Congenital Heart Disease

One of the primary roles of cardiac MR imaging has been the assessment of congenital heart disease. Initially used to define cardiac anatomy as an adjunct to echocardiography, cardiac MR now plays a pivotal role in both anatomical and functional assessment of shunts, admixture lesions, transpositions, and the surgical correction of these lesions. Unlike X-ray angiography, cardiac MR is noninvasive, does not use iodinated contrast agents or ionizing radiation, and is, therefore, suitable for both children and adults. This unit presents the basic techniques for the evaluation of congenital heart disease. While sequence parameters described are meant to be as generic as possible, parameters are most appropriate for the Siemens 1.5 T Vision or Symphony and may need to be altered for magnets of different field strengths and manufacturers. Basic Protocol 1 (imaging congenital heart disease) will take 30 to 45 min to complete, depending upon the complexity of the heart disease. Alternate Protocol 1 (intracardiac shunt assessment) and Alternate Protocol 2 (valve assessment), each take an additional ~15 min to perform when run with Basic Protocol 1. Basic Protocol 2 (great vessel assessment) will take 30 to 40 min, but can be performed following Basic Protocol 1, for a total examination time of 1 to 1.5 hr.

IMAGING CONGENITAL HEART DISEASE

BASIC PROTOCOL 1

The basic components of the congenital heart MR examinations are (1) a black-blood technique to assess anatomy, and (2) a bright-blood gradient recalled cine technique to assess for the presence of intracardiac shunts, to assess for valvular abnormalities, and to assess ventricular function.

For young children, nonbreath-hold black-blood methods that employ double inversion recovery half-Fourier single-shot turbo spin echo (HASTE) or fast spin echo (FSE) techniques are the most optimal. These are not only nonbreath-hold, but are faster than traditional spin echo (SE) imaging. Segmented *k*-space cine gradient echo images (fast low angle shot—FLASH; fast cardiac gated gradient echo—FASTCARD), especially those that are fully balanced by refocused gradients (true fast imaging with steady state free precession—true FISP), give better results in a short examination time. Most of these require breath-hold, but some, such as true FISP, can give adequate images with shallow respiration.

While black-blood imaging provides an anatomical overview of the heart, cine images are vital for the diagnosis of many entities including small intracardiac shunts, which may otherwise be missed, and for the assessment of surgically created shunts and baffles. Bright-blood cine images can provide qualitative assessment of congenital valvular disease (aortic stenosis and bicuspid valve, Ebstein's anomaly) and qualitative assessment of shunt size by visual assessment of the flow jet.

Additional phase-contrast imaging can help to quantify shunts and can provide velocity information of the blood flow that can be used to calculate the pressure gradient across a stenotic valve or aortic coarctation.

Finally, contrast-enhanced techniques are the best means of assessing pulmonic stenoses in patients with tetralogy of Fallot or congenital rubella, congenital arteriovenous malformations, pulmonary slings, or anomalous pulmonary venous return.

Table A10.1.1 lists the hardware necessary to perform an MR examination for congenital heart disease assessment. An MR system with higher gradient strengths (>20 mT/meter)

Contributed by Pamela K. Woodard and Jie Zheng
Current Protocols in Magnetic Resonance Imaging (2001) A10.1.1-A10.1.19

Table A10.1.1 Equipment Parameters for Cardiac Imaging, Basic Protocol 1

Coil type	Torso phased array coil (or dedicated cardiac coil, if available)
Gradient coil strength	At least ≥20 mT/m (or whatever the system permits)
Cardiac gating	Yes, preferably fiberoptic cables
Peripheral gating	No
Respiratory gating	No
Respirator	If required by patient
Oxygen	Yes, 2 liters nasal cannula for most patients (to ensure breath-holding >15 sec)
Motion cushions	Under feet, can be used for patient comfort
Use of contrast agents	No
Power injector	No
Monitoring equipment	Heart rate, oxygen saturation, and blood pressure can be monitored with MRI-compatible equipment. This is required if i.v. contrast, anesthesia, or sedation is administered.

and faster rise times (≤300 μsec) that allow gated turbo spin echo and segmented cine gradient echo imaging is preferable.

NOTE: Be sure that technologists and nurses have immediate access to any emergency equipment that may be relevant to a given study, or that may be needed for a particular patient, such as crash carts or oxygen.

Set up patient and equipment

1. Interview and screen the patient to ensure that he or she has no contraindications to an MR examination. Contraindications include a cardiac pacemaker or defibrillator, intracerebral aneurysm clip, or ferromagnetic materials in or near vital structures, including the eyes.

   A number of references have been published listing the MR compatibility of specific implanted devices (Shellock, 1999). Contacting the manufacturer of a device may also be helpful if MR compatibility remains a question.

   In addition, question the patient about a history of claustrophobia, as this is often a reason for terminating an examination.

   If contrast administration is planned, obtain an allergy history. Especially, ask about a history of allergy to Gd-DTPA if contrast agent is used.

   Also, question the patient about health conditions, including those related to his or her heart disease, that could require emergency equipment during the scanning procedure. Determine whether blood oxygenation, pulse or blood pressure monitoring is required in addition to cardiac gating.

   If the patient is a young child, arrange to have the child sedated under the auspices of the hospital's anesthesia services.

   Generally standard screening forms are used for all patients scanned in a magnetic resonance system.

   Patients may be accompanied into the magnet room by a friend or family member, who can sit in the room during the scan and comfort the patient as needed. This companion must be screened as well to ensure the absence of loose metal objects on the body or clothing.

2. Have the patient change into a gown and remove all jewelry. If the procedure is a research protocol, have the patient sign any necessary consent form.
3. Tell the patient what will occur during the procedure. In particular, instruct the patient how to hold his or her breath.
   a. Headphones or earphones are used to protect the ears from the noise induced by the gradients. Instruct the patient that he or she will be able to hear you via these headphones and that microphones in the magnet will permit them to talk to you at any time.
   b. Provide adults and older children with a safety squeeze-bulb alarm (or similar device) and demonstrate how this works. (Infants and very young children will be monitored by the nurse anesthetist.)
   c. The patient may call out at any time if he or she feels it necessary.

   At the authors' institution, patients are instructed to take a breath in, blow it out, take a breath in again, relax, and hold it. This allows images to be obtained in mid-respiratory cycle (~15 to 20 sec will be required for each breath-hold for each cine gradient echo acquisition). Some of the newer sequences, such as true FISP, may require shorter breath-holds. Assess the need for supplementary oxygen to improve the breath-holding capacity, and if necessary, administer 2 liters oxygen via nasal cannula. Advise the patient of the importance of not moving during the acquisition periods and of not taking deep breaths during the nonbreath-hold acquisitions.
4. Have the patient mount onto the table. For some systems, it will be important that the patient lie within the center of the spine coil, which may be the posterior elements for the phased array system.
5. Once the patient is on the table, place ECG (electrocardiogram) leads on the patient according to manufacturer's guidelines.

Table A10.1.2 Primary Clinical Imaging Parameters for Sequence 1 (Turbo FLASH Scout Scan)

Patient position	Supine
Scan type	Gradient echo
Imaging plane (orientation)	3 transverse, 1 coronal, and 1 sagittal (5 images)
Central slice or volume center	Center of chest
Echo time (T_E)	As short as possible
Repeat time (T_R)	As short as possible
Flip angle (FA)	15°
Fields of view (FOV_x, FOV_y)	400 mm, 400 mm
Resolution (Δx, Δy)	1.56 mm, 4.17 mm
Number of data points collected (N_x, N_y)	256, 96
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	6–10 mm
Number of slices	5
Slice gap	Variable
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Slice location	Variable
Saturation pulses	Not applicable
ECG gating	Yes
Scan time	5 sec

The types of electrodes available include individual electrodes in a packet of 3 or 4, or 4 together on a single patch (Quatrode, InVivo). Electrodes with graphite tips cause the least artifact. Lead placement may be either on the chest or back. Leads placed on the chest are less likely to come off if the patient moves and may be more comfortable to the patient. Alternatively, placement of leads on the back may reduce motion artifacts related to breathing. This is less of a problem with fiberoptic cables. Make sure that the ECG tracing shows high (positive) R-waves. If it does not, it is imperative that the leads either be repositioned or that the lead polarity be adjusted to alternative options.

6. Place a pillow or other support under the knees to make the patient more comfortable.
7. No i.v. cannula is necessary for a basic congenital heart examination.
8. Center the patient's chest in the phased array coil and steady it with the Velcro or buckle straps provided by the manufacturer. Make sure that the phased array body coil (and spine coil, if necessary) are plugged in.
9. Center the heart to the "0" location with the laser light marker device available on most systems and bring the patient into the magnet.
10. Once the patient has been centered in the magnet, check again to be sure that the ECG tracing demonstrates sharp positive *R*-waves for suitable triggering. If not, then with the patient still within the magnet, exchange lead polarity until a suitable tracing is obtained.

Table A10.1.3 Primary Clinical Imaging Parameters for Sequence 2 (HASTE)

Patient position	Supine
Scan type	Single shot fast spin echo
Imaging plane (orientation)	Transverse (may also be run sagittal or coronal)
Central slice or volume center	Center of heart
Echo time (T_E)	43–63 msec (effective)
Repeat time (T_R)	Infinity
Delay time (T_D)	R-to-R interval, use to blank *R*-wave for every other beat trigger
Flip angle (FA)	180°
Fields of view (FOV_x, FOV_y)	300–350 mm, 300–350 mm
Resolution (Δx, Δy)	1.17–1.37 mm, 1.41–1.65 mm (will depend upon FOV)
Number of data points collected (N_x, N_y)	256, 212
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5–8 mm (children especially benefit from thinner slice thickness)
Number of slices	21
Slice gap	None
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	No
Slice series	Ascending
ECG gating	Yes (can run without gating, but images are better with gating)
Scan time	Depends upon volume to be covered, (2 × (number of slices) × (R-to-R inverval))

Table A10.1.4 Primary Clinical Imaging Parameters for Sequence 3 (T_1-Weighted TSE)

Patient position	Supine
Scan type	Fast spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Cardiac region to be assessed
Echo time (T_E)	12 msec (or minimum)
Echo train length (ETL)	9
Repeat time (T_R)	<900 msec (and <90% of the R-to-R interval)
Delay time (T_D) after *R*-wave	0 msec
Flip angle (FA)	180°[a]
Fields of view (FOV_x, FOV_y)	300–350 mm, 300*r*–350*r* mm, with *r* = rectangular field of view, depending on body habitus
Resolution (Δx, Δy)	1.17–1.37 mm, 1.17*r*–2.73*r* mm (depends upon FOV, with *r* = rectangular field of view)
Number of data points collected (N_x, N_y)	256, 128–256, depending on body habitus
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	6–8 mm
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	No
ECG gating	Yes
Scan time	15–20 sec per image

[a]The system displays the flip angle of the refocusing pulse. The flip angle of the first pulse of this sequence is 90°.

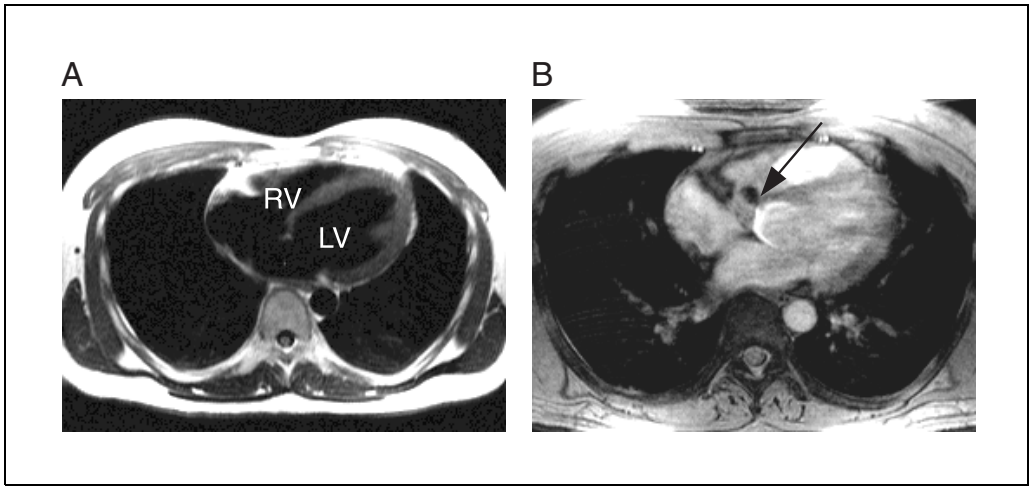

Figure A10.1.1 Transaxial black blood HASTE (**A**) and cine GRE (**B**) images at the same cardiac level. Image from the cine sequence demonstrates the jet from a small membranous ventricular septal defects (VSD; arrow). The VSD cannot be identified on the static black-blood images (RV, right ventricle; LV, left ventricle).

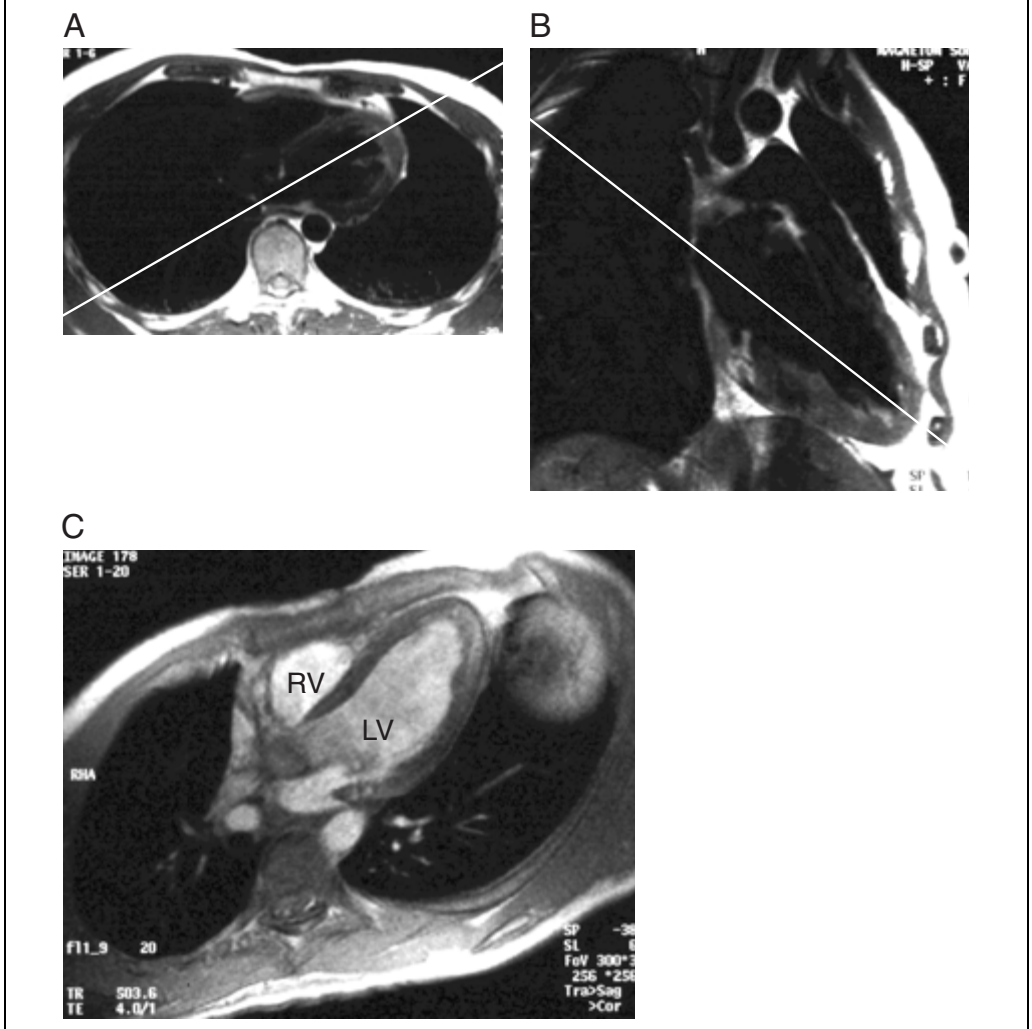

Figure A10.1.2 Multiple orthogonal views can be prescribed from initial images. Here a transaxial black blood image (**A**) was used to set up a long-axis two-chamber view (**B**). The long-axis view was then used to set up a horizontal long-axis view (C) of the heart. (RV, right ventricle; LV, left ventricle).

If still not satisfactory, then bring the patient table out of the magnet, check the lead connections, and reposition the leads until a satisfactory tracing is obtained.

Sequence 1: Rapid multi-plane scout

11. To assist with placement of subsequent acquisitions, run a gradient echo multi-plane scout scan according to Table A10.1.2.

    Some systems will allow the imager to modify the sequence to add groups of images, or to change image orientation. The authors often run a 5-image turbo FLASH scout. Those with faster MR systems can run a true FISP sequence.

    This is a nonbreath-hold sequence.

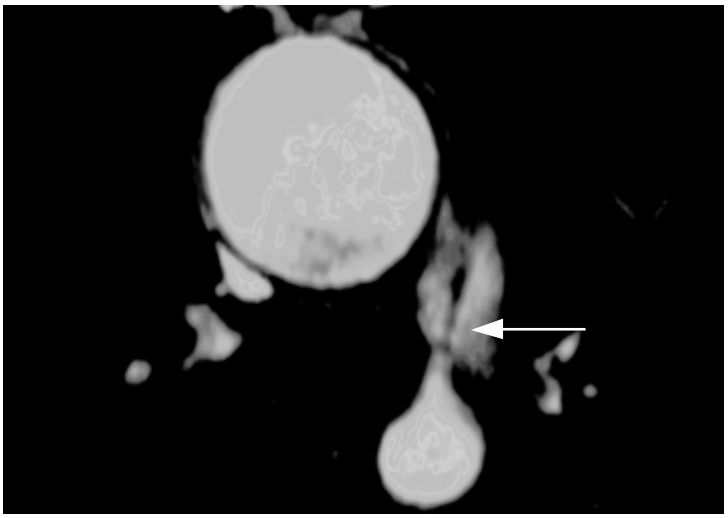

Figure A10.1.3 Image from a bright-blood cine GRE sequence shows a small patent ductus arteriosus (PDA) connecting the descending aorta and the main pulmonary artery. An arrow points to a small jet. This PDA was barely visible on black-blood anatomic MR imaging.

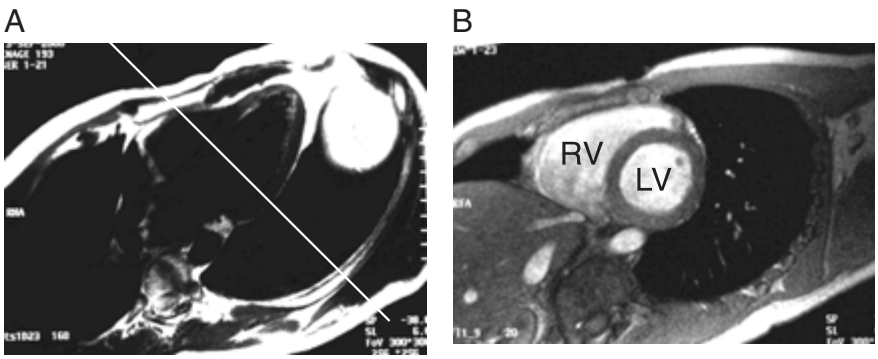

Figure A10.1.4 Horizontal long-axis black-blood image can be used to set up multiple short-axis cine sequences that can be used to provide information about left ventricular function. (RV, right ventricle; LV, left ventricle).

Sequence 2: 2-D Transverse half-Fourier turbo spin echo (HASTE or double inversion recovery FSE)

At the authors' institution either a single shot HASTE or dual-segment HASTE sequence is obtained at least transaxially, and often in multiple planes (sagittal and coronal) to cover the thorax. The authors have found that the dual-segment sequence provides better signal-to-noise ratio (SNR). This sequence can be run acquiring ≤5 slices in a single breath-hold, or 21 slices can be performed with shallow breathing. This is an ideal sequence to run for anatomic imaging on pediatric patients. For best image results, slice series (excitation order) should be ascending. The dual segment sequence images often have an $N_y/2$ artifact (signal from the anterior chest wall runs through the image). This can be displaced posteriorly and out of the body by not using a rectangular field of view.

Dual-segment HASTE is a segmented HASTE imaging sequence with two separated acquisitions for one slice. Unlike conventional single-shot HASTE sequence, each segmented acquisition acquires half of required *k*-space data in one cardiac cycle with a

Table A10.1.5 Primary Clinical Imaging Parameters for Sequence 4 (Cine Gradient Echo)

Patient position	Supine
Scan type	Segmented *k*-space 2-D cine gradient echo
Imaging plane (orientation)	As determined by imager
Central slice or volume center	Cardiac region to be assessed
Echo time (T_E)	4.8 msec (or minimum)
Number of lines per segment	9
Repeat time (T_R)	80–100 msec (temporal resolution)
Delay time (T_D)	0 msec
Flip angle (FA)	20°
Fields of view (FOV_x, FOV_y)	300–350 mm, 300*r*–350*r* mm, with *r* = rectangular field of view, depending on body habitus
Resolution (Δx, Δy)	1.17–1.37 mm, 1.17*r*–2.73*r* mm (depends on FOV, with *r* = rectangular FOV)
Number of data points collected (N_x, N_y)	256, 128–256, depending on body habitus
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	8 mm
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	No
Number of cardiac phases[a]	(R-to-R interval) × 85%/T_R (~8–15, multiple frames per slice position)
ECG gating	Yes
Scan time	15–20 sec

[a]See annotation under Basic Protocol 1, step 14.

sequential phase-encoding order. This segmentation reduces the data acquisition window in each cardiac cycle and thus shortens the T_E, which increases signal-to-noise ratio.

12. Run sequence 2 according to Table A10.1.3.

Sequence 3: 2-D T_1-weighted turbo spin echo (depending on quality of sequence 2)

13. If the quality of the HASTE images is poor, instruct the patient to hold their breath and run a T_1-weighted turbo spin echo (TSE) sequence according to the parameters in Table A10.1.4 transaxially through the heart, or in other imaging planes to further assess specific regions.

The HASTE images can then be used to locate specific areas in question and position T_1-weighted TSE images. The effective (or total) T_R should be ~85% to 90% of (or 100 msec less than) the patient's R-to-R interval (time between R waves). For T_1-weighting, T_R should be <900 msec. It should be noted that shorter T_R times, however, will limit the number of slices that can be obtained in each acquisition. If one wishes to cover the entire heart in adults, rather than using the sequence to assess a limited region, it may be necessary to run this sequence multiple times. In addition, usually only one image can be acquired in a single breath-hold. Either one image can be acquired at a time (this eliminates respiratory motion artifact), or the patient can be instructed to perform shallow breathing.

Table A10.1.6 Clinical Imaging Parameters for Cine GRE, Gradient Refocused (True FISP)

Patient position	Supine
Scan type	Segmented *k*-space 2-D cine gradient echo
Imaging plane (orientation)	As determined by imager
Central slice or volume center	Cardiac region to be assessed
Echo time (T_E)	1.6 msec (or minimum)
Number of lines per segment	10
Repeat time (T_R)	64 msec (temporal resolution)
Delay time (T_D)	0 msec
Flip angle (FA)	60°
Fields of view (FOV_x, FOV_y)	300–350 mm, 300*r*–350*r* mm, with *r* = rectangular field of view, depending on body habitus
Resolution (Δx, Δy)	1.17–1.37 mm, 1.17*r*–2.92*r* mm (depends on FOV, with *r* = rectangular field of view)
Number of data points collected (N_x, N_y)	256, 120–256, depending on body habitus
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5–8 mm
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	No
Number of cardiac phases	(R-to-R interval) × 85%/T_R (multiple frames per slice position)
ECG gating	Yes
Scan time	5–10 sec

Sequence 4: 2-D fast cine gradient echo (GRE) in multiple planes

Cine gradient echo images can be performed at 10-mm intervals through the heart transversely, or selectively. At the authors' institution, routine cine imaging through the heart transaxially has proved invaluable in demonstrating small atrioseptal defects or ventriculoseptal defects that otherwise would not be identified (Fig. A10.1.1). These transaxial images are also useful in the visual assessment of the mitral and tricuspid valves, along with 4-chambered long axis views (Fig. A10.1.2). In addition, selected images can be performed through surgically created shunts (e.g., Blalock-Taussig or Glenn Shunts) to assess patency or through areas of suspected pathology (e.g., in a region of suspected patent ductus; Fig. A10.1.3). Double oblique sagittal and coronal images are obtained through the aorta and pulmonary trunk. Long axis images can be set up off of the coronal image to show both the aortic and mitral valves in a single plane. Two to three short axis images (Fig. A10.1.4) can be obtained if ventricular function is a question.

14. Set the imaging parameters as shown in Table A10.1.5. Instruct the patient to hold their breath and run sequence 4.

    This sequence will provide multiple cine frames throughout the cardiac cycle in a single slice position per breath-hold. The parameters may be adjusted depending on 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 cardiac phases should be set according to one of the following formulas:

Number of cardiac phases = (R-to-R interval) × 85%/T_R

or

Number of cardiac phases = (R-to-R interval − 100 msec)/T_R.

For imagers with faster magnets, gradient refocused, true FISP-type sequences (Table A10.1.6) can provide sharp, detailed images with minimal breath-holding.

ALTERNATE PROTOCOL 1

INTRACARDIAC SHUNT ASSESSMENT

Gradient recalled echo cine MRI has been demonstrated to be very useful in determining the presence of atrial septal defect (ASD), ventricular septal defect (VSD) or patent foramen ovale (PFO). Cine sequences are vital in diagnosing the presence of intracardiac shunts and in performing assessment of the lesion. These should be performed at least transaxially throughout the region of interest (ROI). Without cine MR, it is quite possible to miss a small ASD, VSD, or PFO on black-blood anatomic imaging alone. Bright-blood cine MR not only demonstrates the presence of the lesion, but also demonstrates the extent of the lesion and direction of the shunting. Further assessment can be made via additional cine imaging orthogonal to the jet. Cine imaging in long axis and short axis orientations can be used to demonstrate sequelae of the lesion, for instance right ventricular size and function in the presence of a VSD.

In addition to gradient recalled echo cine imaging alone, phase contrast sequence can confirm shunt direction and provide quantitative information (Didier and Higgins, 1986; Schectem et al., 1987). In-plane imaging can provide qualitative assessment.

Through-plane phase contrast imaging through the ascending aorta and pulmonic outflow tract can be performed to estimate right and left ventricular stroke volumes in order to assess the extent of a shunt (shunt ratio). In normal individuals, the left and right ventricular stroke volumes should be equivalent. Stroke volumes can be estimated using phase contrast sequences, as described in this unit, or can be assessed using multiple short axis cine sequences through the heart to calculate an exact stroke volume using software packages provided by a vendor. Using either method, assessing the difference in left and right ventricular stroke volumes can accurately assess the extent of a shunt if no valve disease is present to introduce additional factors that could alter ventricular stroke volume (Didier and Higgins, 1986).

Set up patient and equipment

1. Repeat Basic Protocol 1.

Sequence 5: Through plane cine phase contrast for shunt assessment

2. To ensure accuracy of velocity measurement and to avoid aliasing, make sure the v_{enc} (velocity encoding anti-aliasing limit) of the sequence is above the assumed velocity of aortic or ventricular flow. Unless a stenosis is present, a v_{enc} of 250 cm/sec should be adequate.
3. Use adequate temporal resolution—as many phases as possible.
4. Acquire the sequence described in Table A10.1.7 two times, once through the ascending aorta and once through the pulmonary trunk, each 3 to 4 cm above the valve plane.

It is not necessary to ask the patient to hold his or her breath.

Table A10.1.7 Primary Clinical Imaging Parameters for Sequence 5 (Through-Plane Phase Contrast)

Patient position	Supine
Scan type	Cine phase contrast, 2-D gradient echo
Imaging plane (orientation)	Single slice through plane of ascending aorta and pulmonary trunk (3–4 cm above valve). Run the sequence two times, once through each vessel.
Central slice or volume center	Aorta or pulmonary trunk
Echo time (T_E)	6.5 msec (per rf-pulse)
Number of lines per segment	1
Repeat time (T_R)	28 msec (temporal resolution)
Delay time (T_D)	0 msec
Flip angle (FA)	30°
Fields of view (FOV_x, FOV_y)	300–320 mm, 300–320 mm, depending on body habitus
Resolution (Δx, Δy)	1.17–1.25 mm, 1.17–2.21 mm
Number of data points collected (N_x, N_y)	256, 145–256, depending on body habitus
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	6 mm
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	No
Number of cardiac phases	(R-to-R interval) × 85%/T_R multiple phases
Vascular options	v_{enc} = 250 cm/sec
ECG gating	Yes
Scan time	Depends upon heart rate (N_y × (R-to-R inverval))

5. Use the software provided by most systems for quantitative analysis to convert the signal obtained into velocity measurements.
6. Once the images are acquired, use the software provided by the system to place a circular ROI to match the diameter of the aorta on each phase image (or, if the system allows, each magnitude image corresponding to each phase image). The position of the ROI should be hand-adjusted on each image to insure accurate placement.
7. Use the software to generate velocity curves and tabulate the area within the specific ROI.
8. Repeat steps 6 and 7 for the pulmonary trunk.
9. For each vessel, calculate the mean velocity in systole. Multipy the average velocity (systole) by cross-sectional area to estimate the stroke volume. The ratio of stroke volumes (left to right) is the shunt ratio.

   In normal individuals, the left and right ventricular stroke volumes should be equal.

   Note that the ratio may be affected by concomitant valve disease.

VALVE ASSESSMENT

Cine images (sequence 4, Table A10.1.5) can be obtained to visually assess the jet from a stenosis or turbulence caused by regurgitant flow. Aortic and pulmonic valves can be visually assessed in a double-oblique (oblique sagittal and coronal) orientation (Fig. A10.1.5). A long-axis view, set up off of the coronal image, can be used to assess the aortic valve and mitral valve simultaneously. Transaxial view may also help in the assessment of the mitral and tricuspid valves.

Qualitative evaluations can be made to assess valve stenoses, or aortic and pulmonic insufficiency using phase contrast sequences.

For stenotic valve pressure gradients, the authors use a through-plane phase-contrast sequence with a high v_{enc} (in order to obtain accurate velocity measurement and avoid

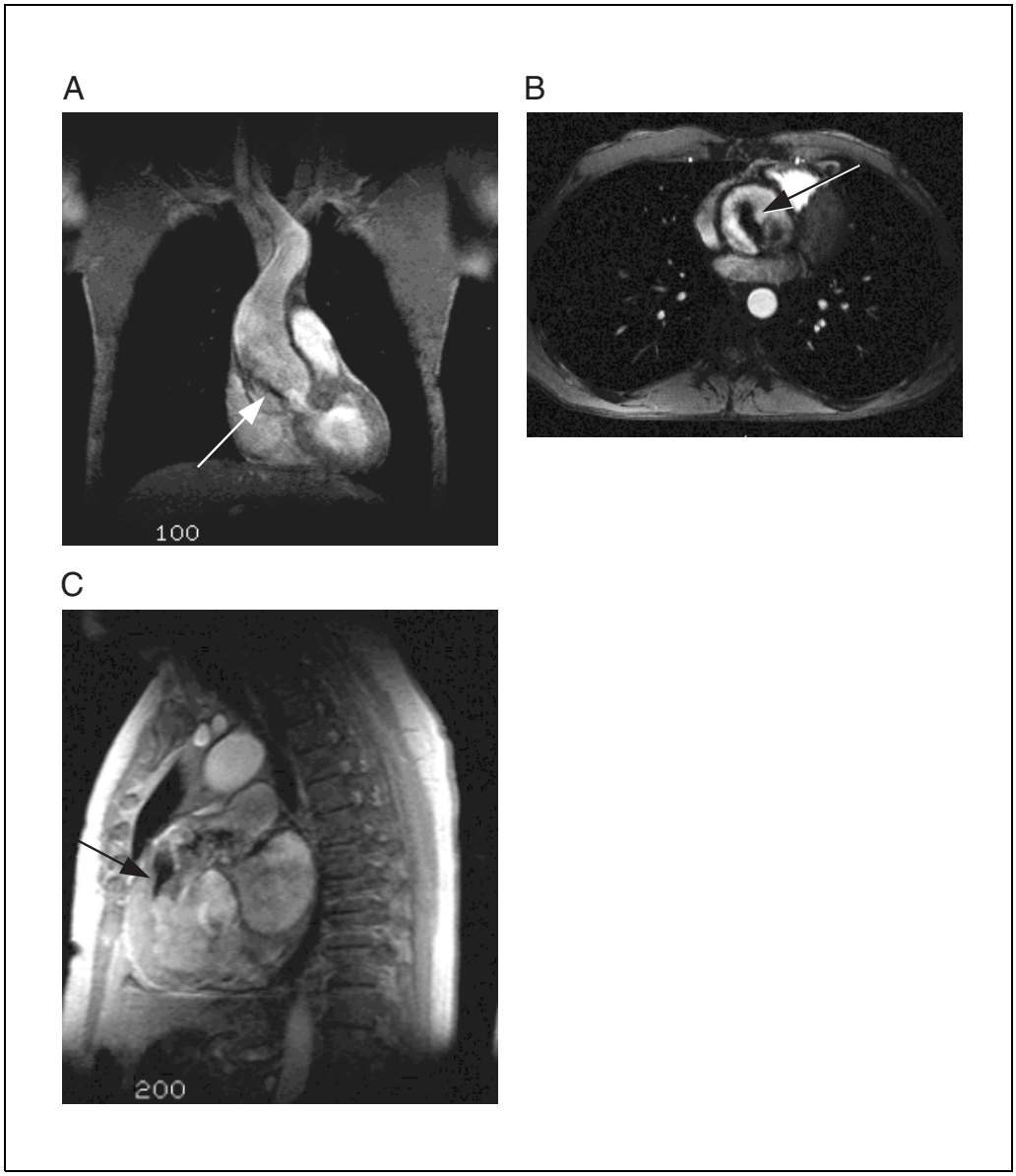

Figure A10.1.5 Cine GRE images demonstrate post-stenotic dephasing. (**A**) A coronal image shows a domed, bicuspid aortic valve. A jet (arrow) indicates stenosis. (**B**) In the same patient, the black area of post-stenotic dephasing or jet (arrow) can be identified on a transaxial cine image. (**C**) A double-oblique image through the pulmonic valve in a patient with tetralogy of Fallot shows a jet (arrow) distal to subpulmonic soft tissue, indicative of infundibular subpulmonic stenosis.

aliasing). This is set up through and perpendicular to the "jet" created by the dephased flow. This usually turns out to be a plane ~2 cm above and parallel to the valve. Once images are obtained, the manufacturer's quantification package usually can be used to obtain both mean and peak velocity measurements. Follow the manufacturer's instructions for use of this package. However, the software will usually allow placement of an ROI to encompass the jet as seen on either the magnitude or phase images. One will need to manually adjust the position of the ROI for each frame because of the constant motion of the heart. One can estimate the mean pressure gradient and peak pressure gradient across a stenotic valve by using a modified Bernoulli's equation $\Delta P = 4v^2$ (the difference between pressure, P, is proportional to the square of velocity, v; P is in units of mmHg; v is peak velocity in units of meters/sec; Didier et al., 2000). A hemodynamically significant stenosis is usually considered to have a pressure gradient >25 mmHg. Bernoulli's estimation of the pressure gradient from velocity can also be used to assess the hemodynamic significant of an aortic coarctation.

Regurgitant volume can be estimated, but is affected by other regurgitant or stenotic valves, therefore, assessment is less reliable. Aortic or pulmonic valve regurgitant volumes can be assessed by directly calculating the difference between the right and left ventricular stroke volumes using multiple short axis cine sequences or, more simply, by estimating right and left ventricular stroke volumes using phase contrast sequences. This is done in a fashion similar to evaluation for shunt assessment. Run the cine phase contrast sequences through the plane above and parallel to the aortic and pulmonic valve. Calculate the mean velocity in systole for each using the manufacturer supplied quantification package, making sure the area of the ROI matches the cross sectional area of the vessel (i.e., aorta or pulmonary trunk) being measured. Average velocity (systole) multiplied by cross-sectional area estimates the stroke volume. The difference between right and left ventricular stroke volume is the regurgitant volume (Chatzimavroudis et al., 1997).

If there is another diseased valve, regurgitant flow can be estimated by calculating the area under the retrograde volumetric flow curve (not velocity curve) in diastole (Higgins, 2000).

Set up patient and equipment

1. Repeat Basic Protocol 1.

Sequence 6: Through-plane cine phase contrast for valve assessment

2. To ensure accuracy of the velocity measurement and to avoid aliasing, make sure the v_{enc} of the sequence is above the assumed velocity of the flow to be measured. For insufficiency calculations, a v_{enc} of 250 cm/sec should be adequate. A v_{enc} of 500 cm/sec should be used for assessment of stenoses.

3. Use adequate temporal resolution to have as many cardiac phases as possible.

4. For insufficiency assessment, acquire the sequence described in Table A10.1.8 two times, once through the ascending aorta and once through the pulmonary trunk, each 3 to 4 cm above the valve plane. For stenosis assessment, acquire the sequence perpendicular to the stenotic jet.

   This is not a breath-hold sequence.

5. Use the software provided by the manufacturer for quantitative analysis to convert the signal obtained into velocity measurements as in steps 6 through 8 below.

6. For insufficiency assessment (to determine right and left ventricular stroke volumes), place a circular ROI to match the diameter of the aorta on each phase image (or if the system allows, each magnitude image corresponding to each phase image). The

Table A10.1.8 Primary Clinical Imaging Parameters for Sequence 6 (Through-Plane Phase Contrast)

Patient position	Supine
Scan type	Cine phase contrast, 2-D gradient echo
Imaging plane (orientation)	For aortic or pulmonic insufficiency: through plane of ascending aorta and pulmonary trunk (3–4 cm above valve). Run the sequence two times, once through each vessel. For aortic, mitral or pulmonic stenosis: perpendicular to jet
Central slice or volume center	Above aortic and pulmonic valve plane for insufficiency; through jet for valve stenosis
Echo time (T_E)	6.5 msec (per rf-pulse) for v_{enc} = 250 cm/sec; 5.5 msec for v_{enc} = 500 msec/sec (needed for stenotic valves as jet velocity is anticipated to be high)
Number of lines per segment	1
Repeat time (T_R)	23 msec (temporal resolution)
Delay time (T_D)	0 msec
Flip angle (FA)	30°
Fields of view (FOV_x, FOV_y)	300–320 mm, 300–320 mm, depending on body habitus
Resolution (Δx, Δy)	1.17–1.25 mm, 1.17–2.21 mm
Number of data points collected (N_x, N_y)	256, 145–256, depending on body habitus
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	6 mm
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	No
Number of cardiac phases	(R-to-R interval) × 85%/T_R
Vascular options	v_{enc} = 250 cm/sec for insufficiency; v_{enc} = 500 cm/sec for stenotic valve assessment
ECG gating	Yes
Scan time	Depends upon heart rate (N_y × (R-to-R inverval))

position of the ROI should be hand-adjusted on each image to insure accurate placement. For stenosis assessment, place a circular ROI to encompass the through-plane measurement of the jet.

7. Use the software to generate velocity curves and, for stroke volume measurements to calculate regurgitant volumes to tabulate the area within the ROI.

8. For stenosis assessment, determine the mean and peak velocity within the jet. Use the modified Bernoulli's equation to calculate pressure gradients. For regurgitant

volume, for both the aortic and pulmonary artery measurements, calculate the mean velocity in systole. Average velocity (systole) multiplied by cross-sectional area estimates the stroke volume. The ratio of stroke volume (left to right) is the shunt ratio.

In normal individuals, the left and right ventricular stroke volumes should be equal.

Note that the calculated regurgitant volume may be affected by disease in other valves, or by the presence of a shunt.

ASSOCIATED GREAT VESSEL ASSESSMENT

BASIC PROTOCOL 2

Contrast-enhanced gradient recalled echo sequences can be used for assessment of both congenital aortic and pulmonary artery anomalies. This includes assessment of pulmonary artery stenoses or atresia as seen in tetralogy of Fallot, and aortic arch anomalies such as seen in coarctation, William's syndrome (supravalvular aortic obstruction), or Shone's syndrome (congenital hypoplasic left heart syndrome). Assessment of pulmonary embolism is covered in *UNIT A13.1*. Performing two scans, one timed to pulmonary artery contrast enhancement and the second timed to aortic enhancement, can allow assessment of complex congenital heart disease using a single contrast bolus.

Table A10.1.9 lists the hardware necessary to perform an MR examination for associated great vessel assessment.

Materials

Normal saline (0.9% NaCl), sterile
Gadolinium-based MR contrast agent (e.g., Magnevist, Omniscan, Prohance, or OptiMARK)

Set up patient and equipment

1. Set up patient as in Basic Protocol 1, steps 1 to 6; skip step 5.
2. Question the patient about allergies, especially allergic reaction to prior administration of MR contrast agents.

Table A10.1.9 Equipment Parameters for Cardiac Imaging, Basic Protocol 2

Coil type	Torso phased array coil (or dedicated cardiac coil, if available)
Gradient coil strength	≥20 mT/m (or whatever the system permits)
Cardiac gating	No
Peripheral gating	No
Respiratory gating	No
Oxygen	Yes, 2 liters nasal cannula for most patients (to ensure breath-holding >15 sec)
Motion cushions	Under feet, can be used for patient comfort.
Use of contrast agents	Yes
Power injector	Yes, mandatory for dynamic contrast enhancement of vessels
Monitoring equipment	Heart rate, oxygen saturation, and blood pressure should be monitored with MRI-compatible equipment

3. Instruct the patient in breath-holding techniques. This is especially vital for protocols during which i.v. contrast will be administered, as there are limited chances to acquire a respiratory artifact-free study.
4. Inform the patient that you will be administering a contrast agent, and that the patient may feel a cold sensation in their arm at the time of infusion.

   The total amount of contrast agent is 40 ml.
5. Start a 20- to 22-G antecubital i.v. Attach this line securely to the patient so that movement into or out of the magnet will not pull at the patient's arm.

   It is preferable to insert the i.v. line prior to imaging and to leave the patient in the magnet, with no intervening motion between the scans run before contrast agent injection and those run after injection.
6. Repeat Basic Protocol 1, steps 8 and 9.
7. Perform a multi-image turbo FLASH scout sequence according to the parameters in Table A10.1.2, if not already obtained.
8. Perform a transaxial black-blood HASTE or double inversion recovery TSE/FSE sequence according to the parameters in Table A10.1.3 through the heart, if not already obtained.

Sequence 7: Test bolus

9. Perform the test bolus sequence according to the parameters in Table A10.1.10. This can be performed in any plane that demonstrates the desired vessel(s) well. For the

Table A10.1.10 Primary Clinical Imaging Parameters for Sequence 7 (Test Bolus)

Patient position	Supine
Scan type	T_1-weighted gradient echo (Turbo FLASH), inversion or saturation recovery preparation
Imaging plane (orientation)	Transverse or sagittal
Central slice or volume center	Through vessel to be imaged
Echo time (T_E)	1.8–3.2 msec (or minimum)
Repeat time (T_R)	2.4–6 msec (effective 1000 msec)
Inversion time (T_I)	20 msec
Delay time (T_D)	Not applicable
Flip angle (FA)	8°
Fields of view (FOV_x, FOV_y)	300–350 mm, 300–350 mm
Resolution (Δx, Δy)	1.17–1.37 mm, 2.34–2.73 mm
Number of data points collected (N_x, N_y)	256, 128
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	10 mm
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Number of repetitions	50
Swap read and phase encoding	No
Saturation pulses	No
ECG gating	No
Scan time	50 sec

test bolus, use 2 ml of gadolinium-based i.v. contrast agent, followed by 15 ml sterile normal saline. Inject at 2 ml/sec.

Some manufacturers provide an automatic bolus-tracking program and will inform the imager to start the scan when the signal in the desired vessel reaches a prescribed signal intensity. (The imager usually indicates the desired vessel with ROI placement.) If the manufacturer has this bolus-tracking program in place, it is not necessary to perform a test bolus. Rather, follow the instructions provided by the manufacturer for contrast bolus-tracking program.

This is not a breath-hold sequence.

10. Using images from the test-bolus, determine the time to peak enhancement (each image takes 1 sec to acquire).

Sequence 8: 3-D contrast enhanced gradient recalled echo MR angiography

11. Instruct the patient to hold their breath and run the 3-D gradient recalled MR angiography sequence according to the parameters in Table A10.1.11 without contrast in the coronal plane, using a slab volume large enough to cover the desired vessels, yet small enough to be obtained in a single breath-hold.
12. Prepare to run the 3-D gradient recalled MR angiography sequence according to the parameters in Table A10.1.11 with contrast agent. The dose should be ~0.2 mmol/kg, at an injection rate of 2 ml/sec. As 2 ml was used for the test dose, 38 ml can be used for the MR angiogram (this is the remainder of two bottles of contrast agent). Calculate the scan delay using the following equation.

Table A10.1.11 Primary Clinical Imaging Parameters for Sequence 8 (MR Angiography)

Patient position	Supine
Scan type	3-D gradient recalled echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Great vessels
Echo time (T_E)	0.77 msec
Repeat time (T_R)	2.2 msec
Flip angle (FA)	25°
Fields of view (FOV_x, FOV_y)	300–350 mm, 300–350 mm, depending on body habitus
Resolution (Δx, Δy)	0.59–0.68 mm, 0.79–0.92 mm
Number of data points collected (N_x, N_y)	512, 380, depending on body habitus
Display matrix(D_x, D_y)	512, 512
Slice thickness (Δz)	1.5 mm (interpolated from 3 mm)
Number of slices	64 (interpolated from 32)
Slab thickness	96 mm (can be less, for a shorter breath-hold)
Slice gap	0 mm
Number of acquisitions (N_{acq})	1
Number of repetitions	1 (or 2)
Swap read and phase encoding	No
ZIP 2[a]	Yes (by factor of 2)
Saturation pulses	No
ECG gating	No
Scan time	20–27 sec (or 40–54 sec), depending on volume covered

[a]Slice interpolation.

scan delay = (time to peak enhancement) + (injection duration)/2 − (scan time)/2

Time to peak enhancement is obtained from the test bolus; scan time is determined from the precontrast scan time; and injection duration is the amount of contrast agent to be injected divided by the injection rate (e.g., if the contrast agent is to be injected at 2 ml/sec, and the amount of contrast agent is 38 ml, the injection duration is 19 sec).

13. Instruct the patient to hold their breath and begin the scan. Inject the contrast agent at the scan delay calculated in step 12 after the start of the scan.

    If two vascular phases are to be imaged (e.g., pulmonary arterial and pulmonary venous), or if the patient has a shunt, two measurements can be acquired, one right after the other, with a delay interval for a second breath-hold programmed between the two measurements. Images will be constructed after both measurements are acquired.

14. Use the noncontrast-enhanced images as a mask and subtract them from the contrast-enhanced images at the console or a satellite system, using vendor-provided software.

COMMENTARY

Background Information

Cardiac MR is ideally suited for congenital heart disease assessment, providing information on both anatomy and function. Often, it can provide answers to questions that otherwise could not be answered noninvasively. Echocardiography has long been the principal method of noninvasive imaging of congenital heart disease, however, with advances in functional imaging, cardiac MR can provide both functional assessment of valves, shunts, and ventricular motion, as well as high resolution anatomic assessment. Furthermore, MR assessment is not limited to the heart, but can provide information regarding the aorta and pulmonary arteries that often cannot be obtained with transthoracic echocardiography. Information provided by MR may include assessment of pulmonary artery stenoses in patients with tetralogy of Fallot, congenital rubella, or pulmonic atresia, assessment of the aorta for right-sidedness versus left-sidedness, or aneurysmal dilatation, as well as assessment for the presence of bronchial or chest wall collaterals. Moreover, 3-D breath-held MR angiography methods can be used to assess for the presence of anomalous coronary arteries or congenital aneurysms, as found in patients with Kawasaki's disease.

Critical Parameters and Troubleshooting

Cardiac gating

An adequate ECG tracing with sharp, upgoing *R*-waves and smaller *T*-waves is required for most cardiac imaging. MR compatible ECG leads with conductive gel should be used. Leads with graphite tips may reduce susceptibility artifact in the regions of the leads. To reduce unnecessary noise, good electrical contact between the electrodes and skin is essential. For good skin contact, chest hair may need to be shaved at the points of electrode contact. If difficulty persists, the skin may be cleaned with NuPrep. In patients with congenital heart disease, the position of the heart and axes of the conduction pathways across patients will vary. This will be especially true in patients who have enlarged hearts with ventricular apex displacement or abnormal situs. Situs and other anomalous cardiac anatomy may necessitate right-sided lead placement or placement of the leads on the patient's back rather than chest. Check to see that the leads are positioned correctly and, if necessary, vary the lead polarity options (I, II, AVR, etc). If gating is still inadequate, reposition the ECG leads, using new adhesive pads. If *T*-waves are larger than the *R*-waves, the electrode patch or individual electrodes may need to be moved more laterally. If ECG tracings are no longer visible, check the patient to ensure that leads and cable have remained connected and that there is no break in the cable or cable casing. If patient motion is continually a problem, consider fiberoptic lead use. In the authors experience, while fiber optic leads eliminate patient motion artifact and reduce MR interference, interference induced by the rf-pulse is not entirely eliminated.

MR imaging parameters

For most cardiac imaging, the effective T_R must be shorter than the R-to-R interval. Ide-

ally, if the T_R (or T_R plus T_D) is 100 msec less than the R-to-R interval, imaging will fall in mid-diastole, during the least cardiac motion. A cine gradient echo sequence images multiple phases of the cardiac cycle at a single slice position. For optimal use of cine gradient echo sequences, the number of cardiac phases times T_R should be ~85% to 90% (or 100 msec less than) of the R-to-R interval.

Motion and breathing artifacts

Sequences that can be acquired relatively rapidly, such as multislice HASTE and true FISP, can be obtained during shallow breathing with adequate results. Thus, they are particularly useful in imaging the pediatric patient. Likewise, cine gradient echo images can be performed with multiple signal averages without breath-hold. As described in *UNIT A11.2*, an anterior saturation band can be placed over the subcutaneous fat of the anterior chest wall in order to help reduce breathing-related motion artifact.

Anticipated Results

The goal in studying congenital heart disease with MR is to define the anatomy of the disease. If the patient has been operated upon, the radiologist should look for complications known to occur subsequent to the particular type of surgery performed. In patients who may have an intracardiac shunt, cine sequences can be performed to identify its location. In some instances, the shunt can be quantified. The valves should be assessed to identify the presence of stenosis or insufficiency. The aortic valve can be interrogated to determine whether it is tricuspid (normal) or bicuspid. Pressure gradients across stenotic valves can be determined. In some instances, valvular insufficiency can be quantified. Short axis cine images can provide information regarding ventricular size and function. Finally, contrast-enhanced non-ECG gated MR angiography can provide information about the pulmonary arteries and aorta, assessing pulmonary artery size, the presence of pulmonary artery stenoses, aortic dissection, or aortic aneurysm. Three-dimensional (3-D) coronary MR angiography can also be performed to determine the presence of congenitally anomalous coronary arteries of importance, especially, if the patient is to go on to surgical repair. Faster and stronger gradients permit the acquisition of most of this information, if not all, in a single MR examination.

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This textbook is an excellent reference for the interpretation of all congenital heart imaging, going over the anatomy, physiology and embryology of each congenital heart defect in detail.

Higgins, 2000. See above.

Provides an overview of multiple modalities and their uses in cardiac imaging, including cardiac MR.

Contributed by Pamela K. Woodard and Jie Zheng
Mallinckrodt Institute of Radiology
Washington University Medical Center
St. Louis, Missouri