Cine Magnetic Resonance Imaging for Evaluation of Anatomy and Flow Relations in Infants and Children With Coarctation of the Aorta

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Sixteen cine magnetic resonance imaging (MRI) studies were performed in 14 patients aged 1 week to 17 years (mean age, 46 months), who had coarctation of the aorta confirmed at angiography or surgery. Conventional echocardiographic-gated MRI was first performed in axial and rotated sagittal views and was used to identify the slice locations for cine MRI. Cine MRI was performed by gradient-recalled acquisition in steady state with a 30° flip angle, 12-msec echo time, 22-msec pulse repetition time, and a 128×256 acquisition matrix. Coarctation anatomy was extremely well defined in all but one patient who had vascular clips at the coarctation repair site. The smallest descending aortic flow diameter on cine MRI showed excellent agreement with angiography (r = 0.90). Lucent jets of high-velocity flow through the site of coarctation were imaged in eight patients, and jet length correlated well with the angiographic severity of coarctation (r = −0.81). Two patients were restudied after surgery, and they exhibited excellent repair and normal flow patterns. Cine MRI provides high-resolution imaging of coarctation anatomy with a dynamic spatial and temporal visualization of flow and with excellent detail of vascular anatomy and flow both proximal and distal to the coarctation. (Circulation 1988;78:142–148)

It is well recognized that two-dimensional echocardiography can diagnose and estimate the severity of coarctation of the aorta.1–3 Adequate imaging of the coarctation site is usually possible in neonates, but difficulties can be encountered in older patients or in patients after surgery in whom the distance between the ultrasound transducer and the descending aorta is greater and in whom the image resolution is poorer. Doppler ultrasound has further enhanced the noninvasive assessment of these patients,4,5 and favorable results in predicting pressure gradients across the coarctation have been reported.3–7 However, the pressure gradient measured across a coarctation will not necessarily reflect the degree of obstruction since it is dependent on a number of other factors including the length and shape of the obstruction, the amount of flow through the coarctation, and the presence and the extent of collateral blood flow. In addition, pressure gradients measured during cardiac catheterization are subject to the progressive distortion of the pressure waveform as it is transmitted through the arterial system.8 Although Doppler ultrasound can accurately measure the pressure gradient from the peak velocity, it may not always accurately reflect the severity of coarctation since coarctations are sometimes long segments with tortuous obstruction. In addition, confusion can arise in newborn infants in whom a restrictive right-to-left ductus arteriosus can produce a flow-velocity pattern in descending aorta that mimics coarctation.9

Magnetic resonance imaging (MRI) is a noninvasive technique that is not limited by the problems of acoustic penetration encountered with ultrasound examination. Conventional echocardiographic-gated cardiac MRI provides excellent visualization of structural detail in a variety of congenital heart lesions10–12 including coarctation,13,14 but it does not provide for the dynamic appreciation of cardiac structures or their relations to flow, which is usually...
The aim of the present study, therefore, was to assess the clinical value of cine MRI in the study of patients with coarctation of the aorta and to evaluate the flow-velocity relations at the site of coarctation.

Patients and Methods

Sixteen cine MRI studies were performed prospectively in 14 consecutive patients who presented with clinical evidence of coarctation of the aorta or who had undergone surgical repair of coarctation. Patients were not selected but represented our referrals over an 8-month period. Patients’ ages ranged from 1 week to 17 years (mean age, 46 months). Nine of the patients had native coarctation, two of whom had repeat studies after surgery. Four other patients who had clinical evidence of recoarctation after previous surgical repair were also studied, and the remaining patient was studied after balloon angioplasty for significant recoarctation. The diagnosis and severity of coarctation or the extent of recoarctation was confirmed during catheterization or during surgery in all patients.

MRI was performed with a commercially available superconducting magnet (General Electric Signa System, Milwaukee, Wisconsin) with a field strength of 1.5 Tesla. Nine patients, all under 2 years old, were studied while lying supine within the head coil; two patients were studied lying prone on a 5-in. surface coil; and the remaining three patients were studied with the body coil. Ten patients, all under 5 years old, were sedated with chloral hydrate, 80–100 mg/kg orally, 20–30 minutes before study. Coarctation severity was measured to the nearest 0.5 mm on cine MRI and at angiography, and correlations were performed with Spearman’s rank

provided by echocardiography and color Doppler flow mapping. Magnetic resonance velocity mapping\textsuperscript{15} and cine MRI\textsuperscript{16} have recently been introduced with scan sequences that allow rapid data acquisition and provide a dynamic visualization of flow-enhanced images. Advantages of cine MRI for clinical cardiac application have recently been the subject of preliminary reports,\textsuperscript{17} and it appears that the technique has the potential to allow appreciation of the complex anatomic-flow relations that exist in many cardiac lesions displayed in a format similar to a cine angiogram but without the need for invasive study or the introduction of contrast material.

\textbf{FIGURE 1.} Axial view of conventional echocardiographic-gated magnetic resonance image. Panel A: Ascending (A) and descending (D) aorta in cross section. Panel B: Same axial view as Panel A but showing angle of rotation (\ldots\ldots) required from sagittal plane to allow subsequent imaging in the plane of the aorta with the line transecting the ascending and descending portions of the aorta in cross section.

\textbf{FIGURE 2.} Conventional echocardiographic-gated magnetic resonance image in rotated sagittal view in a patient with severe coarctation (\rightarrow). Note discrete narrowing at the site of coarctation in the proximal descending aorta. Image appears quite similar to a sagittal view in this case because the angle of rotation is only 14° as shown in Figure 1B.
correlation. Angiograms were calibrated with a grid and the known size of the descending aortic catheter.

Gated Cardiac Imaging

Echocardiographic-gated MRI was performed in all patients, first in sagittal and axial views to estimate the appropriate oblique rotation and then in the rotated sagittal view to visualize the entire aortic arch and descending aorta and to confirm the exact slice locations for cine MRI. Multislice acquisitions were acquired with a 5- or 10-mm slice thickness with or without interslice spacing to a maximum of nine slice locations. Images were acquired with a single excitation for localizing scans and a single echo with an echo time of 25 msec. The repetition time varied with each patient depending on heart rate, and individual scan times ranged from 2 to 4 minutes. Gated cardiac imaging was first performed in the sagittal plane to determine whether adequate visualization of the area of coarctation could be obtained without oblique imaging. The sagittal view was also used to determine the start and ending locations for gated imaging in the axial plane to include the ascending and descending portions of the aorta and aortic arch. From an axial slice showing the ascending and descending aorta in cross section, the angle of rotation required from the standard sagittal plane was measured to allow imaging in the true plane of the aorta (Figure 1). Oblique imaging was achieved by manipulation of the field gradients, allowing any angle of rotation about multiple axes to be obtained with the angle of rotation in each individual patient determined as shown in Figure 1. A conventional, echocardiographic-gated image in this rotated sagittal plane from a patient with coarctation is shown in Figure 2. Although the image appears quite similar to a standard sagittal image, the angle of rotation is critical for imaging in the true plane of the aorta.

Cine Magnetic Resonance Imaging

Cine MRI was then performed in the rotated sagittal plane with slice locations chosen from previous localizing gated scans. One or two slice locations were chosen in each patient with either a 5- or 10-mm slice thickness depending on the patient’s size. Cine MRI was performed with the technique of gradient-recalled acquisition in a steady state (GRASS) scanning with a flip angle of 30°, an echo time of 12 msec, and a repetition time of 22 msec/slice. Images were obtained with two excitations and a 128 × 256 acquisition matrix, and 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 was determined by the cardiac cycle length in msec divided by the repetition time. Therefore, for a heart rate of 100 beats/min (cycle length, 600 msec) and one slice location (repetition time, 22 msec), 27 frames/cardiac cycle would have been reconstructed. If two slice locations were acquired, the repetition time would have been 44 msec, and only 13 frames/cycle would have been reconstructed at each slice location.

Results

Satisfactory MRI studies were obtained in 13 of the 14 patients with oblique “sagittal” imaging; however, adequate imaging of the full extent of the coarctation site was possible in only seven patients (50%) with standard sagittal views. The angle of rotation required varied somewhat between patients, and although the rotation angle was as small as 14°, it allowed imaging of the full extent of the coarcta-

FIGURE 3. Stop frame of a cine magnetic resonance imaging sequence from a patient with mild coarctation. Note excellent visualization of the extent of the coarctation despite a very tortuous segment of descending aorta.

FIGURE 4. Plot of linear regression comparison of the smallest flow diameter at the coarctation site on cine magnetic resonance imaging with the coarctation diameter measured subsequently at angiography.
tion, which compared well with subsequent angiographic data even when the descending aorta was quite distorted (Figure 3). The anatomy of the coarctation was extremely well defined with oblique cine MRI in all but one patient, in whom the presence of vascular clips at the site of coarctation repair caused a considerable signal void on cine MRI despite being stainless steel. Scan times for cine MRI ranged from 1.5 to 3 minutes depending on heart rate, and the total patient time within the magnet ranged from 40 minutes to 1 hour, which included the time for reconstruction and visual display of the cine MR images.

The anatomic severity of coarctation assessed by cine MRI was similar to that obtained with conventional MRI in the same oblique plane [coarctation diameter, $5.5 \pm 4.4$ mm (mean $\pm$ SD) vs. $5.5 \pm 4.2$ mm, respectively; $r=0.98$], but flow velocity observations were obtained from cine MRI and provided additional information about physiology and severity. In the 11 patients also studied angiographically, the smallest flow diameter of the coarctation site on cine MRI correlated well with the coarctation diameter measured at angiography (Figure 4). Of additional interest, however, the flow-enhanced GRASS scanning used by cine MRI also produces a high-intensity signal for relatively low-velocity blood flow, and high-velocity flow, as found in high-velocity laminar jets through obstructive or regurgitant valves, produces a low-intensity or dark signal area as does turbulent flow. Diastolic lucent jets from high-velocity flow across the coarctation (Figure 5) were seen originating from the coarctation site in eight patients, six of whom had severe native coarctation and two of whom had severe recoarctation. In all cases, these lucent jets persisted throughout diastole and were always associated with high-diastolic flow velocities greater than 0.8 m/sec on continuous-wave Doppler (Figure 6). The maximum length of the lucent jets imaged on cine MRI compared well with the coarctation severity measured at angiography or surgery (Figure 7). No lucent jets were identified in the two patients with mild native coarctation nor in the remaining patient with native coarctation, who had a significant lesion found at catheterization. In this patient, despite a significant coarctation, increased diastolic flow velocities were not found on continuous-wave Doppler, and large collaterals were subsequently identified at angiography. A lucent jet was not seen in the patient studied after successful angioplasty. In the remaining patient who presented with mild recoarctation without vascular clips, some narrowing of the proximal end of a tube graft was identified during MRI, but no lucent jet was seen, and angiography subsequently confirmed the presence of

**Figure 5. Early diastolic stop frame of a cine magnetic resonance imaging sequence in the rotated sagittal view from a patient with significant native coarctation. Note the coarctation narrowing (white arrow) and the lucent high-velocity jet (dark arrow) originating from the coarctation site and extending distally into the descending aorta.**

**Figure 6. End-diastolic stop frame of a cine magnetic resonance imaging sequence (Panel A) showing persistence of lucent jet to end diastole. Panel B: Continuous-wave Doppler spectral tracing from the same patient demonstrating high-diastolic flow velocities (−→).**
only very mild recoarctation at the proximal graft insertion with a gradient of only 20 mm Hg. Also, in the two patients who were restudied after repair of a significant native coarctation, lucent jets that had been present on the initial study had disappeared after successful repair. In fact, all the patients with lucent jets on MRI had continuous-wave Doppler velocities greater than 3.5 m/sec in systole and greater than 0.8 m/sec at end diastole across their coarctation; conversely, when lucent jets were absent, the systolic and diastolic velocities were always less than 3.5 and 0.8 m/sec, respectively.

In the eight patients with diastolic lucent jets at the coarctation site, marked poststenotic dilatation was present in the three patients in whom the jet was directed more obliquely toward the aortic wall, and little poststenotic dilatation compared with the size of the precoarctation site was seen in the five patients with centrally directed jets.

Discussion
In our study, cine MRI appeared to provide accurate noninvasive imaging of the anatomy and flow relations in patients with coarctation of the aorta, information which, in some patients, was only previously possible by invasive investigation. The major advantages of cine MRI over conventional noninvasive techniques is that, unlike echocardiography, it has no limitation of imaging planes, and unlike cine computed tomography, it requires no injection of contrast medium. In addition, cine MRI is inherently volumetric with variable slice thickness.

Our study suggests that cine MRI provides high-resolution imaging of the anatomy and flow relations of coarctation. Accurate estimation of the severity of the coarctation was possible in all patients studied before surgery and in 13 of the 14 total patients in our group in whom satisfactory images were obtained.

It is possible to obtain accurate detail of the coarctation anatomy with conventional echocardiographic-gated MRI, and the additional information supplied or the importance of the cine MRI imaging facility could be questioned. We believe that the dynamic spatial and temporal information about the flow jets at the coarctation site provided by cine MRI is a valuable and important addition to the imaged structural detail, and the technique allows this information to be visualized in a format similar to that of cineangiography. Indeed, the visualization of flow jets is a particular advantage of the technique over angiography since these jets may be important not only for estimation of coarctation severity but also may allow separation and analysis of ductal flow, which is a potential source of confusion in the evaluation of neonates with coarctation by spectral Doppler,18 particularly where the site of coarctation is close to the insertion of the ductus.

The exact significance of these lucent-flow voids seen on cine MRI is not totally clear since the velocity of flow in the ascending aorta at peak systole causes flow lucency in normal patients. The lucent-flow jets visualized by cine MRI through and distal to narrowed orifices may be a result of many factors including high-flow velocity and flow turbulence.18 The association of jet length with coarctation severity in this study may be a reflection of the flow velocity and pressure gradient across the obstruction rather than a function of the anatomic severity. This would seem to be confirmed by the temporal association of these lucent-flow voids with the presence of high-flow velocities on Doppler examination. The effects on these lucent jets of flow volume, flow rate, and pressure drop across the obstruction remain to be fully established. However, a lucent jet at the site of coarctation would appear to reflect the presence of a significant obstruction and is a valuable adjunct to imaging of coarctation anatomy where doubt may exist as to the severity of the lesion. This was true in the two patients with significant recoarctation in whom, because the aorta was quite distorted over a long segment, definitive assessment of the severity of coarctation was difficult on conventional MRI, but the presence of a lucent jet at and distal to the major site of coarctation confirmed the presence of significant obstruction. However, the absence of a lucent jet does not necessarily preclude the presence of significant coarctation as demonstrated in the one patient with significant coarctation in whom no jet was visualized and high-diastolic flow velocities were not seen on Doppler ultrasound, probably reflecting the presence of significant collaterals that were visualized angiographically in this patient.

Our study would also suggest that oblique plane imaging is essential for accurate assessment of aortic coarctation by cine MRI. The use of the standard
of the aorta, high-resolution two-dimensional images could not be obtained in six of the patients in this study; on the other hand, cine MRI was successful in 13 of the 14 patients. Of the six patients in whom echocardiography failed to provide high-quality anatomic definition, four were patients after surgery, and one other was 16 years old. Cine MRI was successful in providing high-resolution images in these six patients. Doppler ultrasound was successful in providing gradient information in 12 of the 14 patients but gave no information about morphology of the coarctation. Cine MRI potentially can provide both types of information.

MRI is a significant advance in the noninvasive assessment of these patients, and it may have particular value in the serial follow-up of patients after coarctation repair in whom echocardiographic examination is more difficult. It was not the purpose of this study to suggest that cine MRI can or should replace echocardiography, but to illustrate its complementary role. Indeed, it may be more appropriate to regard cine MRI as a potential replacement for angiography in patients with coarctation in whom further information with respect to anatomic detail and flow relations is still required after echocardiographic examination.

In conclusion, cine MRI can enhance the noninvasive assessment of patients with coarctation of the aorta. It can provide dynamic, high-resolution, flow-enhanced images in any desired plane through the heart and great vessels. The information it provides is comparable to angiography, but additional flow-velocity information is obtained without the need for contrast media or invasive study. In addition, the noninvasive nature of the technique makes it ideal for the serial assessment of patients after coarctation repair or balloon angioplasty procedures for recurrent aortic obstruction. We believe that cine MRI will play an increasingly valuable role in the assessment of patients with coarctation of the aorta.

References


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