Cine magnetic resonance imaging after surgical repair in patients with transposition of the great arteries

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ABSTRACT Cine magnetic resonance imaging (MRI) was used for postoperative evaluation of eight patients who underwent intra-atrial baffle procedure for surgical repair of D-transposition of the great arteries (D-TGA). Their ages ranged from 9 months to 8 years. Younger patients were sedated with chloral hydrate (80 to 100 mg/kg) orally. MRI was performed with use of a General Electric Signa system operating at a field strength of 1.5 tesla. A body or head coil was used depending on the size of the patient. Images were obtained by use of a technique of gradient-recalled acquisition in steady state (GRASS) that utilizes a low flip angle and shorter repetition and echo times. Five patients had widely patent venae cavae and three had superior vena caval obstruction at the junction of the right atrium with a dilatedazygos vein. There was no evidence of pulmonary venous obstruction in any of the patients. Right ventricular function was assessed in four patients and their ejection fractions ranged from 58% to 81%. Tricuspid and mitral regurgitation were observed in three and two patients, respectively. Both right and left ventricular outflow tracts were well visualized and showed no evidence of obstruction. Cine MRI is an entirely noninvasive, nonionizing, and safe procedure in young patients and appears to be a valuable alternative method for evaluating patients after surgical repair of D-TGA. With advancing technologies and an accumulation of experience with cine MRI, it appears that this new technique will play an important role in patient care for children with congenital heart disease.


SYSTEMIC OR PULMONARY venous pathway obstruction is the most common anatomic complication of the intra-atrial baffle procedure by either Mustard or Senning procedure for D-transposition of the great arteries (D-TGA).1, 2

Several investigators have reported the value of electrocardiographically gated magnetic resonance imaging (MRI) for evaluation of congenital heart disease.3–10 Recently, rapid MRI techniques (cine MRI) using low flip angles, gradient-refocused echoes, and short repetition time have provided dynamic visualization of blood flow.11–13 This new cine MRI technique allows us to appreciate the complex anatomic/flow relationships of congenital cardiac defects as moving rather than stationary images.

We used cine MRI for the postoperative evaluation of patients who underwent intra-atrial baffle procedure for repair of D-TGA and report our preliminary experience with this new diagnostic modality.

Materials and methods

Eight patients from 9 months to 8 years old were evaluated by cine MRI. Body weight ranged from 6.7 to 32 kg. All patients underwent the Mustard or Senning procedure during infancy for correction of D-TGA. Postoperative cardiac evaluation included history, physical examination, electrocardiogram, and echocardiogram by the Doppler method. All patients had cardiac catheterization and an angiocardiogram.

Patients under 5 years of age were sedated with oral chloral hydrate (80 to 100 mg/kg) 30 min before the procedure. This drug provided excellent sedation in all patients without respiratory or circulatory compromise.

MRI was performed with use of a commercially available General Electric Signa system operating at a field strength of 1.5 tesla. For infants weighing less than 20 kg, a 16 or 28 cm round coil (knee or head) was used and this small coil provided excellent images of the heart. Older children were placed in the regular body coil. The smallest field of view for cine mode was 24 cm. Images were obtained by use of a technique of gradient-recalled acquisition in steady state (GRASS) that utilizes a flip angle of 30 degrees, echo time of 12 msec, and repetition time (TR) of 21 msec. Images were obtained by use of two excitations and an acquisition matrix of 128 × 256. A maximum number of four

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slices was available per cine scan, although for congenital heart disease only one or two slice locations were necessary to cover the area of interest with a 5 or 10 mm slice thickness without interslice gap. For assessment of ventricular function, a 5 or 10 mm slice thickness with 5 mm interslice spacing provided improved image quality for adequate edge detection between myocardium and flowing blood. Images were reconstructed by Fourier transform and displayed continuously in dynamic form throughout the cardiac cycle.

The number of frames per cardiac cycle available for reconstruction is determined by one cardiac cycle length (RR interval, in msec) divided by the TR, which is 21 msec. Therefore, for a heart rate of 100 beats/min (RR interval = 600 msec) and a single slice location, 28 frames per a cardiac cycle will be reconstructed. If two slice locations are acquired, the TR will be 42 msec and 14 frames per cardiac cycle will be reconstructed for each slice. Since detailed data on anatomy are more valuable than those on function for assessment of congenital cardiac defects, a lower number of images per cardiac cycle provided adequate information in young children.

Electrocardiographically gated cardiac imaging was initially performed in all patients to localize the optimal slice locations for cine MRI. Multislice acquisitions were acquired in the coronal, sagittal, axial, and oblique views with the use of a 5 or 10 mm slice thickness without interslice spacing to a maximum of nine slices per scan. To obtain high-quality electrocardiographic signals for cardiac gating, particular care was taken with respect to electrode positioning, proper skin contact, and consistent triggering to the R wave, without T wave interference, before the study. When the superior vena cava was not well visualized in the coronal view, the oblique software system was used to position the patient’s heart in the right anterior oblique view. The images were displayed on the monitor screen in a cine mode for analysis. Observation of the changes in anatomic configurations and blood flow density throughout the cardiac cycle was facilitated with this method. The shape and dynamic changes of the cardiac structures, such as cardiac chambers, myocardium, cardiac valves, and great vessels, were appreciated. Specific anatomic details were then analyzed more closely with use of a stop frame image.

Assessment of right or systemic ventricular function was performed in four patients with the use of end-diastolic and end-systolic frames of the midventricular area. A border between the endocardium and blood was detected and systolic (SA) and diastolic areas (DA) were measured by planimetry. Right ventricular function was assessed in a sagittal view. Ejection fraction (EF) was estimated by a formula:

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\text{EF} \, (%) = \frac{\text{DA} - \text{SA}}{\text{DA}} \times 100
\]

Results

In all patients, the vena caval systems, cardiac chambers, pulmonary venous system, and great arteries were well visualized, although the atrioventricular and semilunar valves were not clearly seen. Five patients had widely patent venae cavae without any evidence of obstruction. Three patients had severe narrowing of the superior vena cava at the junction of the right atrium with a dilated azygos vein (figure 1). There was no evidence of inferior vena caval obstruction in any patient. The superior vena cava was well outlined in either the coronal or right anterior oblique view. On axial view, pulmonary venous pathways and newly formed left atrium were adequately visualized and showed no evidence of obstruction (figure 2). Both the great arteries and ventricular outflow tracts were seen on sagittal view and showed no evidence of narrowing (figure 3). Right ventricular function was normal in children whose ejection fraction was measured (figure 4), and ranged from 58% to 81%. Tricuspid regurgitation was observed in three patients as a signal void area in the left atrium and mitral regurgitation was seen in two patients in the right atrium. Superior vena caval obstruction was confirmed in two patients by angiography and in one patient by surgery. The status of pulmonary venous return and inferior vena cava and atrioventricular valvular regurgitation was evaluated by measurement of pressures or evaluation of angiograms and confirmed the cine MRI findings in all cases. All MRI area ejection fractions were within 5% of the value determined by the area of fraction on lateral plane angiography.

Discussion

The most common anatomic complication of the intracardiac baffle procedure for d-TGA is systemic or pulmonary venous pathway obstruction. Supraventricular arrhythmia due to extensive intra-atrial reconstruction has been present in two-thirds or 67% of patients after surgery. Functional impairment such as

**FIGURE 1.** Cine MRI in a 3.5-year-old child after Mustard operation. Coronal image demonstrates narrowing at the junction of the superior vena cava and right atrium (arrow). A radiolucent area is seen just above the obstruction, presumably due to turbulent flow due to obstruction.
tricuspid insufficiency and right or systemic ventricular dysfunction have been another dilemma after this procedure since the right ventricle and tricuspid valve are not structured for the systemic load.\textsuperscript{14, 15}

Systemic and pulmonary venous pathways have been extensively evaluated by two-dimensional and pulsed Doppler echocardiography,\textsuperscript{16–18} radionuclide imaging,\textsuperscript{19} and digital subtraction angiography.\textsuperscript{20} All of these techniques have some drawbacks. The echocardiogram has superb spatial resolution to identify anatomic detail, but its tomographic nature and limited depth resolution restrict its value in visualizing extra-cardiac structures, particularly when they are distant from the transducer. Also, usefulness of imaging with two-dimensional echocardiography is very limited in patients after median sternotomy for surgical repair because of the scarring process, which interferes with echocardiographic examination. Radionuclide imaging is a sensitive detector of physiologic data, but gives suboptimal spatial orientation and anatomic detail. It also has very limited value for the assessment of right ventricular function because of its anatomic position. Digital subtraction angiography provides efficient use of x-rays because it entails use of a fluoroscopic imaging chain (image intensifier and high-resolution tele-vision camera), logarithmic amplification of the signal, and temporal mask-mode subtraction, resulting in images of excellent quality, but its invasive nature and the amount of radiation exposure with this technique are disadvantages in small children.

As relates to the long-term effects of intra-atrial baffling procedures, there has been much concern about the long-term function of the right ventricle because it must still eject blood into the high-resistance systemic circulation after surgical repair. Several authors have reported right ventricular dysfunction and tricuspid insufficiency after the intra-atrial baffle procedure. Doppler echocardiography has specifically been used to assess the degree of tricuspid regurgitation without providing quantitative assessment. Right ventricular volume and function can be extremely difficult to assess by two-dimensional echocardiography because of its anatomic configuration. To date, no noninvasive method provides adequate information with regard to right ventricular function.

Cine MRI, the newest imaging technique, can now provide not only accurate images of the anatomy of cardiac structures, but also noninvasive functional assessments of the cardiac chambers and walls and flow relationships.\textsuperscript{21–23} The major advantages of cine MRI

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FIGURE 2. Axial views from a 15-month-old infant after surgical repair reveal normal pulmonary venous return into the newly formed left atrium. The arrows point to pulmonary veins. S = spine.
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blood has a bright signal intensity relative to the myocardium on cine images due to continuous entry of unsaturated spins and images can be generated more quickly due to a short repetition time.

We were able to obtain images of excellent quality for anatomic and functional analysis of cardiac chambers, great arteries, and veins in those children after surgical repair by cine MRI. The degree of stenosis in the vena caval system was comparable to that measured by the angiocardiographic technique. The right ventricular ejection fraction measured was also extremely close to the angiographic value. In patients with valvular regurgitation, signal loss beneath the valve itself is probably due to turbulent high-velocity regurgitant flow. Color flow mapping in these patients showed the same phenomena, but quantitative assessment of regurgitant volume by either of these methods needs further study. We were very impressed by the quality of images by cine MRI, especially those of the right ventricle on the sagittal plane. In cine MRI, the subject's own flowing blood serves as the contrast material, providing images of excellent quality, including those of right ventricular volume and wall thickness. Until now, only angiocardiography could provide this information with regard to the right ventricle. In the axial view, both pulmonary venous pathways were clearly depicted and no patients showed baffle leak either on cineangiography or cine MRI.

Cine MRI is in an early stage of development and clinical application and at present there are still several

FIGURE 3. Sagittal views after surgical repair for d-TGA show wide right and left ventricular outflow tracts without any evidence of obstruction. Note the ascending aorta arises from the anterior or right ventricle and the pulmonary artery arises from the posterior or left ventricle.

FIGURE 4. Sagittal cine images in a 6-year-old child after intra-atrial baffle procedure (Mustard operation) for d-TGA. Top, Diastolic frames. Frame 42 (top left) was obtained during end-diastole. Bottom, Systolic phases. Frame 7 (bottom right) was obtained during late systole. Right ventricular function can easily be assessed from images like these.
drawbacks associated with it. Cine MRI provides superb anatomic detail, but assessment of cardiac function may be limited because images are not acquired in real time and imaging is time consuming. The information is compiled from cumulative data from 128 cardiac cycles, but this method simulates real-time cardiac imaging in the same way that radionuclide angiography and functional analysis can be achieved, comparable to angiography. However, our experience suggests that certain factors are of particular importance in order to obtain high-quality images. Any movement of the patient during scanning can cause significant image loss, and therefore it is extremely important that young children be sedated properly and older children should be informed about the importance of staying still during image acquisition. Although not a major problem, significant heart rate variation remains a potential problem with this technique and it is unlikely that high-resolution imaging can be performed in patients with severe arrhythmia. One further potential problem in patients who have had complex cardiac surgery is the image voids produced by vascular clips, which create false-negative images. Similar image voids have been seen in images from patients with sternal wires, but these did not interfere with cardiac or vascular imaging. A long reconstruction time after the actual scanning prolonged the procedure, but recently we have been reconstructing images after all acquisitions are completed, thus limiting the patient’s actual scanning time to less than 1 hr. Also, acquisition of a limited number of slices during each scan procedure, with the selection of the proper oblique views with the present software, can lead to prolonged examination time. With further advances in computers and software systems, it is likely that the time required for image reconstruction will decrease substantially. Easy manipulation of software systems for the oblique view can effectively shorten the examination time, so that the patient can tolerate the procedure without any discomfort and more information for patient care can be obtained.

Recently, a cardiac analysis software package system was developed that allows rapid calculation of cardiac volume and regional wall motion of an area of interest by edge detection based on the marked signal contrast between blood and the myocardium. Since the areas and volumes can be obtained at any phase of the cardiac cycle and any portion of the ventricle, end-systolic and end-diastolic volumes are obtained and ejection fraction and cardiac output can be derived. A quantitative assessment of regional wall motion can also be obtained.

The use of a head or knee coil was extremely valuable in enhancing high-resolution images in young patients and we did not encounter any problems with use of these coils. Electrocardiographic gating was not affected by use of these coils and they further reduced potential movements of neonates and infants during the procedure.

In conclusion, our preliminary experience suggests that cine MRI can provide high-resolution anatomic and functional information similar to that obtained by cineangiography. It can provide dynamic, high-resolution, and flow-enhanced images that are inherently volumetric in any desired plane through the heart and great vessels. The method is particularly useful in small children since it is entirely noninvasive and requires no radiation, yet provides sufficient data for patient management. The only major drawback is that cine MRI cannot as yet estimate pressures and resistances in cardiac chambers and great vessels, which may be mandatory for proper management of certain patients with complex cardiac lesions. With advancing technologies and an accumulation of experiences with cine MRI, it appears that this new technique will play an increasingly important role and will become an invaluable part of patient care in children with congenital heart disease.

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