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Transthoracic Three-Dimensional Echocardiography in Adult Patients With Congenital Heart Disease

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Objectives. **This study sought to assess both the feasibility and potential role of transthoracic three-dimensional echocardiography for the evaluation of adult patients with congenital heart disease.**

Background. **The unrestricted views with depth perception provided by three-dimensional echocardiography with dynamic volume-rendered display may enhance visualization of cardiac structures and detection of abnormalities in patients with congenital heart defects.**

Methods. **We studied 33 patients with various heart defects (mitral valve anomalies in 9, aortic valve anomalies in 5, subaortic membrane in 5, ventricular septal defect in 4, transposition of the great arteries in 3, tetralogy of Fallot in 2, other defects in 5). Cross-sectional images of the specific region of interest were acquired from either the parasternal or apical window with the rotational technique (2° interval with electrocardiographic and respiratory gating) and postprocessed for resampling in cubic format. From these three-dimensional data sets a multitude of cut planes were selected, presented in volume-rendered dynamic display and analyzed by two observers for comparison with standard two-dimensional images to assess their additional information.**

Results. **Three-dimensional reconstruction was possible in all patients. Structures of interest were evaluated from unusual viewpoints, providing both cardiologists and surgeons with immediate feedback. When compared with standard two-dimensional images, additional information was provided for 12 patients (36%). The mitral valve, aortoseptal continuity and interatrial septum were the structures for which three-dimensional echocardiography was most useful.**

Conclusions. **Transthoracic three-dimensional echocardiography is feasible and facilitates spatial recognition of the intracardiac anatomy in a significant proportion of patients and enhances diagnostic confidence of complex congenital heart disease.**

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Two-dimensional echocardiography facilitates recognition of congenital cardiac abnormalities but requires a systematic examination to identify complex anatomy and pathologic features from tomographic images (1). Thus, cardiologists must mentally integrate sequentially obtained two-dimensional images to build up a three-dimensional objective image, which is difficult in the presence of complex congenital defects. The ultimate goal of noninvasive cardiac imaging in congenital heart diseases should provide a comprehensive objective rendering of cardiac abnormalities with dynamic display.

Over the past few years, there have been considerable efforts to produce three-dimensional reconstruction of cardiac ultrasound images, and numerous techniques have been applied (2,3). However, these efforts have been hampered by limited precordial acoustic windows (4), inadequate display (5) and amount of time requested for reconstruction (6). From our preliminary experience with precordial three-dimensional echocardiography in an unselected cohort (7), we judged that rotational acquisition with dynamic volume rendered display is feasible and potentially has additional diagnostic value in specific areas of congenital heart disease.

In this prospective study, we performed transthoracic three-dimensional reconstruction in 33 patients with congenital heart defects. The results were compared with the standard two-dimensional studies to evaluate the potential benefit and limitations of transthoracic three-dimensional reconstruction.

Methods

Study patients. We studied a group of 33 patients (mean [±SD] age 27 ± 8 years) with a variety of congenital cardiac disorders during clinically designated conventional transthoracic study. Patients were consecutively selected from those referred to the Adolescent-Adult Congenital Heart Disease Outpatient Clinic at our institution. Good-quality images on two-dimensional echocardiography (either parasternal or apical views) was the prerequisite for admission to the study. Demographic data, cardiac malformations, region of interest, precordial acquisition window and the additional information obtained from three-dimensional reconstruction are reported in Table 1.

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Table 1. Clinical Data and Three-Dimensional Echocardiographic Findings in Patients With Congenital Heart Defects

Pt No.	Gender/Age (yr)	Cardiac Malformation	Three-Dimensional Acquisition		Three-Dimensional Reconstruction (additional information)
			ROI	Window	
1	M/28	Mitral prolapse	MV	PS	Precise site of prolapse
2	F/20	Mitral stenosis	MV	PS	View of MV from above and below
3	M/57	Mitral prolapse	MV	PS	Precise site of prolapse
4	F/28	Mitral stenosis	MV	AP	View of MV from above and below
5	F/23	Mitral prolapse	MV	AP	Precise site of prolapse
6	F/20	Cleft MV	MV	PS	
7	F/28	Parachute MV	MV	PS	
8	M/32	Double-orifice MV	MV	PS	
9	M/16	Cleft MV (ASD I postop)	MV	PS	
10	M/20	Aortic stenosis	AOV	PS	
11	M/26	Aortic stenosis	AOV	PS	
12	M/25	Bicuspid AOV	AOV	PS	
13	F/25	Aortic stenosis	AOV	AP	
14	F/30	Aortic regurgitation	AOV	AP	
15	M/26	Subaortic membrane (postop)	LVOT	AP	
16	M/39	Subaortic membrane (postop)	LVOT	AP	
17	M/30	Subaortic membrane	LVOT	AP	
18	M/21	Subaortic membrane	LVOT	AP	Precise site and shape of obstruction
19	M/36	Subaortic membrane	LVOT	AP	
20	M/28	VSD	IVS	PS	
21	F/31	VSD	IVS	PS	
22	F/27	VSD (postop)	IVS	PS	Precise site of patch dehiscence
23	M/32	VSD, ASD	IVS, IAS	AP	Evaluation of VSD from different viewpoints; view of ASD from left side
24	M/25	Anatomically corrected TGA	MV	AP	Details of left AV valve
25	M/19	TGA, VSD (postop)	IVS	PS	
26	F/18	TGA (postop)	MV	PS	
27	M/22	Tetralogy of Fallot	IVS	PS	View of VSD from left and right
28	M/22	Tetralogy of Fallot (postop)	IVS	PS	
29	F/19	Atrial septal aneurysm	IAS	PS	Extension of aneurysm
30	M/40	Pulmonary stenosis insufficiency	PV	PS	
31	M/19	DORV (postop)	RV-PA conduit	PS	
32	M/25	Tricuspid atresia (postop)	RA-PA conduit	AP	
33	M/34	Ventricular inversion, TGA, tricuspid atresia (postop)	TV	AP	Visualization of imperforated TV; assessment of ventricular inversion and malposition of great arteries

AOV = aortic valve; AP = apical; ASD = atrial septal defect; AV = atrioventricular; DORV = double-outlet right ventricle; F = female; IAS = interatrial septum; IVS = interventricular septum; LVOT = left ventricular outflow tract; M = male; MV = mitral valve; PA = pulmonary artery; postop = postoperative study; PS = parasternal; PV = pulmonary valve; Pt = patient; RA = right atrium; ROI = region of interest; RV = right ventricle; VSD = ventricular septal defect; TGA = transposition of the great arteries; TV = tricuspid valve; Window = echocardiographic window.

Clinical examination procedure. Two-dimensional echocardiographic studies were performed by an experienced sonographer (J.M.G.) while the patient was lying comfortably in the 45° left recumbent position. After diagnostic study for the clinical evaluation, the probe was positioned either at the left parasternal or apical window for acquisition of cross-sectional images for three-dimensional reconstruction. Patient movement during image acquisition were prevented by a thorough explanation of the procedure before the study. Informed consent was obtained from all patients.

Three-dimensional echocardiographic studies. The transducer used for the standard two-dimensional echocardiogram was fixed in a housing with a cogwheel that fits into a cylindric holder. The transducer can be rotated in the holder by means of an externally mounted step-motor controlled by a computer algorithm. After the probe was positioned to find the central axis of the sector images encompassing the region of interest, it was kept stationary during the rotation. Thus, the sampled cardiac cross sections encompass a conically shaped volume with its apex originating in the transducer.

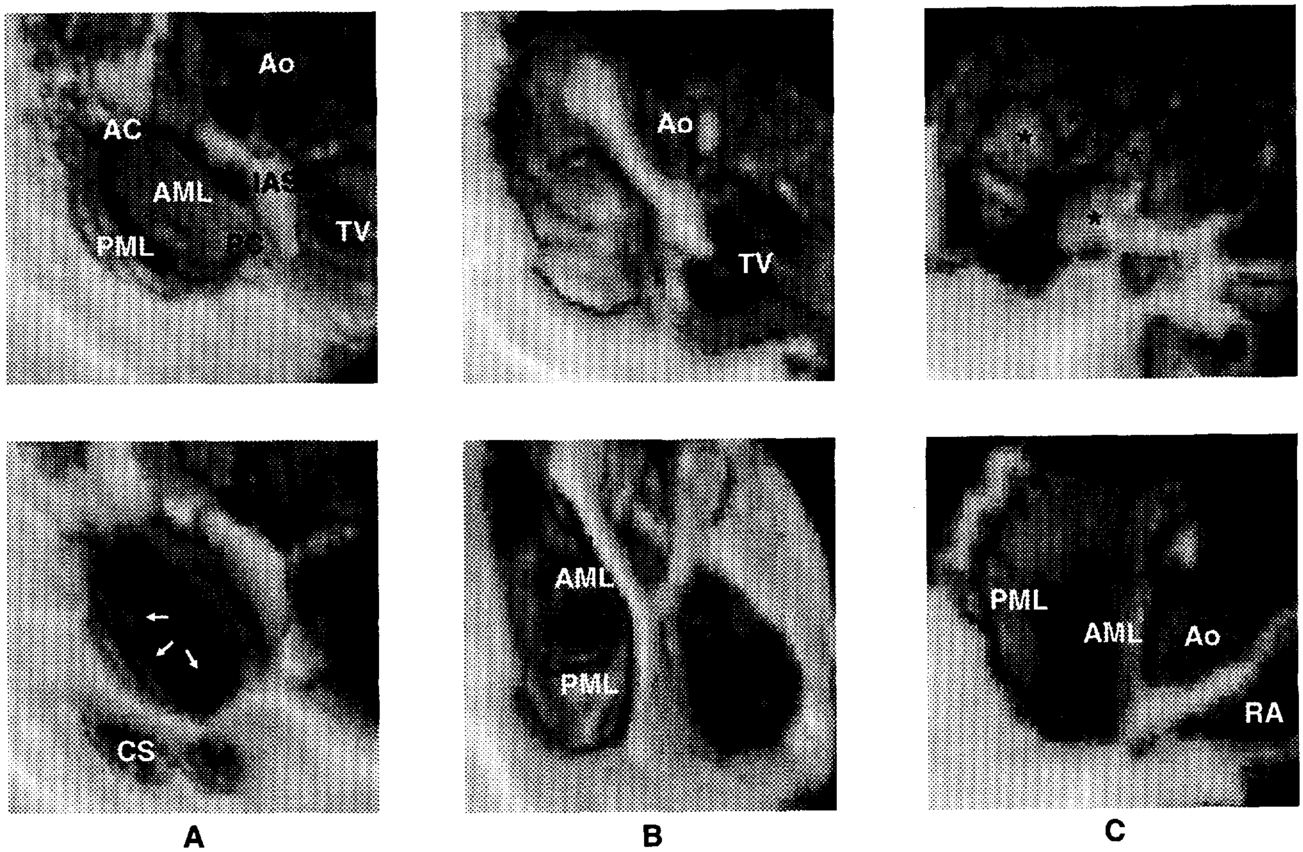

Figure 1. Left atrial views of the mitral valve in a normal subject (**A**), a patient with mitral stenosis (**B**) and a patient with mitral valve prolapse (**C**). The systolic phase is shown in the **top panels** and the diastolic phase in the **bottom panels**. **A,** Cut plane of a view of atrioventricular valves from above, with the mitral valve on the left and the tricuspid valve (TV) on the right separated by the interatrial septum (IAS). The aorta (Ao) lies anteriorly. **Top,** Mitral valve leaflets separated by the posteromedial (PC) and anterolateral commissures (AC), just before closure of the valve. Note the long and narrow posterior leaflet (PML) with a scalloped contour (**arrows**). In diastole, both mitral and tricuspid valves are open. In this phase of the heart cycle, the coronary sinus (CS) moves in the cut plane behind the posterior leaflet. **B,** Diastolic image from a patient with mitral stenosis shows a narrowed mitral orifice, with fusion of the commissures. **C,** Tangential cut plane of the left atrium in a patient with Marfan syndrome reveals the systolic prolapse of all the scallops (**asterisks**) of the mitral valve. The dropouts of the leaflets are due to the tangential intersection of the cut plane with the mitral leaflets. AML = anterior mitral leaflet; RA = right atrium.

Image acquisition. The video output of the echocardiographic system (either a Vingmed CFM750 or a Toshiba Sonolayer SSH-140A) was interfaced to the three-dimensional reconstruction system (Echoscan, TomTec GmbH, Munich, Germany). A number of test runs were always performed to familiarize the patients with the procedure to prevent rotational artifacts in the three-dimensional images and to check the full transducer rotation and the cardiac structures in the conic volume. Image acquisition is controlled by a steering logic that activates the motor and rotates the transducer in steps of 2°. The transducer records a tomographic slice of the heart at each step. Appropriate selection of RR intervals and respiratory phase allows for optimal spatial and temporal registration of the cardiac cross sections. After a cardiac cycle that falls within the preset ranges is selected by the steering logic, the cardiac cross section in a given plane is sampled at 25 frames/s, digitized and stored in the image-processing computer. Then, the step-motor is activated and rotates the transducer to the next cross section where the same steering logic is followed. Cycles that do not fall within the preset ranges are rejected. Finally, 90 sequential cross sections are acquired, each during a complete heart cycle, and fill the conic volume. Calibration and storage of these data in the computer memory require ~3 min.

Image processing. The recorded images were resampled as three-dimensional data sets according to their spatial and temporal location. Conversion from polar to cartesian coordinates allows identification of each point in the x, y and z axes. The gaps between adjacent cross sections in the far field were electronically filled with a trilinear cylindric interpolation. Several algorithms were used to reduce the noise and artifacts that can be created by patient and probe movement.

Image display. Three-dimensional reconstruction was performed by a cardiologist (A.S.) unaware of the two-dimensional echocardiographic findings. From the resampled data sets, any desired cross section can be computed and

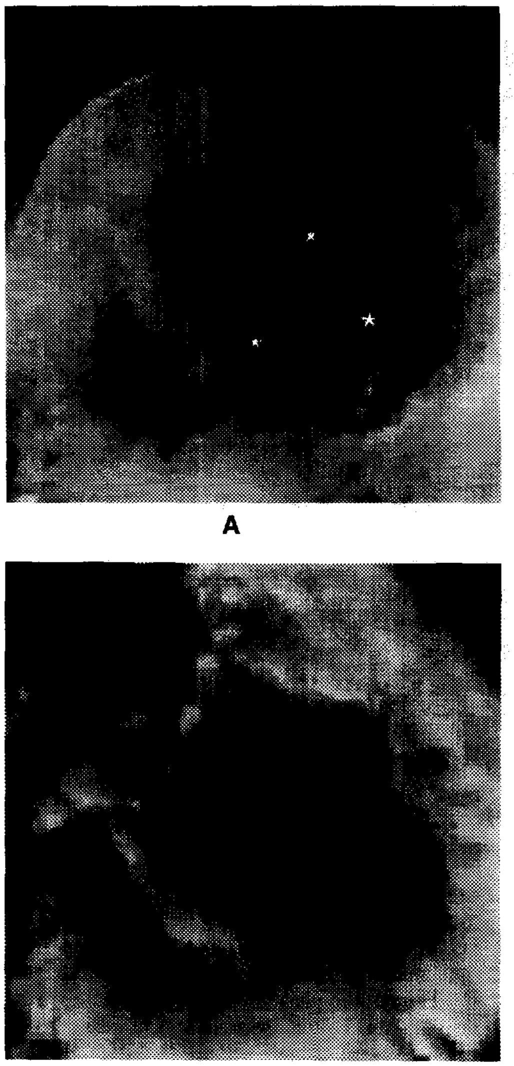

Figure 2. Patient with discordant atrioventricular (AV) connections in diastole (**A**) and systole (**B**). A cut plane at the ventricular level with a view of the AV valves shows that the left-sided AV valve has the structure of a normal tricuspid valve. **Asterisks** indicate the three-leaflet structure of the left-sided valve. IVS = interventricular septum.

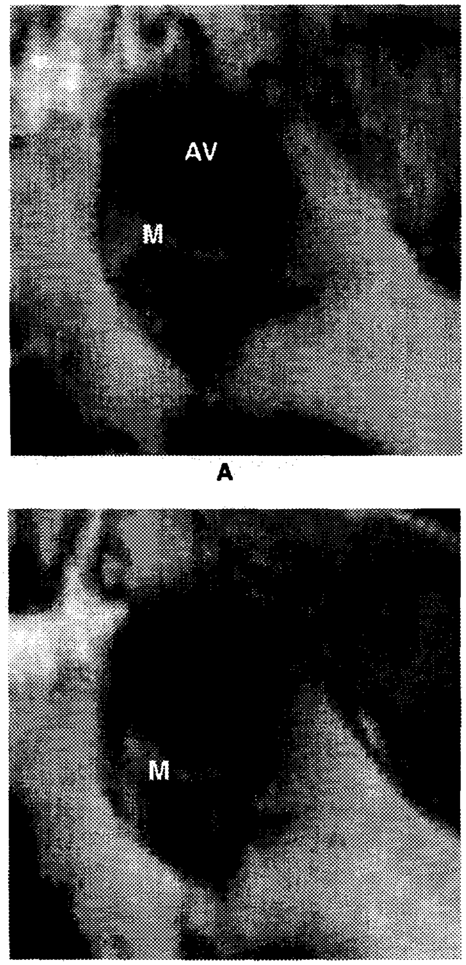

Figure 3. View from the left ventricular outflow tract toward the aortic valve (AV) revealing the presence of a subaortic membrane (M). In diastole (**A**) the aortic valve is shown in the closed position, whereas in systole (**B**) the aortic cusps are open. The borders and extent of the membrane as well as the relation with the left ventricular outflow tract can be appreciated.

displayed in a dynamic two-dimensional format, which allows unlimited cut planes not dependent on the ultrasound window (echocardiography in any plane). Once an appropriate cut plane is computed, a gray level range is selected to separate cardiac structures from the blood pool and background. Three-dimensional rendering techniques, well known from magnetic resonance imaging and computed tomography, are used to create a three-dimensional display (8). These techniques allow the display of tissue gray level information from the whole volumetric data set. Different algorithms (distance, gradient and texture shading) can be mixed to produce a volume-rendered display, either in static (frame by frame) or dynamic cine loop format. In particular, with the distance-shading algorithm, the distance from the observer to the surface of the object is converted into a gray value. With the gradient-shading algorithm, the light emitted from a light source assumed to be mounted on the observer's head is reflected at the surface of the object. With the texture-shading algorithm, a representative gray level of the object, taken at the object's surface, is displayed. Thus, all structures farther away from the selected cut plane can be appreciated with some shadowing as viewed at a distance. The perception of depth can be further enhanced by rotating the cut plane on the output screen.

Image analysis. The three-dimensional reconstructions were analyzed and interpreted off-line by two observers (A.S., J.M.G.) and the findings correlated with those of previously evaluated standard two-dimensional studies. For two-dimensional echocardiography, basic imaging planes obtained from ultrasound windows during standard echocardiography were evaluated. "Any-plane" computer-selected cross sections were generated, guided by the orientation on the three-dimensional volumetric data set. Three-dimensional volume rendering was applied to images from different cut planes, according to previously proposed guidelines (3).

Results

Different regions of interest were selected according to the specific congenital defect, and viewed either from the parasternal (n = 20) or apical (n = 13) window. Three-dimensional acquisition could be performed successfully in all patients without clinical difficulties. The examination, including the calibration procedures, selection of the optimal conic volume with a few test runs and the actual image acquisition, required ~8 to 10 min in addition to the time needed for standard two-dimensional echocardiography. Three-dimensional reconstruction of the images was possible in all patients and allowed display of standard and selected cut planes. The time required for postprocessing the raw data and reconstruction of the images varied from 30 to 120 min.

Mitral valve. Image acquisition of the mitral valve was performed in 11 patients. Anatomic information from the mitral valve apparatus was obtained with volume-rendered display after selection of long- and short-axis cut planes. In particular, the unroofed cut plane of the left atrium and visualization of the mitral valve from above allowed comprehensive assessment of leaflet motion, area orifice and shape and commissure morphology. In patients with mitral stenosis, leaflet involvement and orifice narrowing could be evaluated from the atrial side. Both the site and extent of mitral valve prolapse were demonstrated by volume-rendered display in all patients with this abnormality. Examples of the abnormal findings and comparison with normal findings are shown in Figure 1. In one patient with anatomically corrected transposition of the great vessels (Patient 24), excellent details of the left atrioventricular (AV) valve were obtained (Fig. 2).

Left ventricular outflow tract. Different cut planes of the left ventricle allowed visualization of the outflow tract from below, with adequate evaluation of this area. Five patients were studied, two (Patients 15 and 16) of whom were evaluated after operation for discrete subaortic fibromuscular obstruction, and in both patients good postoperative results were confirmed. In two (Patients 17 and 18) of the other three patients, after careful selection of the optimal cut plane and adequate orientation, the complete extent of the subaortic membrane was seen crossing the outflow tract. Both the site and shape of the discrete fibromuscular obstruction could be clearly evaluated (Fig. 3).

Aortic valve. Five patients were studied for evaluation of congenital aortic valve disease. Volume-rendered display from long-axis cut planes resulted in no additional information over that provided by two-dimensional echocardiography, whereas visualization of the aortic cusps from above or below was possible in two patients (Patients 11 and 13). In the other patients (Patients 10, 12 and 14), assessment of the cusps was inadequate, even after a different selection of the threshold for volume-rendered display.

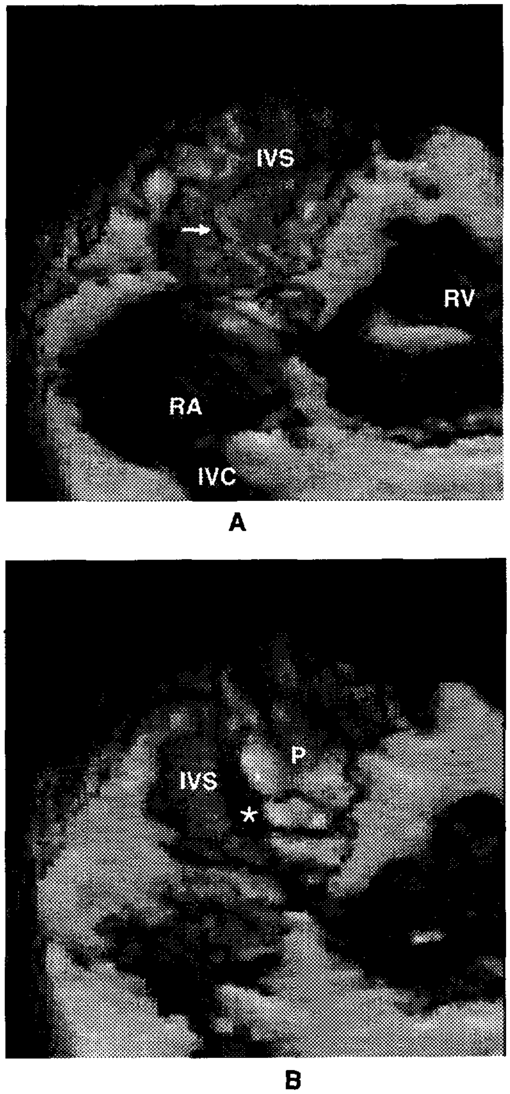

Figure 4. Tangential cut plane through the right heart with a view of the right side of the interventricular septum (IVS) in a patient after surgical repair of a large perimembranous ventricular septal defect. In diastole **(A)**, the border between the patch and the interventricular septum is indicated by the **arrow**. In systole **(B)**, the patch (P) moves toward the observer, revealing a large dehiscence (**asterisk**). IVC = inferior vena cava; RA = right atrium; RV = right ventricle.

Septa. Eight patients were studied, and reconstructions of the interventricular septum were obtained in seven, with combined visualization from the left and right sides.

Three patients had undergone cardiac surgery, and in one of them (Patient 22) patch dehiscence was better demonstrated and spatially defined with tangential cut planes and a viewpoint from the right ventricle, which allowed clear recognition of the margins of the patch moving into the right ventricle during heart cycle (Fig. 4). This finding was later confirmed at surgical intervention.

Four patients with ventricular septal defects of different sizes were evaluated. The relation between the ventricular septum and aortic valve could be assessed with confidence by

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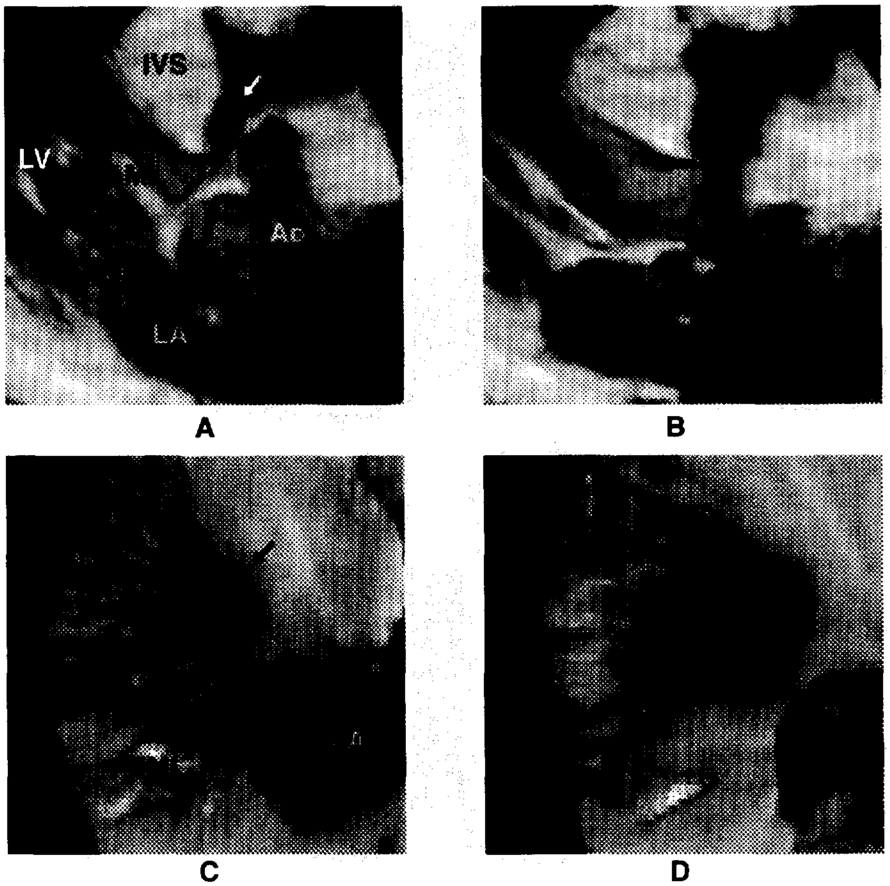

Figure 5. Three-dimensional reconstruction from a patient with tetralogy of Fallot. Long-axis cut plane depicting diastole (**A**) and systole (**B**). The interventricular septum (IVS) and ventricular septal defect (**arrow**) are seen. The aorta (Ao) is widened, and the left atrium (LA) is small. The override of the aorta and septal deviation are well delineated. Cut plane through the left ventricle (LV) with a view of the interventricular septum during diastole (**C**) and systole (**D**). From this unique cut plane, the septal defect (**arrow**) is shown as viewed en face. AML = anterior mitral leaflet; PML = posterior mitral leaflet.

volume-rendered display in one patient with tetralogy of Fallot (Patient 27) (Fig. 5). In another patient (Patient 23), a large perimembranous defect could be well visualized. After appropriate selection of a different cut plane in the same three-dimensional data set, information on the concomitant atrial septal defect as viewed en face was also obtained (Fig. 6). In the two patients with small ventricular septal defects (Patients 20 and 21), the defects were not visualized by three-dimensional echocardiography.

The evaluation of atrial septum was adequate in the two patients studied (Patients 23 and 29). The extent of the aneurysm and its movement during the heart cycle could be assessed in detail in Patient 29 (Fig. 7), and an atrial septal defect was recognized in Patient 23 (Fig. 5).

Other cardiac structures. Three-dimensional reconstruction allowed assessment of extracardiac conduits in two patients (Patients 31 and 32). The spatial relation among the different cardiac structures in a patient with tricuspid atresia after a Fontan connection is represented in Figure 8. From a longitudinal view, adequate tangential cut planes displayed the complex relation among the different structures.

Figure 9 shows a three-dimensional reconstruction in Patient 33 with tricuspid atresia, ventricular inversion and transposition of the great arteries. A cut plane through the atria with a viewpoint from above clearly demonstrates the imperforated tricuspid valve and the complex abnormal spatial relation among the AV valves and great arteries.

Volume-rendered display after three-dimensional reconstruction was not adequate for images of the pulmonary valve acquired in Patient 30.

Discussion

Feasibility. We demonstrated that transthoracic three-dimensional echocardiography is possible from parasternal and precordial windows. Acquisition of images with the rotational technique can be achieved even in patients with limited precordial acoustic windows, provided that an adequate number of imaging planes can be obtained to fill the conic volume; this approach offers advantages over other acquisition techniques (9). The technique of rotational acquisition is relatively easy to perform but requires a training period because of the increase in size and weight of the probe. Studies can be performed in the routine clinical setting, with minimal delay of the standard procedure. Although we demonstrated the feasibility of three-dimensional reconstruction from precordial image acquisition, it should be emphasized that our study included only patients with images of good technical quality.

Morphologic information. One unique feature of three-dimensional echocardiography is its ability to evaluate structures from unusual viewpoints, thus providing both cardiologists and surgeons with immediate feedback. The final display of these reconstructions has a close resemblance to the actual anatomy of the heart. In the present series, information not

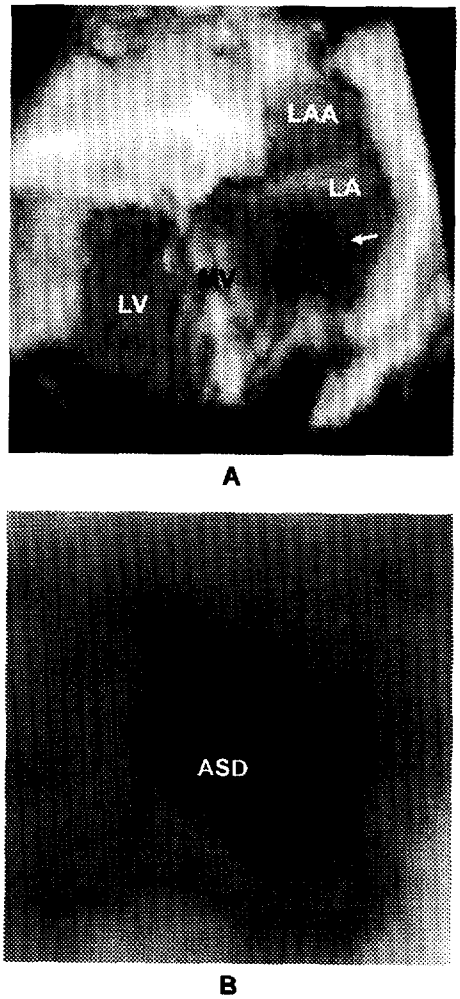

Figure 6. **A**, Cutaway view showing left side of the interatrial septum (Patient 31) and an atrial septal defect (**arrow**). **B**, Detailed image of the defect (ASD). LA = left atrium; LAA = left atrial appendage; LV = left ventricle; MV = mitral valve.

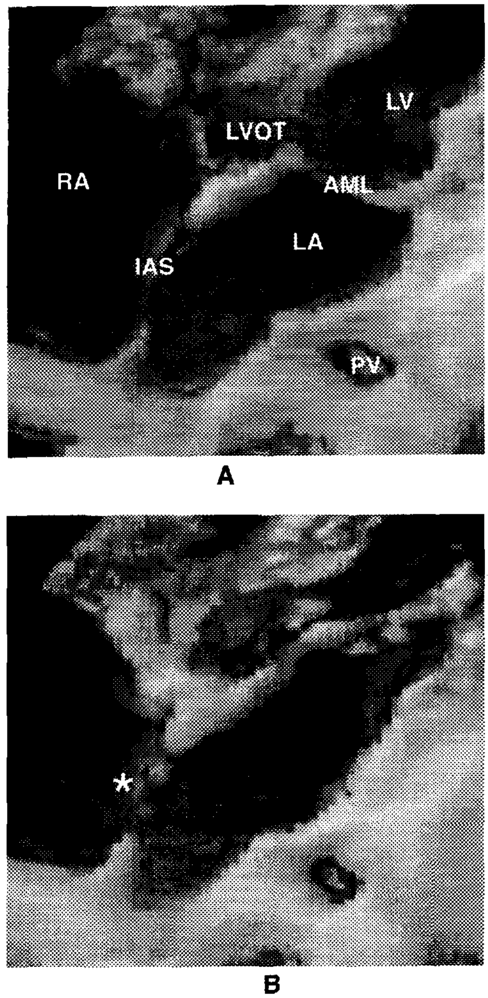

Figure 7. Cut plane through the left (LA) and right atria (RA) with a view from above the interatrial septum (IAS) in a patient with atrial septal aneurysm in systole (**A**) and diastole (**B**). Note the protruding interatrial septum into the right atrium in diastole (**asterisk**). AML = anterior mitral leaflet; LV = left ventricle; LVOT = left ventricular outflow tract; PV = pulmonary vein.

obtained with standard two-dimensional studies was provided for 12 patients (36%) (Table 1). Three-dimensional reconstruction yielded the maximal morphologic information for those cardiac structures that could be interrogated by the scan plane through the entire 180° rotation. The additional data provided were mostly for the mitral valve, aortoseptal continuity and atrial septum. The clarity with which perimembranous ventricular septal defects of adequate size are demonstrated implies that three-dimensional echocardiography may become the diagnostic technique of choice for preoperative evaluation and surgical planning of patients with these congenital heart defects.

Limitations and pitfalls of three-dimensional echocardiography. The sampling rate (25 frames/s) is not as good as that available from two-dimensional echocardiography and is too low to record rapid intracardiac events.

Spatial resolution of three-dimensional data sets deserves some comment. In the conic volume resulting after rotational image acquisition, resolution progressively deteriorates toward the far and lateral fields. Thus, individual points of a tangential cut plane have different resolutions, which may result in distortion of the images.

Optimal gain settings are necessary to avoid degrading definition and increasing amount of nonstructural echoes. Dropouts of parts of thin structures (e.g., aortic valve) may result from attenuation of the echo intensities. Volume-rendered algorithms can only display echoes within a limited range of intensities. As a consequence, anatomic details of these structures may be lost in the display.

Three-dimensional echocardiography failed to provide adequate visualization of small lesions. In our experience, small (trabecular) defects were inconsistently visualized by three-dimensional echocardiography, with some correlation existing between the defect size and defect recognition. This result can be related to the low resolution of this technique or to the fact

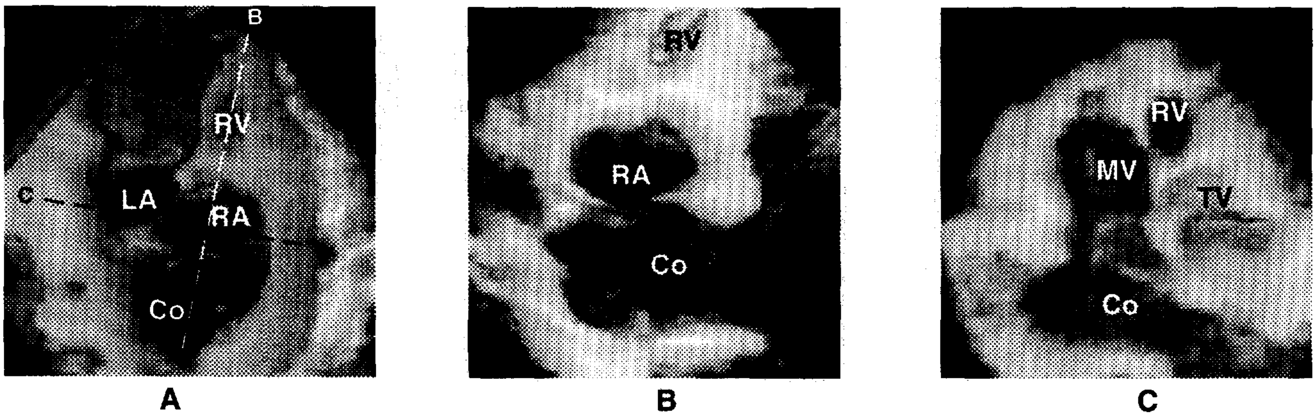

Figure 8. Three-dimensional reconstruction from a patient with tricuspid atresia after a Fontan procedure. **A,** Longitudinal cut plane showing small right ventricular cavity (RV) and dilated left ventricle (LV). Posterior to the right atrium (RA), the cross section of the conduit (Co) is shown. **B** and **C,** Reconstructions derived from the image in **panel A** after the selection of the corresponding cut planes (**dashed lines B and C**). From these reconstructions, long-axis views of the conduit are represented, showing relation to the other cardiac structures. The imperforated tricuspid valve (TV) as seen from above is also recognizable. LA = left atrium; MV = mitral valve.

that small defects burrow through the septum in an oblique and tortuous fashion that hampers the selection of an optimal cut plane.

Clinical implications. Two-dimensional echocardiography provides excellent graphic imaging of the heart and cardiac cross sections with recognizable structures, and most congenital defects can be appreciated with this method. The disadvantage of two-dimensional echocardiography is its lack of complete spatial information, which must be mentally resampled from a multitude of individual tomographic planes of the heart obtained from several chest wall positions. Three-dimensional reconstruction of echocardiographic images has the potential to overcome this problem, and volume-rendered display in particular can lead to the enhancement of anatomic diagnostic capability of echocardiography. What, then, are the

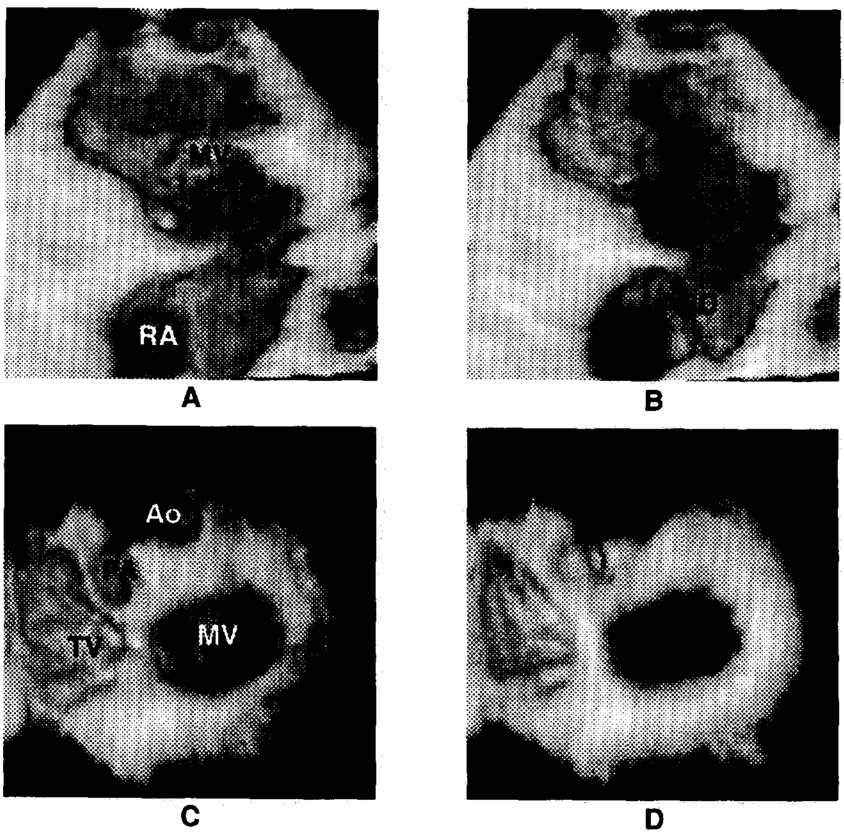

Figure 9. Three-dimensional reconstruction from a patient with transposition of the great arteries and tricuspid atresia. Longitudinal view (**A**) of dilated left ventricle (LV) and large mitral valve (MV). The dilated elongated left atrial cavity (LA) communicates with the right atrium (RA) through a large atrial septal defect (ASD) (**B**). Cut plane at atrial level with a view from above (**C**) reveals imperforated tricuspid valve (TV) in contrast to a mitral valve (MV) that opens normally in diastole (**D**). Note the malposition of the aorta (Ao) and pulmonary artery (PA). The abnormal relation of the atrioventricular valves to the great arteries that lie anteriorly indicates the presence of a ventricular inversion.

benefits of this new technology for patients with congenital heart defects? The results of the present study indicate that three-dimensional echocardiography with dynamic volume-rendered display provides more familiar images of the heart comparable with anatomic specimens, which enhances confidence in the interpretation of the study. Thus, we suggest that the composite approach adopted in the present study provides maximal information and offers considerable advantages over the standard two-dimensional echocardiographic technique alone for studying patients with congenital heart defects.

Clinical experience with three-dimensional echocardiography in congenital heart disease is still limited (4,10–12). Acquisition time is at present short enough to consider three-dimensional imaging part of a standard echocardiographic examination whenever it is judged that it could provide incremental information for clinical decision making. We believe that with further refinements in imaging technology, three-dimensional echocardiography is likely to play a valuable and complementary role in the analysis of puzzling congenital cardiac conditions and will best serve patients by virtue of its comprehensive approach. Finally, the information derived from three-dimensional imaging could aid in the choice and guide in the performance of surgical procedures (13).

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