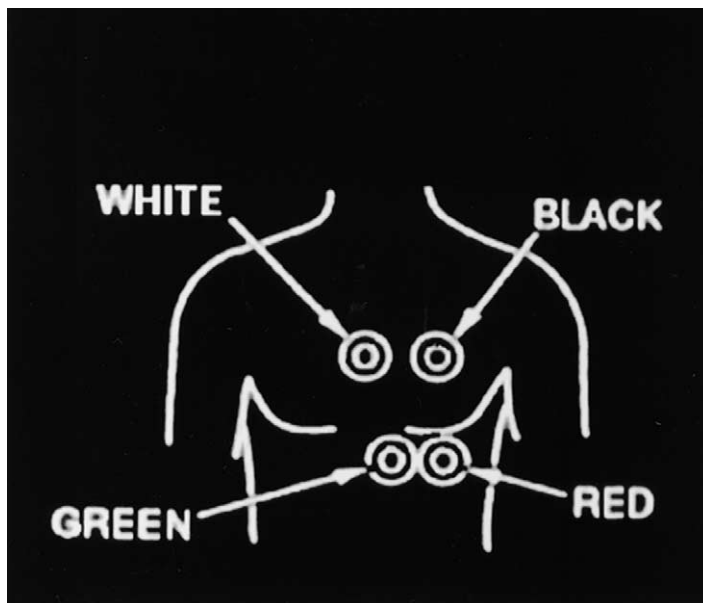


Fig. 1. Cardiac gating is the most commonly used configuration for ECG lead placement.

Note that, for T1-weighting, TR should be less than 900 milliseconds. For double IR sequences, which are dark blood but T2-weighted, the TR should remain long and the acquisition window should cover two heart beats [6,7].

In bright-blood techniques, flowing blood is white or of high signal intensity. These are routinely gradient recalled echo sequences (GRE). Cine GRE sequences that produce a motion picture loop throughout the various phases of the cardiac cycle are particularly useful. Currently, GRE images can be obtained with segmented k-space technique and cardiac gating. A single slice multi-phase or multislice single cardiac phase mode can be performed in a short breath-hold period. Examples for various vendors include TurboFLASH (fast low-angled shot), fast SPGR (spoiled gradient recalled echo), and TFE/FFE (turbo field echo/fast field echo). The parameters for these sequences are adjusted to the patient's breath-holding capability and heart rate. For patients with slower heart rates, sequences that provide a greater number of lines per segment can help to shorten the required breath-hold. The number of phases of the cardiac study should be set according to the formula:

$$\begin{aligned} &\text{Number of cardiac phases} \\ &= (\text{R-R interval}) \times 85\% / \text{TR}_{\text{effective}} [8,9] \end{aligned}$$

Newer, fast, and short echo time (TE) GRE sequences, with completely refocused gradients, provide excellent contrast between the myocardium and blood pool and are commercially known as trueFISP, balanced FFE, or FIESTA.

Various types of MR pulse sequences provide different information. It is important to know that functional abnormalities may not be examined directly by dark-blood techniques, but only inferred by analysis of resultant morphologic changes [8]. For example, aortic regurgitation can be inferred from the findings of an enlarged left ventricle and dilated ascending aorta. A cine-blood technique with high temporal resolution, however, would allow functional analysis, including demonstration of the regurgitant jet and quantification of aortic regurgitation. On the other hand, most cine acquisitions have lower contrast resolution resulting from the short flip angle and short TR employed. The exceptions are the completely refocused GRE sequences that provide excellent contrast-to-noise ratio (CNR). As a result, these trueFISP-type sequences are very useful for segmenting the myocardium from the blood pool and are excellent for functional assessment of the

myocardium. Nevertheless, it should be remembered that, because the TE is so short in these sequences, less dephasing occurs, decreasing the visibility of stenotic or regurgitant jets. In addition, these sequences are less useful than standard GRE cine sequences for the imaging of valve leaflets [9]. Thus, standard GRE sequences should be used in the assessment of cardiac valves or when attempting to identify intracardiac shunts, including atrial septal or ventricular septal defects. As general rule, imaging should begin with dark-blood sequences to obtain anatomic information and proceed with bright-blood techniques to assess functional abnormalities.

Cardiac imaging planes

The planes generally used for imaging the thorax are the three orthogonal planes of the thorax (transverse, sagittal, and coronal) with the patient supine. As the cardiac axes are not parallel to the body axes, however, sections parallel and orthogonal to cardiac axes (short axis and long axis of the heart) are often favored for cardiac imaging [10–12]. These have the advantage of generally corresponding to the planes used with other noninvasive cardiac imaging modalities. A phase array surface coil or dedicated cardiac coil is necessary to obtain a good signal to noise ratio (SNR). The examination usually begins with a general anatomic survey using a dark-blood technique in one or more of the three planes: axial, coronal, and sagittal.

Scout images: transverse or axial plane

The first plane that may be obtained is an axial survey of the chest. This is the imaging plane most familiar to the general radiologist. Most anatomic structures are easy to identify on this plane, and the overview permits assessment of adjacent thoracic pathology. Transverse or axial images (Fig. 2) at the base of the heart display the normal relationships of the great vessels and cardiac chambers. Portions of the proximal coronary arteries near their origin and pericardium also can be displayed. Axial sections are especially useful in the evaluation of congenital heart lesions and may complement morphologic evaluation of patients with acquired heart disease.

Coronal and sagittal planes

For anatomic imaging, coronal and sagittal planes also can be acquired. The coronal plane

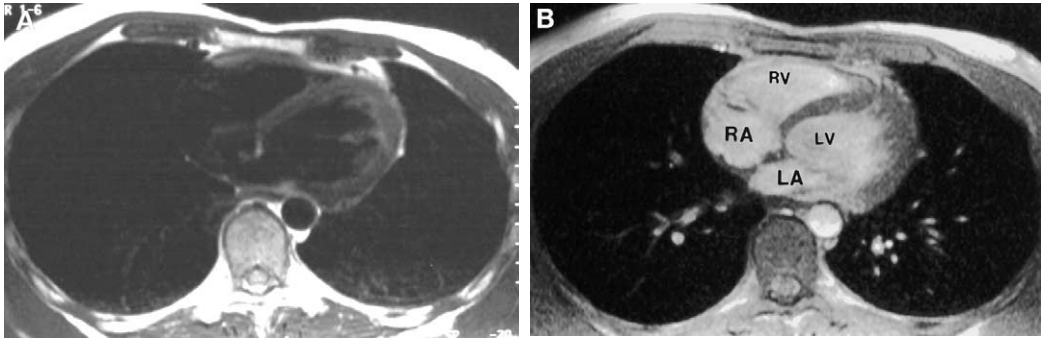


Fig. 2. Transverse or transaxial images. (A) Dark-blood technique: single slice breath-hold turbo spin echo T1 is often used to assess cardiac morphology. (B) Bright-blood technique: breath-hold cine gradient recalled echo sequence is useful in assessing cardiac function. LA, left atrium; RA, right atrium; LV, left ventricle; RV, right ventricle.

(Fig. 3) is often effective for demonstrating the aortic valve. More posteriorly, coronal planes show the entrance of the upper lobe pulmonary veins into the left atrium. It also is useful for showing the diaphragmatic surface of the left ventricle and the extension of pericardium over the proximal portion of the great arteries.

Double-oblique (oblique-sagittal) planes through the pulmonary trunk and aorta (Fig. 4) are useful for demonstrating the pulmonic and aortic valves and outflow tracts. Other anatomy well seen on double-oblique images includes the connections of the superior and inferior vena cavae to right atrium, as well as one or more sinuses of Valsalva. The plane parallel to the axis

of aortic arch, seen on axial images, is used to obtain oblique-sagittal images for evaluation of aortic dissection.

After obtaining any desired orthogonal views, many cardiac MR studies require images parallel to the true short and long axis of the heart. Because the heart lies obliquely in the thoracic cavity, the true long axis of the heart is oriented approximately 45° to the midsagittal plane of the thoracic spine. These short and long axis views of the heart are preferred for quantification of ventricular dimensions and regional contractile function [10–12]. Because similar views are obtained during the echocardiogram, these planes are often familiar to the cardiologist.

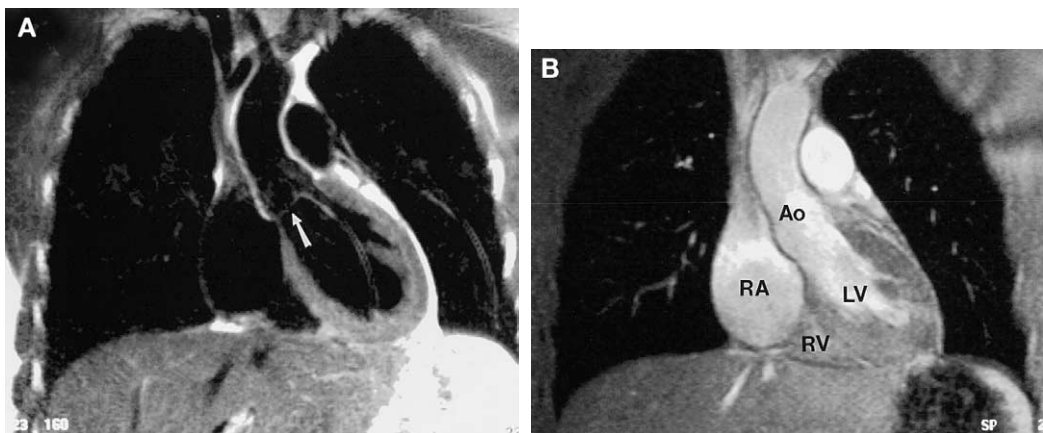


Fig. 3. Coronal images. (A) Dark-blood technique: turbo spin echo T1. This plane nicely demonstrates the aortic valve (arrow). A plane set through the midaortic valve and LV apex provides a 5-chambered view. (B) Bright-blood technique: cine gradient recalled echo. This plane can be used to assess the jet of aortic stenosis or insufficiency. Ao, aorta; LV, left ventricle; RV, right ventricle; RA, right atrium.

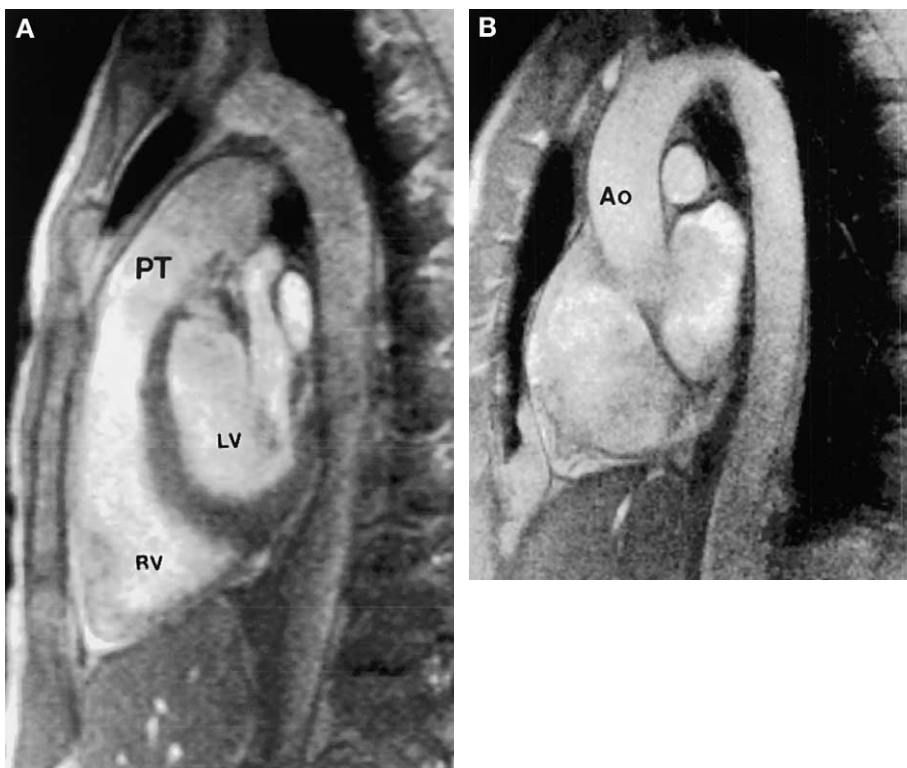


Fig. 4. Bright-blood double-oblique images through pulmonary (A) trunk and (B) aorta (B). Ao, aorta; PT, pulmonary trunk.

Vertical long axis plane (two-chamber view)

The vertical long axis plane or two-chamber view (Fig. 5) is used to evaluate the left heart structures. It reveals information concerning superior-inferior and anteroposterior anatomic relationships and is useful for assessing the mitral valve. This plane is prescribed from an axial image that shows the largest oblique diameter of the left ventricle.

Horizontal long axis plane (four-chamber view)

Images prescribed from the left ventricular (LV) long axis (two-chamber view), set up through the posterior wall of the left atrium, mitral valve, and LV apex, provide a horizontal long axis or four-chamber view of the heart (Fig. 6). The horizontal long axis plane or four-chamber view displays the relationship of the four cardiac chambers to each other on a single image. Cine GRE images obtained in this plane display mitral, tricuspid, and aortic valve function as well as right and left ventricular contraction. This image plane also

can be obtained by oblique transverse imaging through a short-axis scout.

Short axis plane

The short axis plane (Fig. 7) is obtained when images are prescribed perpendicular to the LV long axis seen on a two-chamber view. It shows the true cross-sectional dimensions of cardiac chambers. Initial images in this plane are performed through the papillary muscles, with subsequent images performed toward the heart apex and base. In this plane, the LV myocardium is displayed as a doughnut-shaped ring. Cine GRE images allow visualization and quantification of systolic myocardial wall thickening. This plane also can be used for quantifying LV and right ventricular (RV) volume and mass as well as ventricular ejection fraction when the appropriate software is available. Differences between RV and LV stroke volumes can be used to estimate valvular regurgitation or shunt ratios.

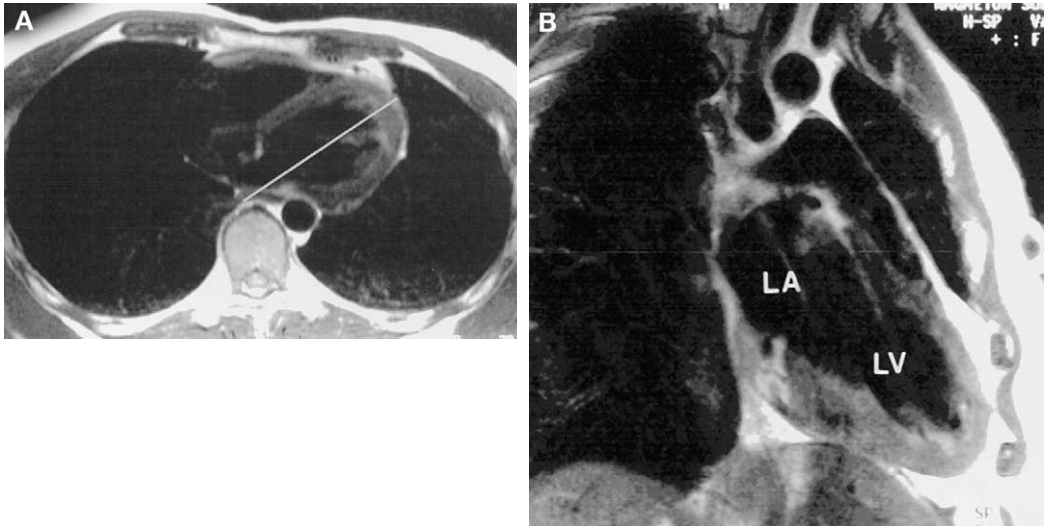


Fig. 5. Two-chambered long axis view. An image obtained parallel to the line shown on (A) the transaxial image provides (B) the vertical long axis plane or two-chamber view. This image plane is ideal for assessing the mitral valve. LA, left atrium; LV, left ventricle.

Long axis view through aortic and mitral valves

This view, obtained through the LV apex and aortic outflow tract, is prescribed from a coronal image (Fig. 8). Theane demonstrates both the aortic and mitral valves. As it displays portions of the left ventricle, right ventricle, left atrium,

right atrium, and ascending aorta, it is sometimes known as the five-chamber view.

Routine clinical studies with cardiac MR imaging

Reasons for a cardiac MR examination most frequently include pre- and postoperative congenital

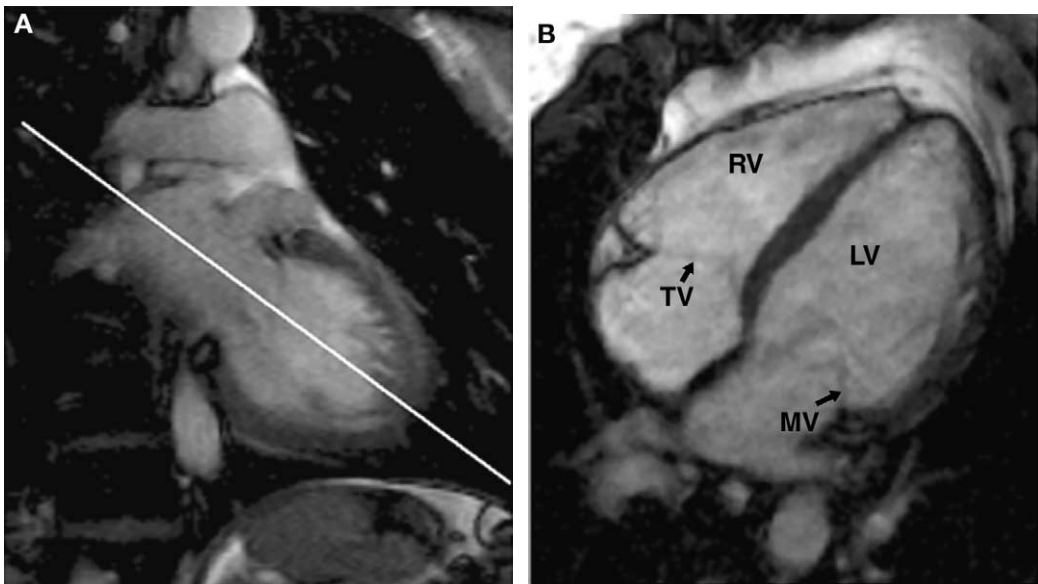


Fig. 6. Horizontal long axis plane or 4-chamber view. An image obtained parallel to the line shown on (A) the vertical long-axis image provides (B) the horizontal long axis or four-chamber view. In this image, both the mitral and tricuspid valves can be assessed. RV, right ventricle; LV, left ventricle; MV, mitral valve; TV, tricuspid valve.

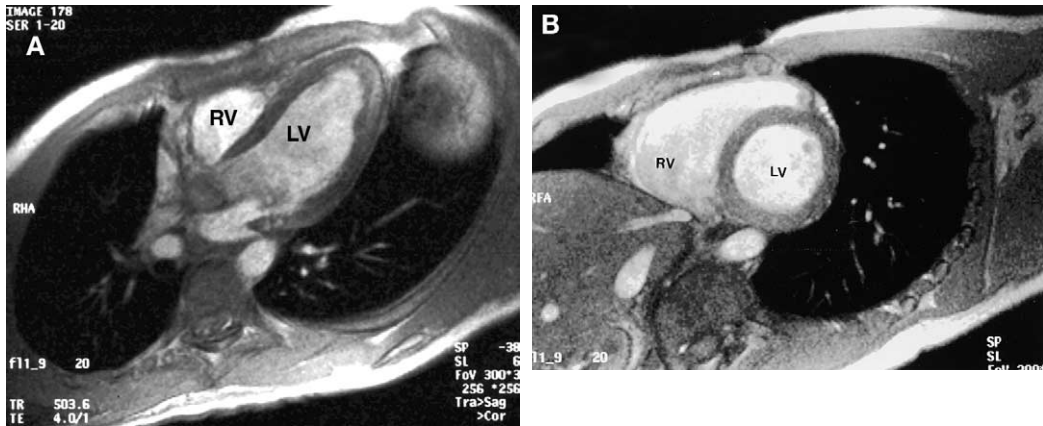


Fig. 7. Short axis plane. Bright-blood technique cine GRE. This image plane is favored in the assessment of LV function. Multiple contiguous short axis images are obtained from the base of the heart to (A) the apex to provide images in (B) the short axis orientation. Functional analysis software then can be used to calculate stroke volume, ejection fraction, and myocardial mass. A horizontal 4-chamber view can be prescribed from a short axis image by drawing a line perpendicular to the LV septum. RV, right ventricle; LV, left ventricle.

heart disease assessment, clinical suspicion of RV dysplasia, pericardial disease (constrictive pericarditis versus restrictive cardiomyopathy), cardiac tumors, anomalous coronary arteries, and valvular disease. In addition to the indications described above, MR imaging now can be used to assess myocardial function and viability. Sequences are also being investigated to assess for proximal coronary artery stenoses. In the following section, we will discuss and illustrate each indication, MR imaging techniques including pulse sequences, and

some clinical cases. Detailed coverage of these topics are included in articles throughout this issue.

Adult congenital heart disease

With better cardiothoracic surgical techniques and technologic advances, many pediatric patients with congenital heart disease (CHD) survive into adulthood and present with sequelae of their surgeries and disease. These include patients with

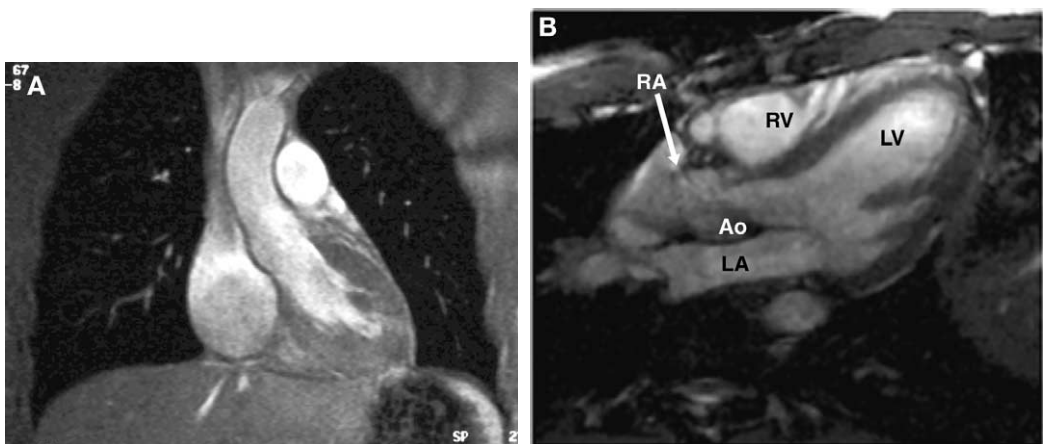


Fig. 8. A line drawn through the LV apex and aortic outflow as prescribed from (A) a coronal image provides a long axis view sometimes known as (B) the 5-chamber view. This view demonstrates both aortic valve and mitral valve function and displays portions of the right and left ventricles and atria and the aorta (5 chambers). RV, right ventricle; LV, left ventricle; LA, left atrium; RA, right atrium; Ao, aorta.

transposition of great vessels (TGA) and patients with tetralogy of Fallot (TOF). Cardiac MR imaging can be used for postoperative follow-up in these patients to assess for occluded shunts (Waterston, Glenn, etc.), obstructed baffles, and stenotic homografts. Cardiac MR imaging also can be used for visualization of previously undetected disease such as patent ductus arteriosus, coarctation of aorta, atrial septal defects, restrictive ventriculoseptal defect (VSD), and anomalous pulmonary veins. To perform cardiac MR imaging for these conditions, one should identify the specific clinical question, know the anatomy of the relevant pathology and cardiac surgery, and be aware of the delayed complications typical of the performed surgery. Therefore, communication between the referring physician and the physician performing the cardiac MR imaging examination is essential. Also in difficult cases, one may obtain consultation via teleradiology with a trained cardiac MR radiologist in an academic center.

General MR imaging protocol for CHD

Black blood sequences such as HASTE, (double IR FSE/TSE), or TSE/FSE T1-weighted sequences are usually used. Bright-blood sequences such as sequential FLASH, FASTCARD, true-FISP, or FIESTA also can be used. Cine sequences (GRE) should be done through the area of suspected pathology to get functional information. Contrast-enhanced MR angiography can be used to assess peripheral pulmonary artery stenoses, bronchial collaterals (pulmonic atresia), or anomalous pulmonary veins.

Contrast enhanced MR imaging

In the cardiac MR assessment of adult patients with congenital heart disease, contrast enhanced MR angiography is useful for evaluation of the aorta, pulmonary artery stenoses, collaterals, and shunts, etc. (Fig. 9). Contrast enhanced MR

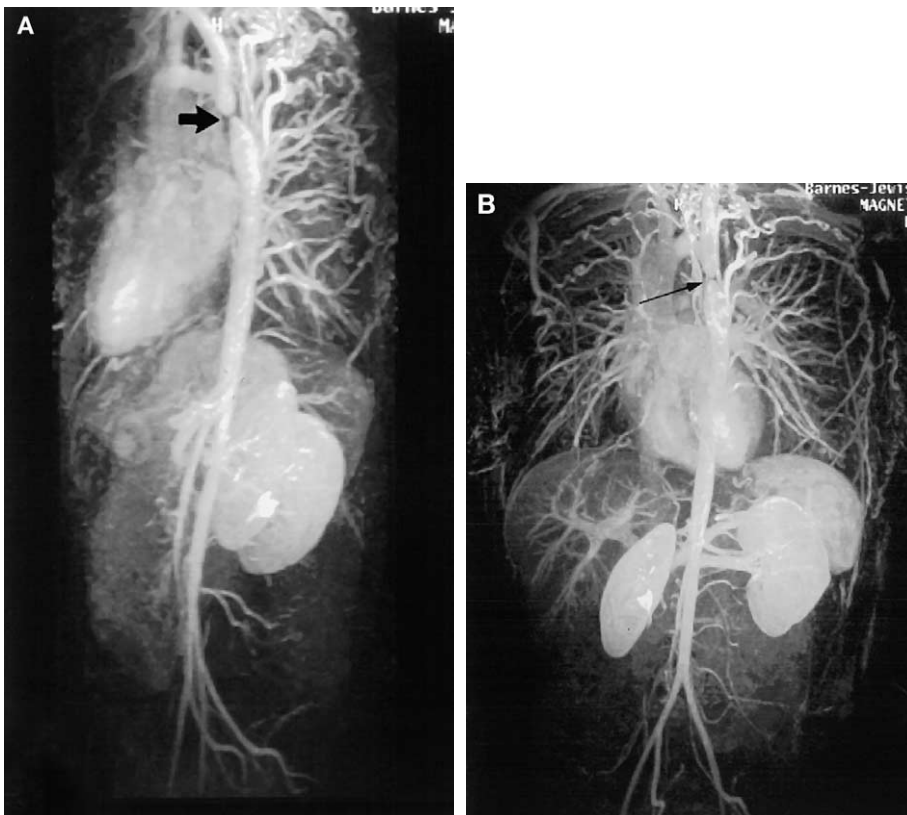


Fig. 9. A 20-year-old female patient with hypertension, unresponsive to medication. (A) lateral and (B) coronal views of contrast-enhanced 3-D MRA clearly show coarctation of descending aorta (*arrow*) and extensive collateral vessels.

imaging is a short breath-hold three-dimensional GRE sequence with short TR and TE and flip angle. No cardiac gating is needed. It requires a test-bolus injection or bolus tracking system such as CareBolus™ (Siemens Medical Systems, Erlangen, Germany) or SmartPrep™ (GE Medical Systems, Milwaukee, WI) to calculate the circulation time and obtain images with maximum arterial enhancement. Injection rate is usually 2 mL/sec of 0.2 mmol/Kg Gd-DTPA of a commercially available MR-compatible power injector is required. Images are usually obtained in a coronal orientation but also can be obtained in a double-oblique orientation to assess the aortic arch. Both pre- and postcontrast images are acquired with the precontrast image serving as a mask for image subtraction. After image acquisition, postprocessed three-dimensional maximum intensity projection (MIP) images can be created. These MIP images should always be evaluated together with source images in order to avoid misdiagnoses secondary to MIP-induced artifacts.

Newer sequences that allow near-real-time assessment of dynamic administration of a gadolinium-based contrast bolus now are also available. These sequences, though by necessity of lower resolution than nonreal-time sequences, are helpful in the assessment of shunts and fistulas [13].

Transposition of great arteries

In D-loop transposition of great arteries (TGA) (Fig. 10), the anatomic relationship of these arteries is reversed. The aortic valve arises anterior

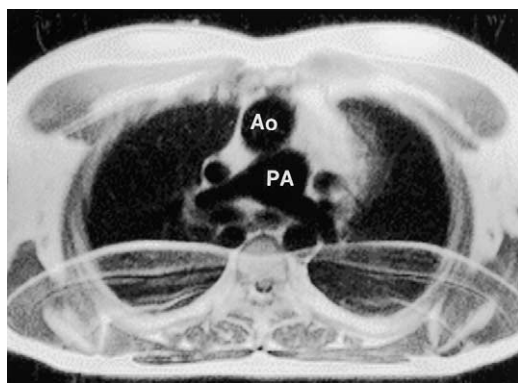


Fig. 10. D-loop transposition of the great arteries. Axial dark-blood HASTE. Note the aorta arising anterior and to the left of the main pulmonary artery. PA, pulmonary artery; Ao, aorta.

to the pulmonic valve. Aortic valve and aorta arise from the right ventricle, which is usually hypertrophied. The pulmonary valve and pulmonary artery arise from the left ventricle. In L-loop transposition, the aorta is left sided and arises from the right ventricle, which may at times be rudimentary. The pulmonary artery arises posteriorly and to the right of the aorta from the left ventricle. If the two ventricles are well developed and there is no interventricular communication, we refer to this entity as congenitally corrected transposition of the great vessels. At times, however, there is a large VSD with a rudimentary right ventricle underneath the aorta. The great arteries are transposed and the two ventricles are inverted. Repair of D-TGA is currently performed using an arterial switch procedure (Jatene). Previously, a Mustard or Senning baffle procedure was used. In the Mustard operation, the intra-atrial septum is removed and bovine pericardium creates anterior (systemic) and posterior (pulmonary venous) baffles (Fig. 11). Most often, the reason for performing an MR exam in these patients who have had a baffle is evaluation for baffle patency, including evaluation for possible stenoses that may develop at the superior vena cava (SVC) as it enters the superior limb of systemic baffle or at the pulmonary veins.

Tetralogy of Fallot

The classic components of TOF are a large ventricular septal defect (VSD), RV outflow tract obstruction, RV hypertrophy, and over-riding aorta. Complete repair of TOF is achieved with VSD closure, and infundibulectomy. Prior to complete repair, some patients undergo a palliative shunt in order to improve pulmonary blood flow. Shunts that commonly have been performed include the Blalock-Taussig, Waterston, Potts, and Glenn anastomosis. The Blalock-Taussig shunt connects the subclavian artery to the pulmonary artery. For evaluation of this shunt with MR, an oblique transverse plane is obtained. The Waterston shunt connects the ascending aorta to the right pulmonary artery. The Potts shunt connects the descending aorta and left pulmonary artery. The Waterston and Potts shunts are best evaluated with MR in the transverse plane. The Glenn shunt connects the SVC to the right pulmonary artery. Coronal images in the plane of the SVC are useful for MR evaluation of this shunt. MR examination in patients with shunts is often performed to assess for shunt stenosis or occlusion (Fig. 12). MR

imaging also can assess for the presence of a stenosis at homograft anastomosis or valve.

Patent ductus arteriosus

The patent ductus arteriosus (PDA) is a normal tubular structure that connects the underside of the descending aorta just distal to the origin of the left subclavian artery to the main or left pulmonary artery just beyond its origin. The ductus usually closes shortly after birth. It can remain patent, however, and occasionally can present in the adult patient. Cine GRE MR sequences can evaluate for the presence of PDA, or one can use a contrast-enhanced GRE technique. As illustrated in Fig. 13, the performance of nontraditional off-axis or orthogonal-plane images may help further to evaluate pathology.

Ventricular septal defect

The anatomic location of intracardiac shunts such as VSD or atrial septal defect (ASD) definitely can be demonstrated by MR imaging. In assessing for a small or restrictive VSD, ASD or patent foramen ovale GRE cine sequences are vital to visualize the jet caused by turbulent flow. The

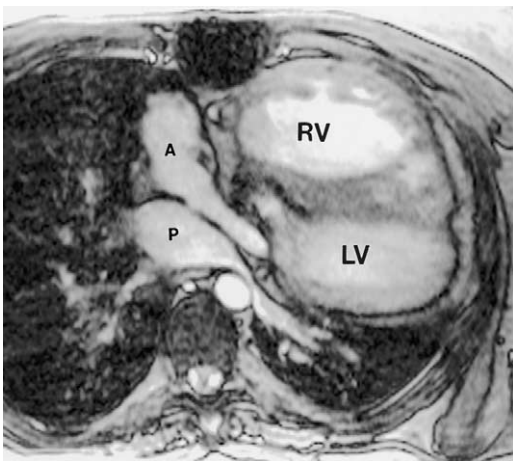


Fig. 11. Transaxial TrueFISP cine image shows a Mustard correction of D-loop transposition of the great arteries. The superior and inferior vena cava supply blood to the anterior baffle directing flow to the left ventricle and pulmonary arteries. The pulmonary veins supply blood to the posterior baffle directing flow to the right ventricle and aorta. The right ventricle, now the principal pumping chamber, has become large and thick-walled. A, anterior baffle; P, posterior baffle; RV, right ventricle; LV, left ventricle.

shunt may be missed if only black-blood anatomic imaging is obtained.

Anomalous pulmonary veins

Because of its multiplanar capability, MR is highly accurate in the diagnosis of partial or total anomalous pulmonary venous connection as well as several other anomalies of the venous system. Anomalous right upper-lobe pulmonary vein (Fig. 14) usually drains into SVC and often is associated with a sinus venosus ASD. An anomalous left upper-lobe pulmonary vein may look like a duplicated SVC but can be differentiated from SVC duplication by following the vessel back to its origin.

Arrhythmogenic RV dysplasia

One of the more frequent and important indications for cardiac MR imaging is the evaluation of patients with potential diagnosis of arrhythmogenic RV dysplasia. This condition is a primary disorder of the right ventricle with partial or total thinning and replacement of muscle by adipose or fibrous tissue and enlargement of the right chambers of the heart. Patients have ventricular arrhythmias and left bundle branch block on



Fig. 12. Axial cine GRE image shows a stenotic Waterston shunt in a patient with pulmonic atresia and hypoplastic right ventricle. The Waterston shunt connects the ascending aorta to the right pulmonary artery. Arrows point to a jet in right pulmonary artery.

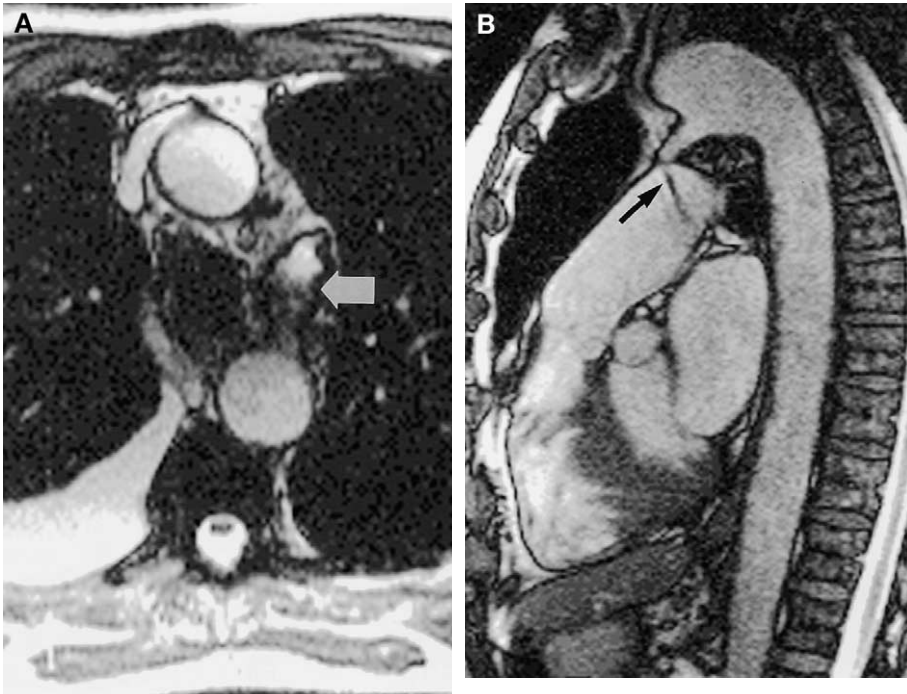


Fig. 13. (A) Transaxial true FISP image shows an abnormal structure (*white arrow*) adjacent to the aorta and superior pulmonary trunk. (B) True FISP sagittal image obtained in plane through the long axis of the structure seen on image A provides greater characterization and demonstrates that the structure is a patent ductus. Turbulent flow through the ductus produces a jet into the pulmonary trunk (*black arrow*).

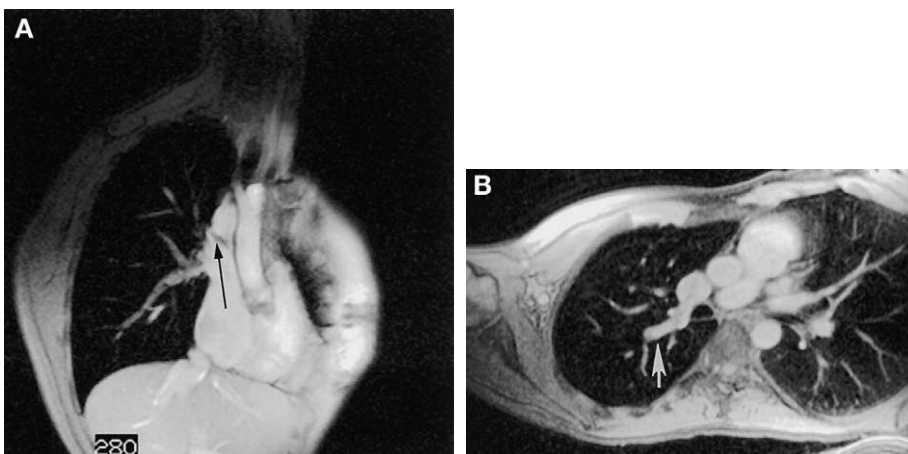


Fig. 14. Anomalous right upper-lobe pulmonary vein. Young woman with Turner's syndrome who had an enlarged RA seen on an echocardiogram. The etiology of the enlarged RA could not be determined. (A) An oblique cine image showed a dilated superior vena cava with a small jet (*black arrow*). (B) Additional imaging in (B) the plane of the jet showed an anomalous right upper-lobe pulmonary vein (*white arrow*).

ECG. The disease may lead to sudden death. RV dysplasia is familial in 30% of cases. Inheritance pattern is possibly autosomal dominant with variable expression and penetrance [14–16].

RV angiography and echocardiography cannot visualize pathologic structural changes of RV dysplasia in the myocardium. Even with endomyocardial biopsy, the diagnosis can be difficult because the disease rarely involves the septum, which is the typical sampling site. Patients are commonly referred for cardiac MR imaging [17,18].

MR findings in RV dysplasia

MR diagnosis is based on the identification of specific anatomic and functional abnormalities of the right ventricle, which include the following (Figs. 15, 16): thinning of the RV free wall, increased myocardial signal intensity from fatty replacement, decreased systolic wall thickening or motion (RV akinesis or dyskinesis) causing focal bulging at the site of myocardial fibrosis, diminished ejection fraction, and impaired ventricular filling in diastole. The right ventricle and atrium can be normal in size or dilated.

MR sequences

MR evaluation of RV dysplasia is achieved by using black-blood breath-hold sequences along with bright-blood cine imaging. Usually, one plane

is obtained in either the long axis or transverse image orientation, contiguous 5 mm slices with no gap. Sagittal or short axis images may also be useful. Cine sequences are very important to assess for areas of RV dysfunction (akinesis, dyskinesis, and focal bulge). Breath-hold fast SE (FSE/TSE T1) can also be performed without and with fat saturation through areas of suspicion. These images often provide sharper images than available with dark-blood HASTE but have the disadvantage in that usually only a single slice can be obtained during a breath-hold period.

Constrictive pericarditis versus restrictive cardiomyopathy

Because both entities have similar clinical signs and symptoms, MR imaging can be particularly useful in differentiating between constrictive pericarditis and restrictive cardiomyopathy. MR imaging is very useful in making this distinction because the pericardium has normal thickness in restrictive cardiomyopathy [19,20]. Constrictive pericarditis results from progressive pericardial fibrosis and calcification, leading to restriction of cardiac ventricles during diastole. Constriction may follow any pericardial injury that causes an inflammatory response such as infectious pericarditis, connective tissue disease, neoplasm, renal failure, cardiac surgery, and radiation therapy. The normal pericardium is very thin (1–2 mm).

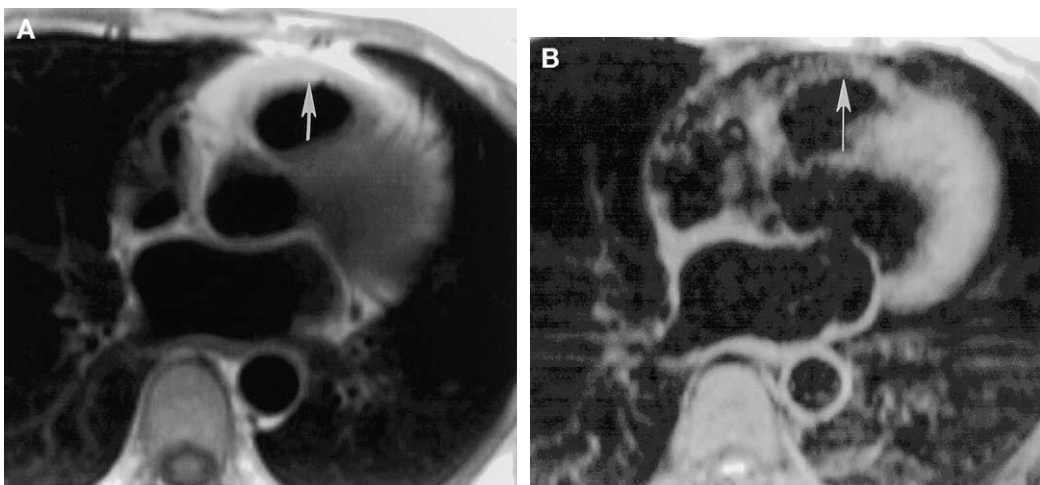


Fig. 15. Biopsy proven case of arrhythmogenic RV dysplasia. (A) Axial turbo spin echo T1-weighted image shows fatty infiltration of the myocardium involving the pulmonary outflow tract (*arrow*). (B) Fat saturated axial TSE T1-weighted image shows signal dropout of this region (*arrow*) because of fatty infiltration.



Fig. 16. Axial bright-blood cine GRE image in another patient with RV dysplasia shows focal bulge (*arrow*) of the right ventricular wall.

A thickness of 4 mm or more indicates pericardial thickening and, in proper clinical setting, is the finding that is diagnostic of constrictive pericarditis (Fig. 17). Other associated findings are markedly dilated inferior vena cava, hepatic veins, and right atrium. Right ventricle has normal or reduced volume. Restrictive cardiomyopathy is uncommon and results from infiltrative conditions leading to myocardial stiffness and restriction. Causes include both infiltrative (amyloid, sarcoid) (Fig. 18) and noninfiltrative (idiopathic, scleroderma) processes, storage diseases, and carcinoid and endomyocardial fibrosis. Beside normal pericardial thickness, the myocardium is thickened. As with constrictive pericarditis, patients with restrictive cardiomyopathy may also demonstrate enlarged atria and dilatation of the inferior vena cava and hepatic veins [21].

The wall thickness of either or both ventricles is usually increased in the restrictive cardiomyopathy associated with amyloidosis [22]. Restrictive cardiomyopathy is frequently complicated by mitral or tricuspid regurgitation. This can be demonstrated and quantified using cine GRE [23]. Stasis of blood in atria can cause high-signal intensity within the atrium on older spin echo images.

Constrictive pericarditis and restrictive cardiomyopathy both have similar clinical signs and symptoms: right-sided heart failure, peripheral

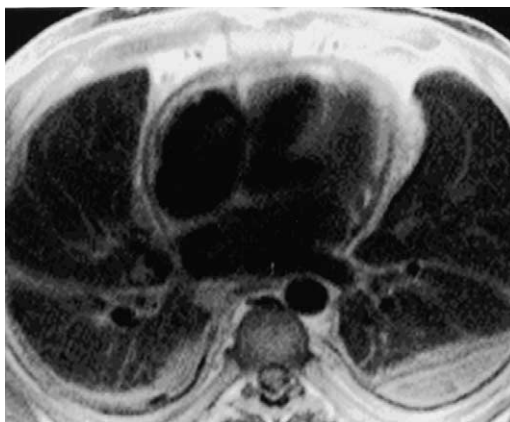


Fig. 17. Constrictive pericarditis. Axial dark-blood HASTE image shows a thickened pericardium (>4 mm), normal myocardial thickness, large right and left atria, and relatively small ventricular size. MR imaging also may show a dilated IVC or paradoxical septal motion because of increased right-sided pressure.

edema, distended neck veins, and Kussmaul's sign (venous pressure fails to drop with inspiration). MR can help cardiologists to differentiate between these two conditions and may be especially useful because constrictive pericarditis can be treated surgically by stripping the pericardium.

MR sequences

Black-blood imaging can be performed in both 4-chamber-long axis and short axis planes. As with



Fig. 18. Patient with sarcoid. Axial dark-blood HASTE image shows normal thickness of pericardium, markedly thickened myocardium, small ventricular volume, and, as with restrictive pericarditis, large right and left atria.

imaging for RV dysplasia, breath-hold TSE T1-weighted images may prove more useful than HASTE or double IR TSE/FSE images which tend to be a bit grainy. Bright-blood cine sequences are also useful, especially in the assessment of myocardial thickness if restrictive cardiomyopathy is suspected. These can be performed in the short axis for both qualitative analysis of myocardial thickness, or quantitative analysis of myocardial thickness, mass, and LV stroke volume using commercially available analysis packages.

It is important to know that calcification of the pericardium in constrictive pericarditis is dark on MR images. If needed, noncontrast CT can help in visualizing pericardial calcification in patients without demonstrable pericardial thickening, but with a high clinical suspicion of constrictive pericarditis.

Cardiac tumors and metastatic disease

Primary cardiac tumors are rare and approximately 80% are benign. Secondary tumors involving the heart are 40 to 50 times more frequent than primary tumors [24]. In general, most metastasis and malignant tumors are broad based or invade the myocardium. Most benign tumors are intraluminal and are attached by a narrow stalk. Most tumors enhance with gadolinium. This helps to differentiate them from thrombus, which does not enhance.

Primary tumors of the heart include myxoma (the most frequent benign cardiac tumor, usually within the left atrium) (Fig. 19), lipoma (usually right atrium, fat saturation helpful), angiosarcoma (most common malignancy, arising from the right atrium), rhabdomyoma (frequent tumor in children), fibroma (low signal on T2), and hemangioma (“light bulb” appearance on T2-weighted images). Secondary tumors of the heart include hematogenous metastatic disease to myocardium and pericardium, but, most frequently, metastatic disease as an extension from tumors of the adjacent lung or mediastinal structures. Extension of tumors of the upper abdomen can also occur through the inferior vena cava (IVC) into the right atrium. The most common mass of the heart in general is a thrombus, which most frequently involves the left atrium or ventricle.

MR sequences

Dark-blood HASTE (double IR TSE/FSE) in one or more planes is useful in evaluation of tumors. This sequence is suggested for its T2 weighting because most tumors have high signal intensity on T2-weighted images. GRE cine sequences also should be performed because they are helpful in the assessment of the tumor attachment point (narrow versus broad-based). Breath-hold TSE T1 pre- and postgadolinium

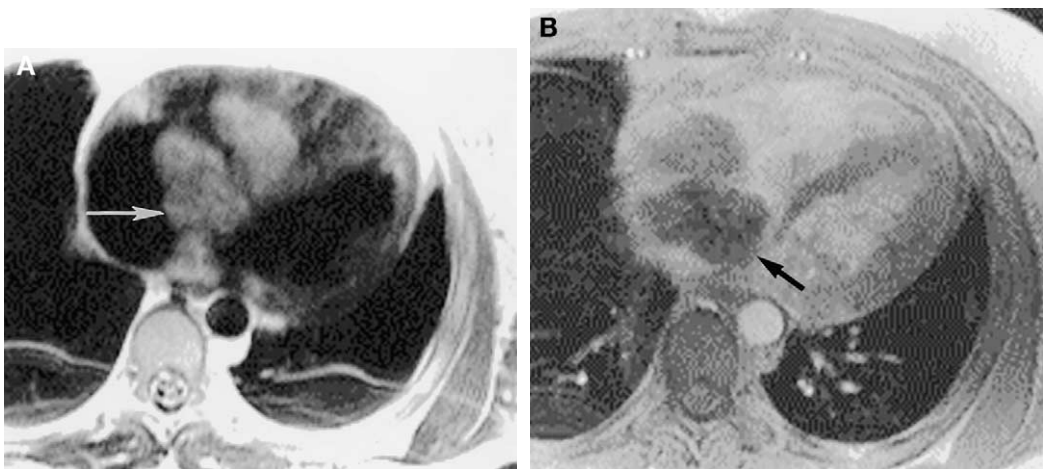


Fig. 19. Right atrial myxoma. (A) Axial dark-blood HASTE image shows a bilobed mass (arrow) straddling the tricuspid valve. Note the relatively bright signal of the mass on this T2-weighted sequence. Images are acquired in diastole and, thus, do not demonstrate the location of the mass throughout the cycle. (B) Axial bright-blood cine GRE image obtained in systole shows that the mass arises from the RA with the point of tumor attachment at the intra-atrial septum.

administration also can be used to determine extent of vascularity and enhancement [24].

Clinical coronary MR angiography

Though coronary MR angiography for atherosclerosis assessment is currently a research examination, it can be applied for certain clinical reasons. Current clinical applications of coronary MR angiography include assessment of anomalous coronary arteries, coronary artery aneurysm, and assessment of bypass graft patency. Some congenital anomalous coronary artery arrangements are associated with sudden death [25]. Anomalous coronary arteries associated with sudden death include an right coronary artery (RCA) or left anterior descending (LAD) traveling between the aorta and pulmonic outflow tract. Some of these anomalies are also difficult to evaluate with conventional coronary angiography. Because of its multiplanar imaging capabilities, MR is useful and can help as a problem-solving tool to evaluate the exact pathway of an anomalous coronary artery in ways conventional radiographic angiography cannot.

Techniques

Because coronary arteries are small tortuous structures subject to continuous respiratory motion and cardiac contraction, it is difficult in general to image the coronary arteries with MR. With the development of commercially available new ultrafast imaging techniques, however, excellent quality MR angiography of the coronary arteries has become feasible to perform clinically. Three-dimensional methods are usually the most useful and now can be performed with either breath-hold or respiratory gating. Techniques most often used are standard GRE techniques, without or with contrast enhancement; newer TrueFISP type sequences, however, provide excellent coronary artery signal. Black-blood methods have also been employed. Two-dimensional breath-hold GRE cines can be useful for assessing bypass graft patency.

Valvular disease

Quantification of blood flow through heart valves is of clinical interest in the assessment of the severity of valvular heart disease. Although valvular stenosis may be evaluated adequately by measuring transvalvular pressure gradients using

Doppler cardiac echo or cardiac catheterization, traditional methods fail to provide consistently reliable and accurate quantification of valvular regurgitation [26]. Cine MR imaging has been found to be an effective technique for evaluating ventricular and valvular function in certain valvular heart diseases [1,23,27–31].

Cardiac MR imaging techniques can demonstrate the presence and quantify the severity of valvular heart disease. MR examination of valvular dysfunction includes direct demonstration of the jet of valvular stenosis or regurgitation as well as demonstration of chamber dilation or hypertrophy. Cine MR imaging displays signal void in areas of turbulent flow related to either valvular disease such as stenosis or insufficiency (Fig. 20). Size of signal loss is dependent on the degree of turbulent flow and on TE. Velocity encoded cine (VENC) MR imaging can be used for measurement of peak velocities through the area of stenosis. Care must be taken to use a sequence with a VENC above the estimated peak velocity in order to avoid inaccuracies caused by aliasing. Using a modified Bernoulli's equation ($\hat{e}P = 4V^2$), the pressure gradient ($\hat{e}P$) across the valve or stenotic segment of the vessel can be estimated when systolic peak velocity (V) is known. A pressure gradient more than 25 mm Hg is hemodynamically significant. The regurgitant fraction in aortic valve insufficiency can be determined by calculating the difference of the right and left ventricular stroke volumes. This is only accurate if no shunt or other valve disease is present [31].

The expanding role of cardiac MR imaging

The role of cardiac MR imaging in the evaluation of heart disease has expanded from the traditional role of anatomic characterization toward functional evaluation. Some of the new clinical applications of cardiac MR imaging include myocardial function studies, myocardial viability, and coronary MR angiography for evaluation of proximal stenosis of coronary arteries.

LV function

Cine GRE sequences permit assessment of LV function and can be performed during rest and pharmacologic stress. Using commercially available software, one can calculate ejection fraction, LV volume, and myocardial mass. Newer completely gradient-refocused sequences and



Fig. 20. (A) Sagittal breath-hold single slice TSE T1-weighted image in a young woman with Takayasu's arteritis. Note the aortic wall thickening (*arrow*). (B) Coronal breath-hold cine GRE in the same patient shows a jet of aortic insufficiency (*arrow*) through the aortic valve toward the left ventricle. The aortic insufficiency is caused by poor apposition of the aortic valve leaflets. Note the dilatation of the sinuses at the aortic root.

bright-blood sequences (TrueFISP, balanced FFE, FIESTA) are ideal for use with these packages because of the increased contrast between blood pool and myocardium in comparison with standard GRE sequences.

LV wall motion abnormalities

LV wall motion abnormalities can be assessed qualitatively, but also quantitatively using saturation tagged sequences and mathematical models. Qualitative evaluation of wall motion abnormalities is usually not required clinically. Fig. 21 shows the typical tagged cardiac sequence in short axis view. The dark lines are tagged lines (saturation bands) forming a diamond (*arrow*) that will deform during ventricular muscle contraction.

Myocardial perfusion and viability

Myocardial perfusion studies are performed using first-pass myocardial TurboFLASH-type sequences capable of rapidly establishing T1 contrast for multiple slices with high temporal resolution. Rapid administration of intravenous (IV)

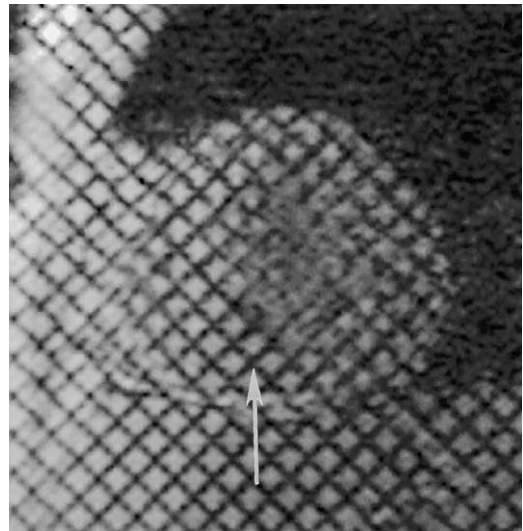


Fig. 21. Saturation-tagged short axis image of the heart. The dark lines are saturation bands forming a grid (*arrow*) that will be deformed during normal myocardial contraction.

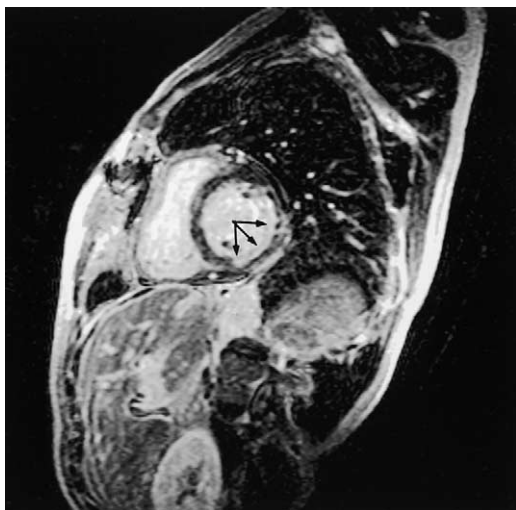


Fig. 22. Subendocardial lateral wall myocardial infarction. Delayed imaging in the short axis is obtained using a contrast-enhanced T1-segmented TurboFLASH sequence. Arrows point to the nonviable myocardium.

gadolinium, to provide a tight bolus, is administered at rest and during pharmacologic stress (IV infusion of adenosine). Depending upon the R-R interval, two to four slice positions can be obtained over multiple phases, demonstrating low signal areas of underperfusion in the myocardium. These low signal areas correspond with regions of ischemia or infarct. Single slice IR FLASH or newer 3D IR-prepped sequences then can be used in a delayed fashion (usually 10–15 minutes after contrast injection) to demonstrate regions of delayed contrast wash-out corresponding to infarcted tissue. Fig. 22 shows an area of infarcted myocardium (*arrow*) that enhances enhanced T1 image (segmented Turbo FLASH technique) on delayed contrast [2,32].

Summary

Because of the enormous economic and social impact of cardiovascular disease in the United States, there is a need for improved noninvasive diagnosis. Cardiac MR imaging is a versatile, comprehensive technique for assessing cardiac morphology and function. With an understanding of cardiac anatomy and physiology as well as MR physical principles, cardiac MR imaging can be performed and play an important role in patient management.

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