TECHNOLOGY

Dynamic three-dimensional echocardiography with a computed tomography imaging probe: initial clinical experience with transthoracic application in infants and children with congenital heart defects

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Abstract

***Objective*—To assess the clinical applicability of a prototype computed tomographic echocardiographic imaging probe in paediatric patients with congenital heart disease.**

***Design*—A phased array echocardiographic transducer (64 elements, 5 MHz) mounted on a sliding carriage was used transthoracically in various positions on the chest. The transducer moves from the outflow tract to the apex of the heart in 0·5 to 1·3 mm increments and records a tomographic slice of the heart at each increment level. Parallel images are recorded at a frame rate of 25–30 images/s. At each level a complete cardiac cycle is recorded. The images are digitised and stored in the image processing computer, which reconstructs the anatomical structures of the heart in a three-dimensional format by means of different grey scales.**

***Patients*—45 paediatric patients (age range 3 days to 17 years) with various congenital heart defects who had been admitted to hospital for diagnostic or therapeutic cardiac catheterisation or surgery.**

***Results*—Good quality echocardiographic pictures were obtained in all but two of the 45 patients. Three-dimensional reconstructions of the heart were possible from transthoracic echocardiograms. The recorded cardiac chambers and valves were displayed in three-dimensions in real time (four-dimensionally). The heart was also displayed in real time in any desired plane and in up to five planes simultaneously without having to change the position of the transducer on the chest. Different parts of the heart were displayed in a view similar to that seen by a surgeon during an operation. Image acquisition took 3–5 minutes and three-dimensional reconstruction of various cardiac structures 20–90 minutes.**

***Conclusions*—The computed tomographic imaging probe facilitates acquisition of echocardiographic data as multiple planes can be obtained from one transducer position. Display of three-dimensional structures of the heart may enhance the understanding of cardiac anatomy.**

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Echocardiography is the most commonly used non-invasive imaging technique for diagnosing congenital heart defects in infants and children. It is easy to perform and can be used repeatedly. One of the disadvantages of cross sectional echocardiography is the need to construct a mental three-dimensional picture of the heart from many cross sectional images. This may lead to significant interexaminer variability[1] and more importantly to false or incomplete diagnosis of the anatomy of heart defects.[2] Three-dimensional reconstruction may potentially improve the diagnostic accuracy of an echocardiographic examination. Three-dimensional reconstruction of echocardiographic studies has been attempted since the late 1970s by various methods,[3–7] some of which require the use of transoesophageal echocardiography.[8] We report our initial clinical experience with transthoracic dynamic three-dimensional echocardiography with a computed tomographic imaging probe in infants and children.[9]

Patients and methods

ECHOCARDIOGRAPHIC EQUIPMENT

A prototype echocardiographic machine equipped with a phased array transducer (64 elements, 5 MHz; TomTec, Munich) was used. The transducer is mounted on a sliding carriage, which is 30 cm long. The transducer can be moved in increments of 0·5–1·3 mm along the carriage by a computer controlled stepper motor. This probe had originally been constructed for use as a transoesophageal device,[9] but it was used transthoracically in this study in various positions on the chest according to the patient's size and shape of thorax. Only parts of the carriage have

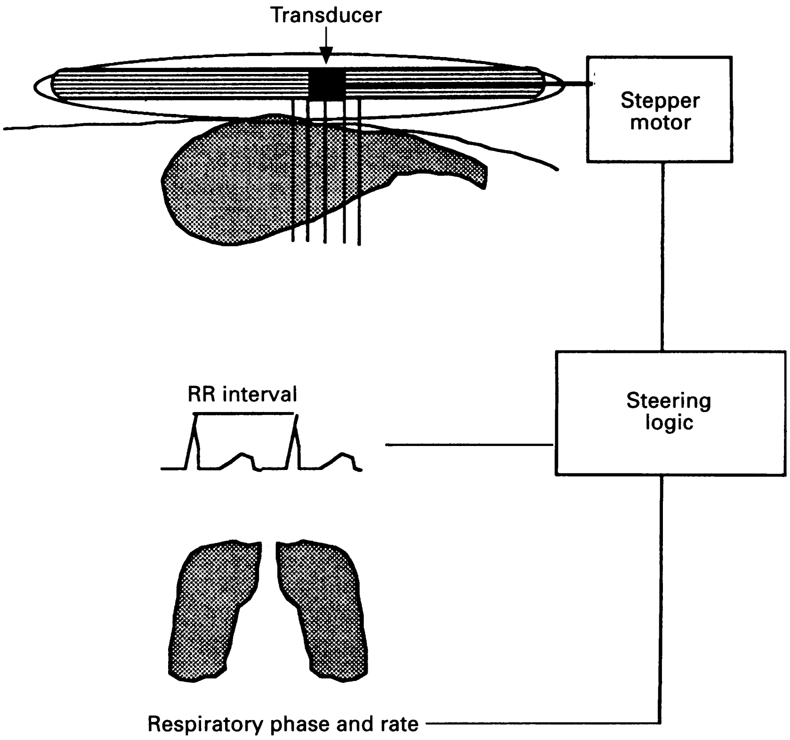


Figure 1 System used to acquire heart and respiratory rate gated parallel tomographic slices of the heart. The transducer mounted on a carriage lies over the heart. Its movement is controlled by the stepper motor, whose steering logic is fed with information on the RR interval and the respiratory rate and phase.

contact with the chest wall because the carriage carrying the transducer is straightened by means of two cables to form a rigid tube before images are acquired. During data aquisition the examiner sees a conventional cross section on the monitor to get information on the transducer's position. The transducer moves from the outflow tract to the apex of the heart in steps of 0·5–1·3 mm and records a tomographic slice of the heart at each step. Electrocardiographic and respiratory gating is achieved by electrocardiographic electrodes. The transducer acquires parallel images of the heart when scanning perpendicular to it. Movement of the transducer on the chest is controlled by a stepper motor. Its steering logic receives input from the electrodes, which record heart and respiratory rate 10 times a second (figure 1). The examiner can set limits for heart and respiratory rate before starting to acquire data; the stepper motor moves the transducer and records tomographic slices only when the patient's heart and respiratory rate are within the limits of the preset RR interval or respiratory rate. At each level a complete cardiac cycle is recorded. The images are digitised and stored in the image processing computer. The recorded images are formatted as three-dimensional datasets by means of electrocardiographic triggering. The image processing computer reconstructs the anatomical structures of the heart three-dimensionally by means of different grey scales. As the three-dimensional image can be displayed in real time four-dimensional echocardiography is possible. In addition, the image processing computer allows the heart to be viewed in many different planes and can reconstruct a three-dimensional image of any view of the heart from any viewpoint.

Cardiac morphology in 45 patients examined by three-dimensional echocardiography

No of patients	*Cardiac morphology*
11	Ventricular septal defect
9	Subaortic stenosis
7	Atrioventricular Septal Defect
4	Atrial septal defect
3	Double outlet right ventricle
3	Transposition of the great arteries
2	Aortic stenosis
2	Ebstein's anomaly of the tricuspid valve
2	Truncus arteriosus
1	Mitral valve replacement
1	Double inlet left ventricle with discordant ventriculoarterial connection

PATIENTS

We examined 45 patients with various congenital heart defects (table). All patients were inpatients at the German Heart Centre in Munich and had been admitted for diagnostic or therapeutic cardiac catheterisation or cardiac surgery. All patients were examined by conventional transthoracic cross sectional echocardiography on the same day.

The patients' ages ranged from 3 days to 17 years. Three were neonates, 14 infants, 10 children aged 2–5 years, 12 children aged 5–10 years, four children aged 10–15 years, and two adolescents. Infants or small children who were restless during the echocardiographic examination were sedated with oral chloral hydrate 60–70 mg/kg.

Results

We acquired good quality echocardiographic pictures in 43 of the 45 patients. One 8 year old boy with valvar aortic stenosis was too restless during data acquisition and one 17 year old girl with Ebstein's anomaly had a poor transthoracic echocardiographic window. Because of the transducer's stiffness we were able to get a complete set of echocardiographic pictures from the subcostal view in only three of the 14 infants examined. The shape of the transducer did not allow for acquiring pictures from the suprasternal notch. In all 43 patients three-dimensional reconstructions of the heart were possible from the results of transthoracic echocardiography. Image acquisition took between 3 and 5 minutes. The recorded cardiac chambers and valves were displayed three-dimensionally in real time (four-dimensionally). Three-dimensional reconstruction of the images of the heart took between 20 and 90 minutes, depending on the complexity of the underlying anatomy. Up to five multiple planes were generated from one echocardiogram, and they were displayed simultaneously. Different echocardiographic imaging planes were generated without changing the position of the transducer on the chest. The various heart defects were displayed in a view that is similar to that seen of a surgeon performing a heart operation. Figure 2 shows the

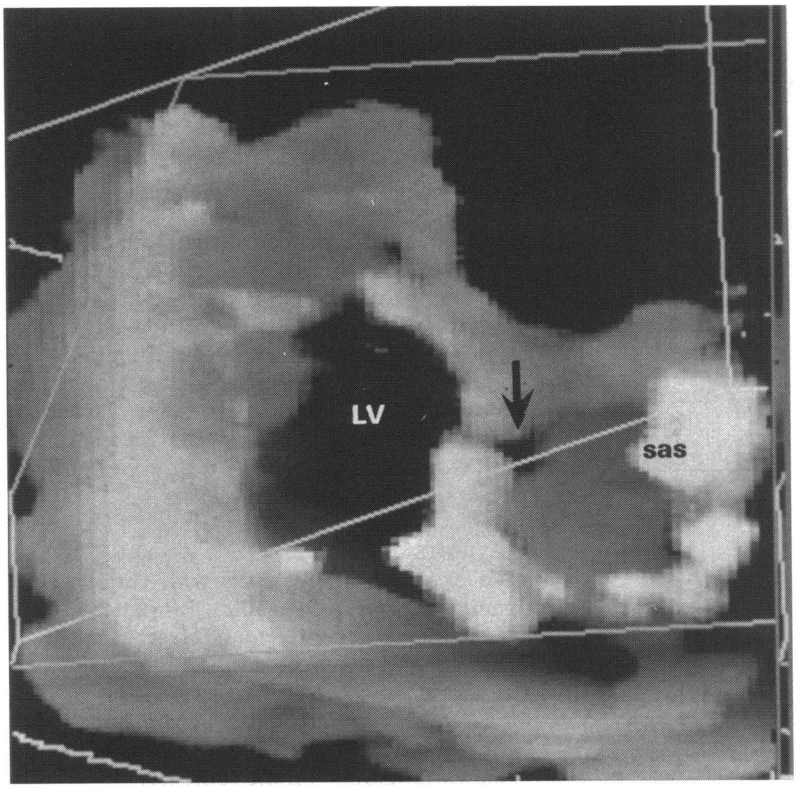


Figure 2 Three-dimensional reconstruction of the left ventricle (LV) in a patient with a hole in the anterior mitral valve leaflet (arrow) caused by resection of subaortic tissue. Some residual subaortic tissue (sas) can still be seen.

three-dimensional reconstruction of a mitral valve in a 5 year old boy with coarctation of the aorta and subaortic stenosis. Three months before this echocardiographic study a subaortic stenosis, which had extended to the anterior mitral leaflet, had been surgically resected. Postoperatively he had significant mitral regurgitation. With three-dimensional echocardiographic reconstruction we diagnosed a hole in the anterior leaflet of the mitral valve, which had been created when the tissue producing the suboartic obstruction had been resected. At the ensuing reoperation the surgeon confirmed the presence and location of the hole in the anterior mitral valve leaflet; it had not been seen prospectively by conventional cross sectional echocardiography.

Figure 3 shows a residual ventricular septal defect in a 6 year old boy with truncus arteriosus type A1 who had undergone corrective surgery at the age of 5 months. A small residual ventricular septal defect can be seen at the lower end of the patch. The lefthand figure shows that the tricuspid valve is open and partially occludes the defect; in the righthand figure, the tricuspid valve is closed and the defect seems to be larger. In these figures the view is similar to that seen by surgeons when they open the right atrium to close a perimembranous ventricular septal defect and look through the tricuspid valve down to the right ventricular apex.

Figure 4 shows the original and three derived parallel cross sectional echocardiographic pictures from a 10 year old boy with valvar aortic stenosis and mild mitral stenosis. During data acquisition the transducer had been in a position similar to a short axis parasternal view. From the raw data we constructed images similar to those acquired in the parasternal long axis position. Also we displayed parallel images which could yield additional information about the mitral valve and the subaortic region.

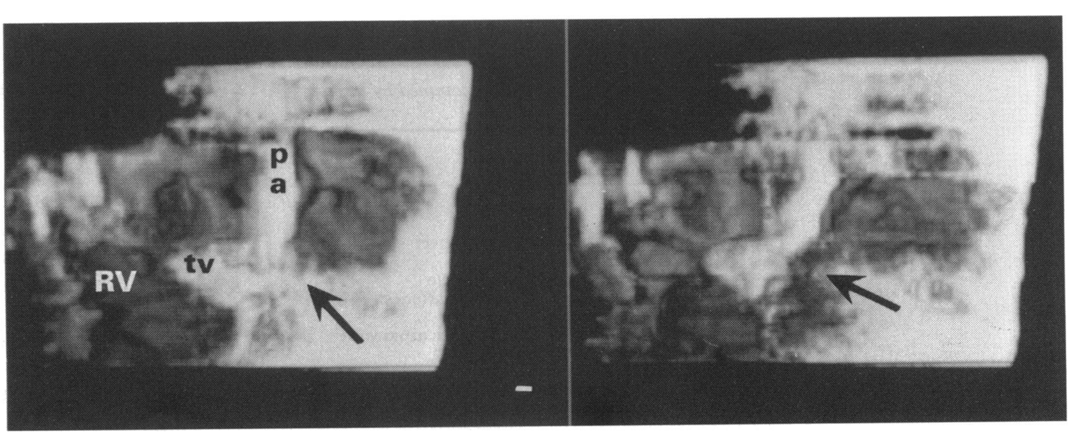
Figure 5 is from a 10 year old boy with a double inlet left ventricle, subaortic outlet chamber, and malposition of the great arteries. His condition had previously been palliated by banding of the pulmonary artery and enlargement of the ventricular septal defect. The results of recent cardiac catheterisation study did not find a pressure gradient across the ventricular septal defect at rest. Three-dimensional reconstruction, however, showed a narrow ventricular septal defect compared with the size of the aortic root with the potential for developing subaortic obstruction (figs 6 and 7).

In two patients the new technique detected defects that had not been picked up by other methods of cardiac imaging or by conventional echocardiography. These defects included the localised hole in the anterior mitral valve shown in figure 2 and a supravalvar membrane in the left atrium in an infant of 6 months who had coarctation of the aorta and a ventricular septal defect. The supravalvar membrane was confirmed at operation.

Discussion

To date several methods have been used to achieve three-deminsional images from

Figure 3 Three-dimensional reconstruction of the crux of the heart. Left: Patch (pa) partially closing a ventricular septal defect. The lower part of the ventricular septal defect is partially closed by tricuspid valve tissue (tv); RV = right ventricle. Right: Ventricular septal defect (arrow) below the patch during systole.



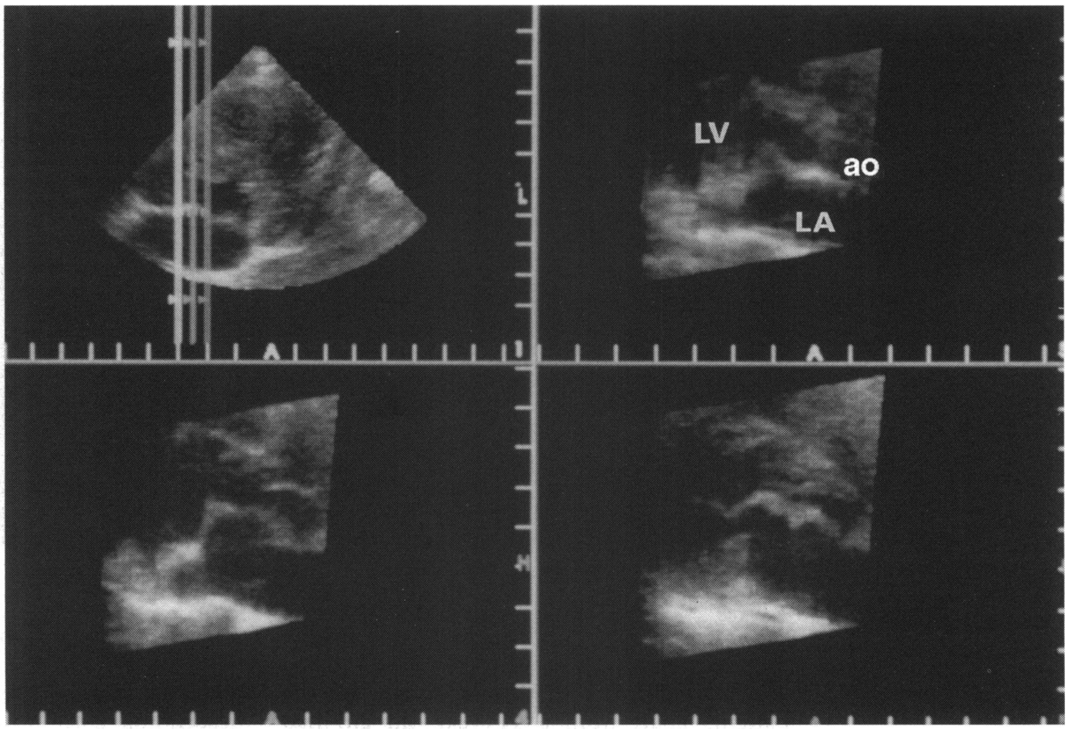


Figure 4 Cross sectional echocardiographic images obtained by slicing in a parallel fashion through the echocardiographically acquired cardiac volume. The upper left hand frame shows the left ventricle and the mitral valve in a view similar to the parasternal short axis view. The three other frames show parallel views 1 mm apart; they are perpendicular to the original view and similar to the long axis parasternal view. LA = left atrium, LV = left ventricle, AO = aorta.

echocardiographic data. One system uses a conventional cross sectional echocardiographic scanner with a spatial locator,[10] which registers transducer and image position and orientation in an external three-dimensional spatial coordinate system. This system can be used transthoracically. Other systems achieve three-dimensional images by moving the imaging plane or performing rotational scanning with multiplane transoesophageal imaging probes.[11 12] These three methods have the advantage of requiring a small acoustic window and the disadvantage of imaging only a small part of the cardiac volume from one scanning position.

We used a fourth method of three-dimensional imaging. Parallel scanning acquires a stack of parallel images by moving the transducer perpendicular to its cross sectional imaging plane; in most cases it records the whole cardiac volume.[13] Previous clinical studies showed that this tomographic approach can achieve good quality three-dimensional reconstruction with transoesophageal echocardiography.[9 13] We used this tomographic method transthoracically. Although the current transducer and carriage system did not permit data acquisition from the subcostal window in most of the infants examined, we were able to obtain three-dimensional

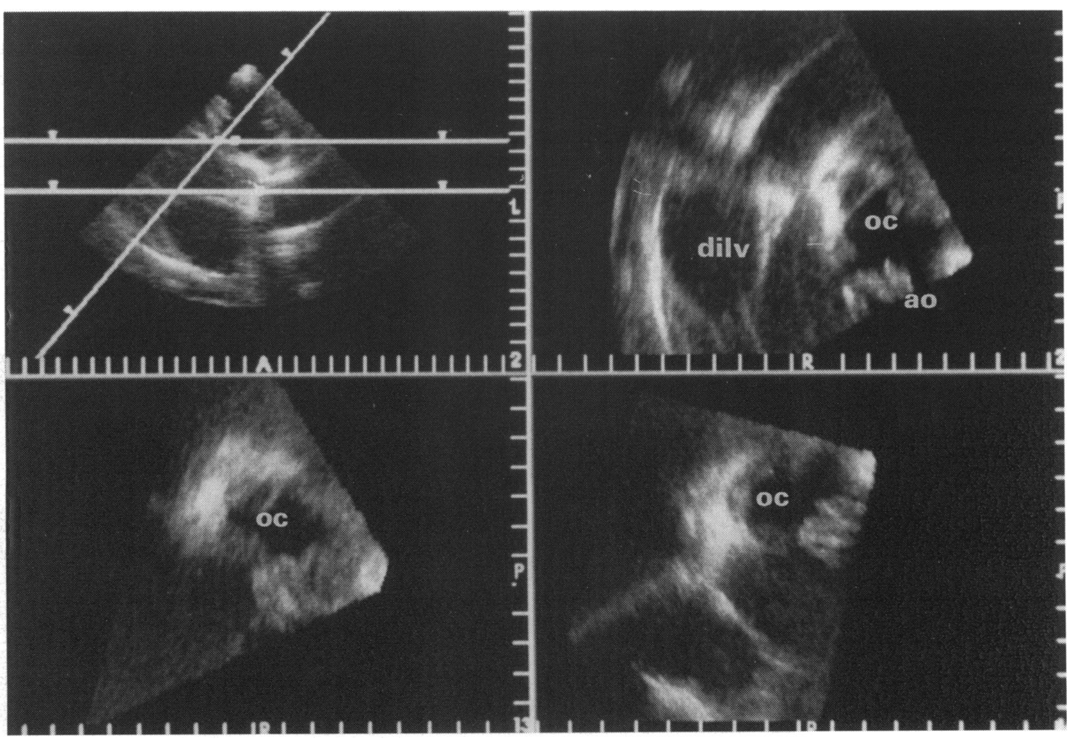


Figure 5 Three frames obtained from a patient with double inlet left ventricle by cutting through the original dataset. The upper left hand frame shows a cross sectional view of the heart that is similar to the long axis parasternal view. The upper right frame was obtained by cutting through the left image at 45°. The two lower frames were obtained by cutting through the original data at 90°, 1 mm apart. dilv = double inlet left ventricle, oc = outlet chamber, ao = aorta.

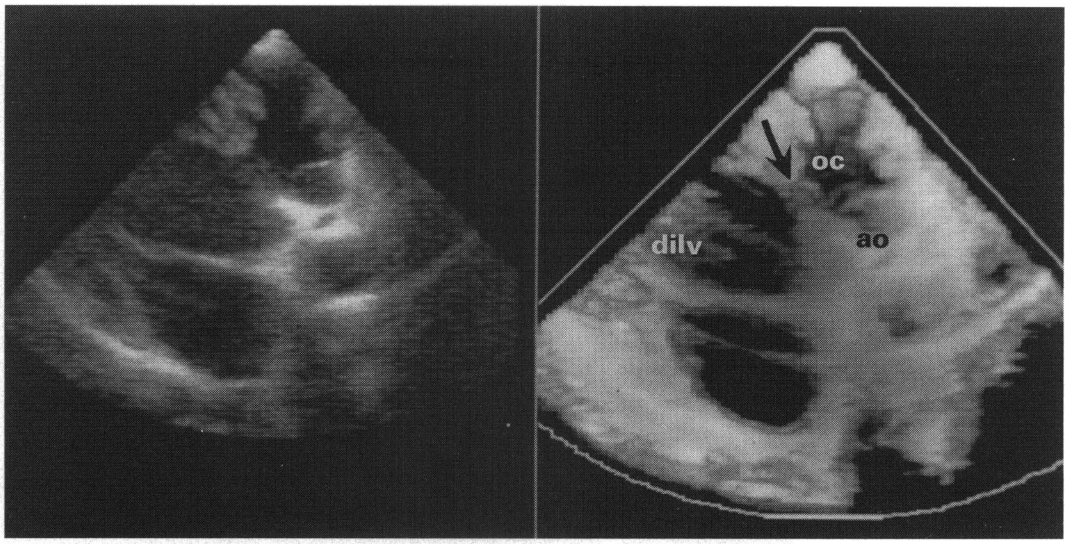


Figure 6 Cross sectional picture and corresponding three-dimensional reconstruction of the same data from the patient with double inlet left ventricle (dilv) featured in figure 5. The ventricular septal defect is indicated by an arrow. Abbreviations are as in figure 5.

echocardiographic pictures from the transthoracic position in newborn babies, infants, and children up to 15 years of age. All the patients apart from a 17 year old girl had good transthoracic echocardiographic windows, which is an essential requirement for being able to perform a transthoracic three-dimensional echocardiographic study. Structures that cannot be properly imaged by conventional transthoracic cross sectional echocardiography such as conduits from the right ventricle to the pulmonary artery or anastomoses from the right atrium to the pulmonary artery (Fontan) cannot be reconstructed three-dimensionally.

The quality of the three-dimensional picture depends entirely on the quality of the acquired cross sectional images and can be improved by an imaging probe with better spatial and temporal resolution than the 5 MHz probe, which was originally designed for transoesophageal echocardiography in adults. The clinical usefulness of this method in infants and newborn babies may be improved by acquiring more than 25–30 frames per second and using a 7·5 MHz transducer. A dedicated transthoracic probe is currently being developed. We hope that its shape will allow images to be acquired from the subcostal position, which usually offers the best echocardiographic window in newborn children and infants.

We were also unable to use the suprasternal echocardiograhic window and could not obtain views of the aortic arch and the descending aorta with our transducer. The transthoracic use of the computed tomography imaging probe yielded additional information of intracardiac anatomy, especially the atrioventricular valve. This method was also helpful in improving communication with the surgeons in our institution as we could display the cardiac anatomy in a view that is similar to the one they have during an operation. This was particularly helpful in the cases of mitral valve anomalies.

Real time three-dimensional echocardiography has the potential of realistic display of cardiac anatomy. To be used routinely it (*a*) should be easy to use (*b*) should not prolong the time needed for image acquisition, and (*c*) should produce the three-dimensional images in a reasonable time. The tomographic system used in this study fulfils most criteria, although refinements in the image processing software are desirable to reduce the time in producing the three-dimensional images.

We conclude that transthoracic three-dimensional echocardiography is feasible in most paediatric patients. It is easy to use, can shorten acquisition time, and may yield additional information on intracardiac anatomy, especially on atrioventricular valves.

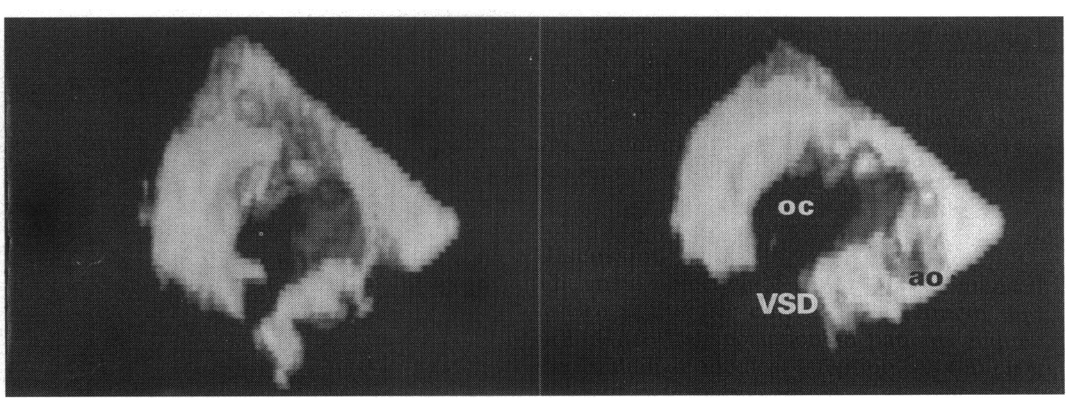


Figure 7 Three-dimensional reconstruction of the ventricular septal defect in the patient featured in figures 5 and 6. This time the view is at the apex of the double inlet left ventricle looking upwards. Abbreviations are as in figure 5. VSD = ventricular septal defect.

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