Evaluation of Congenital Heart Disease by Three-dimensional Magnetic Resonance Imaging

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This study was undertaken to compare electrocardiographically gated magnetic resonance imaging (MRI) to established imaging modalities in the detection of complex intra- and extracardiac morphologic defects. Twenty-three patients with congenital cardiac abnormalities were imaged by four methods: cardiac catheterization, echocardiography, two-dimensional (2D) transaxial MRI, and three-dimensional (3D) MRI surface reconstruction. Observers with experience in congenital cardiac disease diagnosis (two for echo, one for catheterization, two for 2D MR, and three for 3D MR) evaluated the images in a blinded fashion, and the results were analyzed with receiver operating characteristic (ROC) analysis. Overall, cardiac catheterization had the best diagnostic performance. The diagnostic value of routine 2D cardiac MR images and 3D MR reconstruction images were similar to that of echocardiography. All of the modalities performed poorly in the diagnosis of extracardiac defects and atrial septal defects.

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STANDARD CONGENITAL cardiovascular diagnostic imaging modalities such as plain film radiography, echocardiography, angiography, scintigraphy, and computed tomography have been supplemented by the recent development of electrocardiogram [ECG]-triggered magnetic resonance imaging (MRI).¹ MRI is very effective at delimiting the natural boundary that exist between flowing blood and cardiovascular structures²⁻¹⁰ because flowing blood fails to produce an MR signal. As a result, high resolution two-dimensional (2D) images of cardiac and vascular structures may be obtained noninvasively, without exposure to ionizing radiation and without the need for intravascular contrast.

These imaging techniques have been used successfully to diagnose a wide variety of congenital cardiovascular disorders and morphologic malformations, and to assess cardiac function. However, the planar format of the standard modalities is not ideal for fully comprehending the underlying three-dimensional (3D) cardiac

morphology. This is particularly true in patients with complex congenital cardiovascular malformations, in which surgical planning is based on the successful transfer of information from the radiologist to the surgeon and on the surgeon's ability to mentally reconstruct a single complex anatomy from multiple 2D images.

Specialized computer software methods, originally developed for the preoperative evaluation of complex craniofacial deformities^{11,12} have been adapted to allow display of 3D surface reconstruction images of the heart from 2D MR scan data.¹³⁻¹⁷ 3D MR images have demonstrated their potential usefulness in transferring information from the radiologist to the surgeon.¹⁸⁻²⁰ The objective of this study was to examine the diagnostic value of 3D MRI by comparing it with 2D MRI, echocardiography, and angiography.

MATERIALS AND METHODS

Sample

Twenty-three patients with congenital heart disease were included in this analysis (Table 1). Twenty-two underwent cardiac catheterization, 21 had echocardiograms, 22 had MR scans, and 12 underwent surgery soon after imaging. The patients varied in age from 2 days to 22 years, with 6 patients below the age of 1 year, 14 between 1 and 6 years of age, 2 between 7 and 12 years, and 2 older than 12 years. One 4-year-old individual had a full set of images both before and after surgery and was used twice, so the total sample is 24 hearts from 23 patients.

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Table 1. Cardiac Characteristics of the Sample

Anatomical Region	Diagnosis		Total
	Normal	Abnormal	
Heart			
Atrium			
Left	19	5	24
Right	17	6	23*
Ventricle			
Left	18	6	24
Right	3	20	23*
Atrial septal defect	10	14	24
Ventricular septal defect	10	13	23
Ventricular outflow tract			
Left	18	5	23*
Right	4	20	24
Aorta and Pulmonary Arteries			
Ascending aorta	10	14	24
Aortic root	7	17	24
Main pulmonary artery	11	13	24
Left pulmonary artery	14	10	24
Right pulmonary artery	17	7	24

*Four patients whose combined information did not permit truth determination for just one anatomical region were included in the study.

Cardiac Catheterization

Procedures were performed on a Siemens biplane Angioskop with Koordinat angiographic table (Siemens Medical Systems Inc, Iselin, NJ) with all controls assembled in a mobile console. This system was connected to a Hewlett Packard (Andover, MA) 8890B monitoring and end analysis system. A Gigantos Optimatic x-ray generator (Siemens) (fully automatic 12 pulse unit) produced 1000 mA at 100 kv. Cine exposure was obtained with biplane 35MM Arritechno (Munich, Germany) cine cameras at up to 60 frames/sec. Cinerex (Richfield Park, NJ) PFA Agfa-Gevaert film was utilized and processed on a Jamieson (Dallas, TX) Processor (Model 54).

Echocardiography

During our studies we used an Aloka (Tokyo, Japan) 880 real time echocardiography system for a few studies, but did the bulk of our research with an Aloka 860. Transducer selection varied between a 5 mHz and 3.5 mHz transducer, with the bulk of the studies being performed with the 5 mHz transducer. The test were performed trying to concentrate on minimal depth ranges for higher pulse repetition frequencies (PRF). All studies were done with PRF of 6 kHz or 8 kHz. The depth ranges varied from 6 to 12 centimeters of depth depending upon the patient's size. B-mode scanning angle was kept at 90° with colorflow angle at 46°. The focal distance varied between 40 and 75 mm, again depending upon patient size. One hundred twenty-eight scanning lines of data were maintained during straight B-mode imaging but were reduced to 64 lines per frame when in the color-mode. We strove to keep the frame rate at a maximum of 30 frames per second (FPS) but pending upon the PRF and depth the frame rate sometimes dropped to a minimum of 15 FPS.

Contour edge enhancement was not used. All information was displayed on a Sony (Sony Corp, New York, NY) 13-inch trinitron color TV monitor using a NTSC (National Television System Committee) (3.58 MHz) system. All video recording was performed on standard ½ inch VHS 120 tape with a Panasonic (Panasonic Corp, Seacaucus, NJ) 6200VHS recorder.

MRI

Contiguous ECG-triggered 2D MR images were recorded from the apex of the heart to the aortic arch at several equispaced times in the cardiac cycle for each slice.¹⁸ These images were obtained using spin-echo sequences at 3 to 5 equi-spaced echo-delay time values on a 0.5 or 1.5 Telsa Siemens Magnetom MR scanner. 3D reconstruction requires that slices be contiguous and be obtained at the same pulse-repetition interval. The scans were obtained with 5 or 10 mm slice thicknesses and 5 or 10 mm interslice gaps respectively. A second set of slices was then obtained to fill the 100% gap intervals resulting in an interleaved stack of image sections with no interslice gap. The acquisition time for a single cardiac study in a child with congenital heart disease whose heart rate averaged 100 beats per minute was 1 hour total. Twelve to 36 contiguous transaxial MR slice images were obtained through the heart in these patients (Fig 1A).

3D MRI Processing Techniques

A sequence of ECG gated contiguous transaxial MR slices of the thorax obtained at the same point in the cardiac cycle were used for 3D reconstruction processing. This set of 15 images is sufficient to perform a high-resolution 3D surface reconstruction. The same set of MR thoracic transaxial slices at three to seven different times within the cardiac cycle were originally obtained but typically only one set per patient at a single point in the cardiac cycle was analyzed.

Manual segmentation of individual 2D MR images was employed as a preprocessing step before surface reconstruction. This was supplemented with software originally developed for echocardiography and digital subtraction angiography and with specialized software originally developed for processing high-resolution computed tomography scan data (Siemens Evaluscope DR and Somatom DR). The software was adapted to permit rapid isolation of the heart and great vessels in axial cardiac MR scans of the thorax.

Using a set of image editing functions, including selective erasure and region filling, the heart and great vessels were isolated by an anatomically knowledgeable radiologic technologist operator (R. Yoffie).^{13-15,18,21} Each slice was viewed by the operator who selected the appropriate region of interest within each slice. The acceptability of edited MR slice images for 3D surface reconstruction was determined by radiologists (F. Gutierrez and M. Vannier), and the final 3D images were checked for correctness by a cardiac radiologist (F. Gutierrez).

For this study, the views obtained in each case included cranio-caudal, caudo-cranial, frontal, rear, lateral (right and left) and four chamber images in the majority of cases (Fig 1B). The number of 3D views for each case varied from four to eight with six views available for most cases.

Fig 1. (A) This 7-month-old female has a large ventricular septal defect with right ventricular hypertrophy and enlargement of the main pulmonary artery proximally. This is a large atrio-ventricular canal-type ventricular septal defect. In a representative transaxial slice, the right ventricle is hypoplastic with a thickened wall. This cardiac malformation is essentially a single ventricle. **(B)** There is communication between the right and left ventricular outflow tracts in this caudal-cranial view. Drainage of the superior vena cava into the right atrium can be observed. The mitral valve can be seen between the left atrium and the adjacent left ventricular outflow tract and aortic route.

Truth

Truth was established by means of consensus of an experienced cardiac radiologist (F. Gutierrez) and pediatric cardiologist (C. Canter), who had access to images from all modalities and to all clinical records, including surgical reports (Table 1). The individuals who participated in the establishment of truth did not take part in the rating study.

Observers

The MR slice examinations and 3D reconstruction images were reviewed by a radiologist (J. Brown) with specialty training in magnetic resonance imaging as well as a senior resident (S. Mirowitz) in diagnostic radiology, experienced in MR diagnosis of congenital heart disease. In addition, 3D MRI examinations were reviewed by a senior

fellow in cardiothoracic surgery (J. Laschinger), experienced in MR imaging of congenital heart disease. The echocardiographic examinations were reviewed from video tape by an experienced pediatric cardiology fellow (B. Raisher) and the Technologist Director of the Pediatric Echocardiography Laboratory (D. Sekarski). Cardiac catheterization examinations were read by a cardiac radiologist (R. McKnight).

Patient names, ages, examination dates, and all other individual information was masked on the diagnostic images. All studies were identified with a three-digit number only. Each observer rated 28 cardiac abnormalities on a 5-point scale ranging from 1 (definitely or almost definitely abnormal) to 5 (definitely or almost definitely normal).²² Images were rated only once by each observer.

Analysis

Data were pooled from all observers; that is, each rating by each observer was treated as if it were a separate observation.¹⁸ This was done because of the small sample sizes for most defects and the degenerate nature of the ratings of some defects. Receiver operating characteristics (ROC) curves were produced and areas under the curves (A_z , calculated with the ROCFIT program.^{22,23}

As a supplement to the ROC analysis, areas under the curves for the modalities were ranked from 1 to 4 for each defect, with 1 being the A_z with the largest area and 4 being the A_z with the smallest area. The rankings for all defects were then combined as a summary measure of performance across all regions.

RESULTS

The results of 13 ratings were selected as being representative of the 28 defects (see Tables 2 and 3). Diagnostic performance was generally poor for all modalities. For 4 of 13 regions the greatest A_z was less than 0.70, and for 11 of 13 it was less than 0.80. Considering that 0.50 would be expected by chance, a large portion of the results indicate only a limited improvement over random diagnosis. The overall pattern is that all of the imaging techniques have high value in the diagnosis of ventricular septal defects but have limited value with regard to diagnoses of defects of the atrial septum, outflow tracts, and extracardiac structures.

It was impossible to fit ROC curves in 12 of 13 cases for cardiac catheterization, due to degenerate data. The degeneracy resulted from a high level of confidence on the part of the single observer. Most of the responses were definite, which caused the curves to be vertical or horizontal at some FPF. In effect, observer confidence transformed a rating experiment into a two-alternative-forced-response experiment. How-

Table 2. Areas Under the Fitted ROC Curve Heart

	Atrium	Ventricle
Left		
Cath	*	*
Echo	0.6431	0.6938
MR slice	0.6807	0.7044
3D MR	0.7696	0.6735
Right		
Cath	*	*
Echo	0.6496	*
MR slice	0.8123	*
3D MR	0.7809	0.6497
Septal defect		
Cath	*	*
Echo	0.7167	0.8488
MR slice	0.5344	0.7848
3D MR	0.6595	0.8643
Left outflow tract		
Cath		0.7057
Echo		0.7699
MR slice		0.6411
3D MR		0.5518
Right outflow tract		
Cath		*
Echo		0.6647
MR slice		0.5388
3D MR		0.5720

*Degenerate data.

ever, cardiac catheterization consistently provided the greatest proportion of correct answers.

DISCUSSION

The two most evident patterns in our study are, first, the generally low values of A_z for all modalities for most of the diagnostic problems, and second, the relative equivalence of all modalities except cardiac catheterization. To summarize the results in a simple fashion, modalities were ranked by their value for A_z for each diagnostic test, and a frequency distribution calculated for the rankings (Fig 2). Cardiac catheterization is not included because the results were usually degenerate. Where it is left out the ranks began at 2. For the 13 diagnostic tests selected, Echo, 3D MR, and MR slice were about equal in diagnostic value.

LIMITATIONS

This study has several limitations. First, it is a nonrandomized retrospective study, and second, the patients were not examined under strict uniform protocols. For example, the slice thickness and number of reconstructed 3D views varied from case to case. The examinations

were performed in a nonrandom order, and the sample size is small with a significant overrepresentation of abnormalities. The patients who were included were generally much younger and had more complex lesions evaluated than series examined with MR reported elsewhere.^{10,24} The quality of the examinations is nonuniform and reflects the experience gained with the modalities over the term of the study.

The physicians responsible for truth reported that, subjectively, cardiac catheterization was the most heavily weighted factor used for establishing truth. The apparent superiority of cardiac catheterization to other modalities may, therefore, simply indicate that there was a high degree of agreement between the observer who interpreted cardiac cath studies blindly and those who used cardiac cath to establish truth.

Surgical reports were used to partially control for this problem; yet in many instances, no information was available concerning possible cardiac defects beyond those for which the operation was performed (for instance, if the operation was performed to correct a ventricular septal defect, little if any information was collected at the time of surgery on extracardiac

Table 3. Areas Under the Fitted ROC Curve Aorta and Pulmonary Arteries

Ascending aorta	
Cath	*
Echo	0.6820
MR slice	0.5322
3D MR	0.5452
Aortic root	
Cath	*
Echo	0.7615
MR slice	0.6083
3D MR	0.5361
Main pulmonary artery	
Cath	*
Echo	0.4018
MR slice	0.7524
3D MR	0.6030
Left pulmonary artery	
Cath	*
Echo	0.5584
MR slice	0.6879
3D MR	0.6004
Right pulmonary artery	
Cath	*
Echo	0.4184
MR slice	0.5839
3D MR	0.5802

*Degenerate data.

Fig 2. The values of the areas under the fitted ROC curves (A_i) were ranked for echocardiography, 2D transaxial MR, and 3D MR surface reconstruction, and a frequency distribution calculated for the rankings. Cardiac catheterization was not included because A_i could not be calculated in most cases, but where it is left out the other rankings begin at 2.

defects.) A possible solution to this problem would be to base truth on cardiac prosection of fatalities. No such cases were available for our study.

CONCLUSION

With regard to the ability of conventional diagnostic imaging methods to diagnose atrial septal defects, all modalities performed poorly and were approximately equal in diagnostic

value. For diagnosis of ventricular septal defects, all modalities provided satisfactory results, with cardiac catheterization being of the highest diagnostic value.

The most important conclusion that can be drawn from this study is that the use of images in the diagnosis of congenital heart deformities is a complex exercise. Unlike many radiographic skeletal diagnoses such as fractures,²⁵ where the image is the deciding factor, the diagnosis of cardiac abnormalities is strongly influenced by information in addition to that provided by the images. The exclusion of information about medical history is artificial in any study, but it may be most artificial in studies of the heart.

An additional complexity is the nature of the problem. A congenitally deformed heart is not a normal organ that has been damaged, as is, for instance, a broken bone. It is an organ that is abnormal and behaves as such. Because the functional abnormality lies in the pattern of blood flow, images of flow are likely to give the best diagnosis. Though cardiac morphology is the source of the dysfunction, it is not in itself the problem, and images of morphology are unlikely to ever be as diagnostically useful as images of flow.

3D MRI is good at imaging morphology, and comparable in its diagnostic utility to other techniques that do this. Considering the noninvasiveness of MRI, and the ability of 3D MRI to clearly illustrate complex cardiac anatomy, 3D MRI may in many instances be a viable supplement or alternative to traditional cardiac imaging methods. Certainly, further study of its capabilities is warranted.

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