The detection of atrial and ventricular septal defects with electrocardiographically synchronized magnetic resonance imaging

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ABSTRACT To evaluate the detectability of cardiac septal defects by electrocardiographically synchronized (ECG-gated) magnetic resonance imaging (MRI), 48 subjects were imaged, including 18 normal and 30 abnormal subjects in whom 22 ventricular septal defects (VSDs) and nine atrial septal defects (ASDs) had been diagnosed angiographically. Two radiologists with ECG-gated cardiac MRI experience read the scans in a blinded fashion, and the results were evaluated by receiver operator characteristic curve analysis. The detectability of VSDs appeared greater than that of ASDs, although statistical significance at the .05 level was not achieved. The reported sensitivity and specificity of echocardiography in the detection of VSDs is comparable to MRI, whereas echocardiography probably is superior to MRI for detection of ASDs. Although MRI is potentially valuable in the diagnosis of various complex congenital cardiac defects, echocardiography is probably superior in the detection of VSDs and ASDs.


ELECTROCARDIOGRAPHICALLY synchronized (ECG-gated) magnetic resonance imaging (MRI) is a noninvasive technique that has been successfully applied to the heart by various investigators.1-7 MRI of congenital cardiac malformations has been reported in preliminary studies demonstrating the practicality of the technique.8-10 However, images in these studies were read under unblinded conditions, and only one included normal controls. We have employed controlled, blinded readings to explore the detectability of atrial and ventricular septal defects (ASDs and VSDs) by ECG-gated MRI.

Methods

Instrumentation. Patients were imaged with a commercial MRI system (Technicare, Inc., Solon, OH) that incorporates a superconducting magnet operating at 0.5 T. Small subjects were examined with a radiofrequency coil that has an aperture 28 cm in diameter and was designed primarily to image the head (head coil). Larger patients were examined with an RF coil that has an aperture of 55 cm and was designed to image the adult human torso (body coil).

Images were acquired and reconstructed with software supplied by the manufacturer, by means of a two-dimensional Fourier transform method. A spin-echo pulse sequence was used in all cases with an echo time of 30 msec. All scans were ECG gated with Hewlett-Packard pulse equipment and a Technicare cardiac gating interface.8 The repetition time was equal to the RR interval. Four sets of signals were averaged for each image. The plane selecting excitation pulse (and thus the images) had a nominal thickness of 0.75 cm (full-width-at-half-maximum). Nine to 12 parallel, cross-sectional images were acquired simultaneously, separated by 0.5 cm gaps. A second, similar set of nine to 12 images was then acquired, offset 0.62 cm from the previous collection, to examine the regions between the images of the first collection. When possible, images were obtained in transaxial, coronal, and sagittal orientations. Images were rarely collected in fewer than two orientations. A modified left anterior oblique image set, in which the ventricular and atrial septa were perpendicular to the imaging plane, was obtained in the majority of cases.

Patient selection. Forty-eight subjects were studied over a 6 month period, including 18 normal volunteers and 30 patients with congenital heart disease. Of these, nine patients had angiographically proven ASDs (mean age ± SD 12.5 ± 11 years, range 0.7 to 38), and 22 patients had angiographically proven VSDs (age 7.3 ± 5.4 years, range 0.3 to 21) (table I). The normal subjects (age 21.8 ± 8.9 years, range 6 to 42) were combined with the 30 patients in the ASD/VSD group to complete the study population. Informed consent was obtained from all subjects, or in the case of minors, from the subject’s parent or guardian, in accordance with a protocol approved by the Human...
TABLE 1
Patient findings

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<th>Patient No.</th>
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<th>Echo. Dx</th>
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Dx = diagnosis; 2° ASD = secundum atrial septal defect; PS = pulmonary stenosis; CAVC = common atrioventricular canal; TGA = transposition of the great arteries; TA = tricuspid atresia; PFO = patent foramen ovale; DORV = double-outlet right ventricle; coarct. = coarctation of the aorta.

Investigation Committee of Rush-Presbyterian-St. Luke’s Medical Center. Subjects under the age of 8 were sedated with 50 mg/kg chloral hydrate administered orally. No complications from sedation were experienced.

Image evaluation. Image sets of patients and normal volunteers were randomly ordered and presented to two observers for interpretation without clinical or other information and with identifying marks covered. Observer 1 was a radiologist, experienced in ECG-gated MRI of the heart, who had been exposed intermittently to approximately 95% of the cases over the 6 month period of data acquisition. Observer 2 was a senior resident in radiology who had 2 months experience in ECG-gated MRI of the heart and had been exposed to approximately 20% of the cases over that interval. For each image set the observers independently rated their confidence that a VSD was present, using the following five-category rating scale: 1 = definitely present, 2 = probably present, 3 = possibly present, 4 = probably not present, 5 = definitely absent. The observers then used the same rating scale to indicate in each case their confidence that an ASD was present.

True-positive fractions, i.e., sensitivity, and false-positive fractions, i.e., 1 minus specificity, were calculated for the four decision criterion levels implied by the five-category scale in a manner previously described.14 This was done for responses relating to both VSDs and AS2ds and for both observers. The resulting operating points were plotted in separate receiver operating characteristic (ROC) spaces for VSDs and AS2ds, re- spectively (figures 1 and 2).

The assumption was made that the VSD response data from the two observers lie along the same ROC curve, and a modified form of a program described by Metz et al. (CORROC) was used to fit a single ROC curve to the data generated by the two observers.12 A similar assumption and curve-fitting operation was applied to the ASD response data. The resulting curves for VSDs and AS2ds were plotted separately in figures 1 and 2, respectively, and together in figure 3. Assuming that the response data for VSDs were independent of those for AS2ds, the estimates of the variances and correlation of the normal deviate values of the y intercepts (parameter a) and slopes (parameter b) of the two ROC curves computed by CORROC were then used to test the differences in true-positive fractions for AS2ds vs VSDs at false-positive fractions of 0.05 and 0.10.12, 13

Results

The ROC curves in figures 1, 2, and 3 represent the combined performance of the two observers using ECG-gated MRI in the tasks of detecting VSDs and AS2ds. The curve in figure 1 indicates that observers 1 and 2 should detect VSDs with a sensitivity of approxi-
FIGURE 1. ROC curve and operating points reflecting detectability of VSDs. ◆ = ref 19; △ = ref. 20; ▲ = ref. 21; TPF = true-positive fraction; FPF = false-positive fraction.

mately 0.84 and 0.86 when employing decision criterion levels that yield false-positive fractions of 0.05 and 0.10, respectively. This is substantially better than their performance in detecting ASDs when operating in the same, clinically relevant specificity range (false-positive fraction less than 0.10): the estimated sensitivities for ASD at false-positive fractions of 0.05 and 0.10 are only 0.35 and 0.53, respectively (figures 2 and 3). Despite the great magnitude of the differences between the sensitivities of ECG-gated MRI for ASD vs VSD at false-positive fractions of 0.05 and 0.10, these differences were not statistically significant (p = .23 at both false-positive fractions).

Figures 4, 5, and 6 show representative magnetic resonance images.

Discussion

Electrocardiographically synchronized MRI has been reported to be successful in demonstrating congenital cardiac malformations.8–10 These reports have
indicated that ECG-gated MRI can be used to detect VSDs and ASDs. In a report of 11 VSDs and five ASDs, sensitivities of 90% and 100%, respectively, were reported. In another experiment, an 80% sensitivity was achieved in a combined series of 10 ASDs and VSDs. The sensitivities of MRI for ASDs and VSDs reported in these series may not fairly represent those that would be observed under realistic clinical conditions, since the cases of each type of defect were interpreted under unblinded conditions. Moreover, only one series included normal subjects as controls.

We have attempted to achieve more realistic estimates of the detectabilities of ASDs and VSDs with MRI by having our observers interpret the images under blinded conditions, with abnormal cases randomly mixed with normal controls. Even our experiment may have been biased, however, by the observers’ exposure to some of the test images, although the minimum interval between previous exposure and the test readings was several months.

In the present study, the detectabilities of ASDs and VSDs by MRI are presented by means of ROC curves, which estimate the sensitivity and specificity of each lesion over a wide range of decision criterion levels. The value of this mode of representing observer performance in diagnostic imaging is that it controls for the principal cause of interobserver and intraobserver variability, namely variation of the decision criterion level.

The ability of the observers to detect ASDs in this experiment appeared far inferior to their ability to detect VSDs. Using decision criterion levels that yielded false-positive fractions of 0.05 and 0.10 (i.e., specificities of 95% and 90%), the observers would have achieved sensitivities of only 0.35 and 0.53, respectively, when diagnosing ASDs as compared with sensitivities of 0.84 and 0.86 when looking for VSDs. Despite the large magnitude of these differences, they are not statistically significant (p = .23 at both false-positive fractions). We believe this failure to achieve statistical significance is primarily due to the low statistical power provided by the small number of patients in our series who had ASDs (only nine); we suspect that the results do represent an actual inferiority of ECG-gated MRI in detecting ASDs. Others have reported similar results. Difficulty in detecting ASDs is attributable to the thinness of the interatrial septum and its curved shape, which make it impossible to display in its entirety in any single cross-sectional orientation. This makes it difficult to evaluate the structure for defects by any strictly anatomic criteria with any imaging modality; similar difficulties have been encountered during the application of echocardiography to the detection of ASDs, in which the thinness of the struc-
FIGURE 6. Magnetic resonance image showing a patent foramen ovale. Membrane over the foramen ovale is fenestrated. The structure is very thin, and judgment regarding the presence of a defect is difficult.

ture will allow dropout of echoes to mimic an ASD in normal atrial septa. Thus visualization of an interatrial septal defect per se is not the only criterion used for diagnosis in echocardiography. Functional criteria (paradoxical septal motion and other indications of right heart volume overload) are necessary adjuncts. Moreover, the technique of intravenous injection of tiny air bubbles (contrast echocardiography) has provided another very sensitive and specific functional criterion, the passage of air bubbles from one atrial chamber to the other.16-18

It is to be expected that VSDs should be more readily detected with ECG-gated MRI than are ASDs. The interventricular septum is primarily a thick, muscular structure, easily seen in normal individuals by ECG-gated MRI. Even the membranous portion of the interventricular septum, a more substantial structure than the interatrial septum, is readily demonstrated with ECG-gated MRI. Large to medium sized VSDs are easily detected with MRI (figure 4). However, smaller ("pinhole") muscular VSDs probably are more difficult to detect. We have examined four patients with presumed "pinhole" muscular VSDs, not included in this experiment because none were confirmed angiographically (one confirmed by echocardiography and three diagnosed clinically). Only one was clearly seen on MRI. Difficulty in diagnosis of pinhole VSDs by direct visualization occurs with echocardiography as well, although Doppler two-dimensional echocardiography has been reported to be a sensitive noninvasive test for this lesion.19

To fully understand the usefulness of ECG-gated MRI for detection of ASDs and VSDs, the technique must be compared with the present noninvasive diagnostic examination of choice, two-dimensional echocardiography. We have compared our results with those of several echocardiographic studies reported in the literature.16-21 Operating points representing sensitivities and specificities reported for ASDs and VSDs in these series were plotted in the appropriate ROC spaces (figure 1 and 2). The operating points representing the sensitivities and specificities of echocardiography for VSDs19-21 lie close to the ROC curve for detection of VSDs by ECG-gated MRI, suggesting a similar inherent detectability of VSDs by both means. However, the operating points representing sensitivities and specificities for ASDs for air contrast twodimensional echocardiography16-18 are well above the ROC curve for detection of ASDs by ECG-gated MRI (figure 2), suggesting that contrast-enhanced echocardiography is superior to ECG-gated MRI for detection of this lesion.

Even if the detectability of ASDs with MRI and echocardiography were similar, MRI would have to
offer considerable advantage in ease of diagnosis or cost to become the noninvasive diagnostic examination of choice, and it does not. MRI, although widely considered to be as safe as echocardiography, is more complex and expensive to perform and might routinely require deeper sedation in the case of young patients.

We conclude that ECG-gated MRI is capable of detecting VSDs with sensitivity and specificity similar to two-dimensional echocardiography but that MRI probably is inferior to two-dimensional contrast echocardiography in the detection of ASDs. Electrocardiographically synchronized magnetic resonance images may be easier for those who are not imaging specialists to interpret than echocardiograms, an advantage for surgeons in preoperative evaluation. However, the lower cost and convenience of echocardiography and its probable superiority in the detection of ASDs make it superior to MRI for the detection of cardiac septal defects.

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References


18. Grenadier E, Alpan G, Keider S, Palant A: M-mode and two dimensional contrast echocardiography in adult patients with septal defects.


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D G Lowell, D A Turner, S M Smith, G H Bucheleres, B A Santucci, R J Gresick, Jr and D O Monson

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