Journal of Digital Imaging

VOL 8, NO 3 AUGUST 1995

Three-Dimensional Display of Cardiac Structures Using Reconstructed Magnetic Resonance Imaging

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It is sometimes difficult to understand the three-dimensional (3D) relationship of cardiac and mediastinal structures despite advances in magnetic resonance (MR) imaging techniques. We present a low-cost system for 3D reconstruction of the major mediastinal structures by processing the MR imaging data on a NeXT workstation. MR images of multisection, multiphase, spin-echo techniques stored in a picture archiving and communication system (PACS) data base were used for the reconstruction. The computer program obtained the contours of the multiple components of the mediastinal structures by the combination of automatic and manual procedure. The bundled software of a 3D kit was used for surface rendering of hidden surface removal, shading of the visible parts of the surfaces, perspective transformation, and motion parallax by rotation of the surfaces. 3D reconstruction was performed in 15 patients with cardiac diseases, and the 3D-reconstructed images were compared with the plain chest x rays of the patients. The 3D presentation clearly showed the complex anatomy of cardiovascular diseases and helped elucidate the misconceptions in the interpretation of the plain chest x rays. Our 3D images are used for education and should be viewed by medical students and beginners in radiology at an individual pace with plain chest radiographs, MR images, and legends. Although applied to the heart and the great vessels in this report, this system is also applicable to other structures.

KEY WORDS: three-dimensional display, MR imaging, computer graphics.

DESPITE ADVANCES in the sectional imaging techniques of magnetic resonance imaging (MRI), an overview of an entire heart and its chambers in various projections shown in plain chest radiographs seems an easier and sometimes better way to understand cardiac and mediastinal diseases. For beginners in tomographic images, the assesment of such an overview from two-dimensional (2D) MR images of multiple cardiac slices is frequently difficult, especially in cases with congenital heart diseases. Advances in computer technology that allow creation of 3D images from acquired planar information have overcome these difficulties. However, to date, 3D imaging has not been routinely applied to the imaging of the heart. The purpose of this study is to develop a low-cost 3D-reconstruction system from MRI data and to understand the fundamental concepts in the interpretation of cardiac configuration of plain chest radiographs through reconstructed 3D images.

MATERIALS AND METHODS

The operating system of NeXTSTEP (NeXT Computer, Inc, Redwood City, CA) was chosen as the platform for software development because of its object-oriented user interface. The system hardware was a NeXT workstation and compatible personal computer (PC). The former was NeXT dimension (NeXT Computer Inc, Redwood, CA) with a central processing unit (CPU) (model 68040; Motorola, Austin, TX), 64 Mbyte of random access memory (RAM), an internal 512-Mbyte hard disk drive and a 17-inch color display, whereas the latter was N 1300 (Canon Inc, Tokyo, Japan) with a 486 Intel CPU, 64 Mbyte of RAM, an internal 512-Mbyte hard disk drive, and a 17-inch video graphics array (VGA) color display. The software was developed using the system's built-in interface builder software and a 3D kit, and the programming language was objective-C.[1] The minimum requirements of the PC-based NeXT system for operating the program included an i486-based or Pentium-based compatible PC, industrial standard

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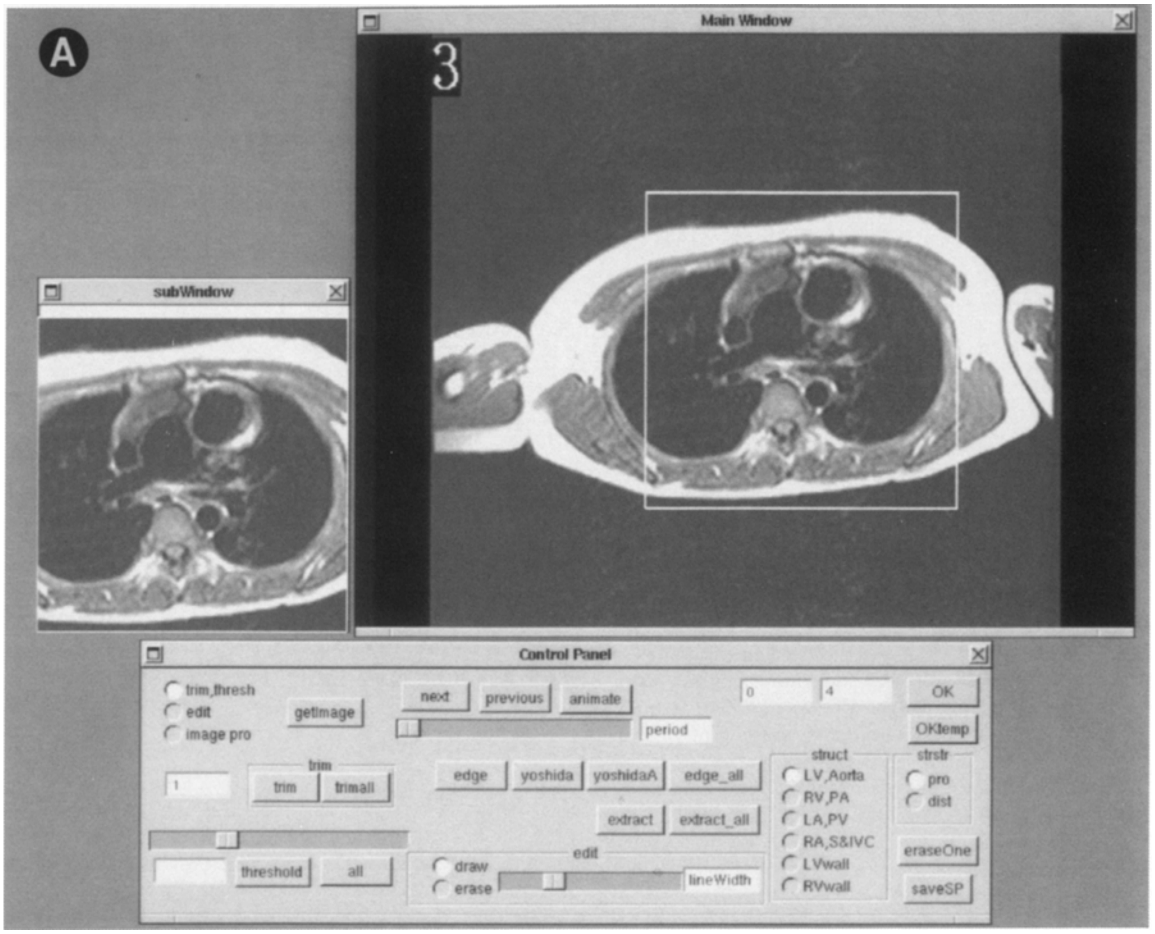


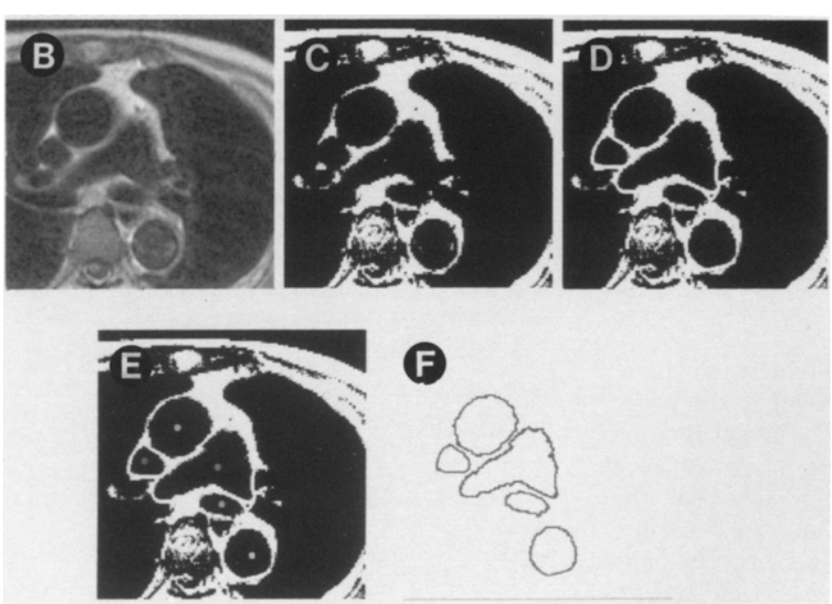


Fig 1. (A) The main frame of the modeling program. The programs were made to obtain the contours of the multiple components of the mediastinal structures by the combination of automatic and manual procedures. Using the radio switches and buttons of the control panel, one can select the modeling, trimming, thresholding, editting and edge detection and contour extraction steps. The main window shows the 512- × 512-pixel matrix at two times the magnification of the original 256- × 256-pixel image and the subwindow shows the half-size, trimmed version of the original image. The processed images during the modeling are shown from B to F. (B) Original trimmed image; (C) thresholding; (D) edited image; (E) starting point; and (F) extracted contour.

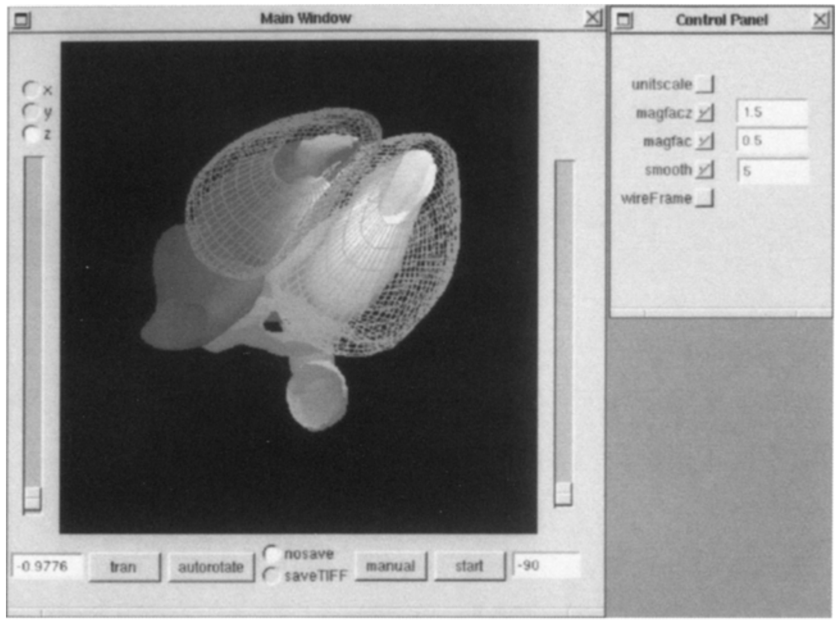


Fig 2. The main frame of the rendering program is shown. Bundled software of the 3D kit was used for surface rendering. Switches of the control panel and the buttons of the main window decide the size and shape parameters of the 3D object.

architecture or extended industry standard architecture bus, 400 Mbyte of hard-disk space and 24 Mbyte of RAM. The cost of our basic PC-based system is approximately $7,000. Electrocardiogram gated MR images of multisection, multiphase, and spin-echo techniques stored in a PACS data base were used for the reconstruction. The image data were transfered to a Macintosh PC where the data format was changed from picture archiving and communication system format to tagged image file format using a conversion software (Hitachi Medico Inc, Kashiwa, Japan). The data were then transfered to the NeXT system and further work on the reconstruction was performed.

RESULTS

3D reconstruction system. We developed programs for 3D modeling (Fig 1), 3D surface rendering (Fig 2), and the demonstration of the

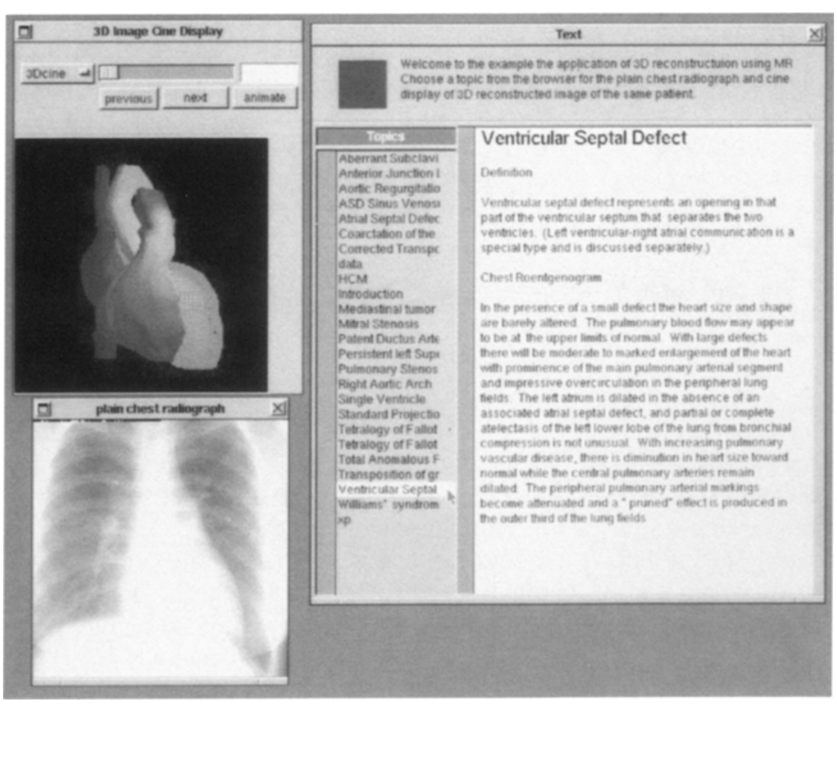


Fig 3. The main frame of the demonstration program is shown.

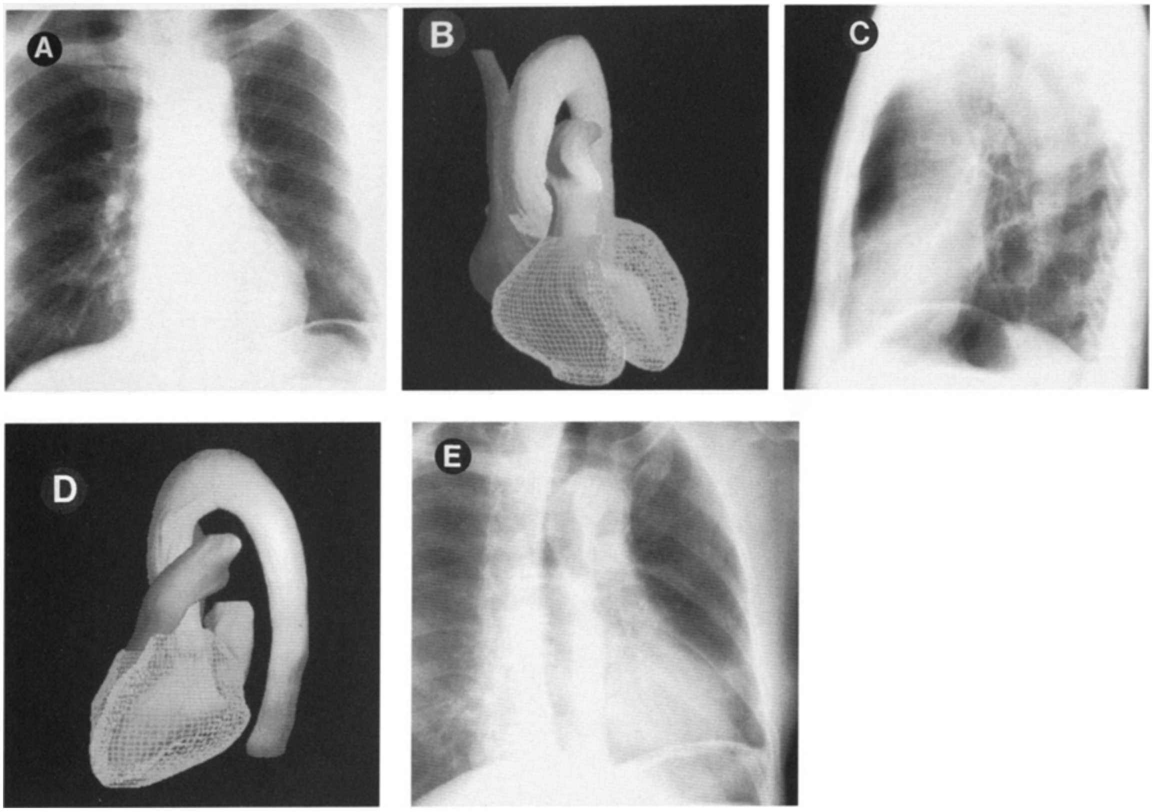
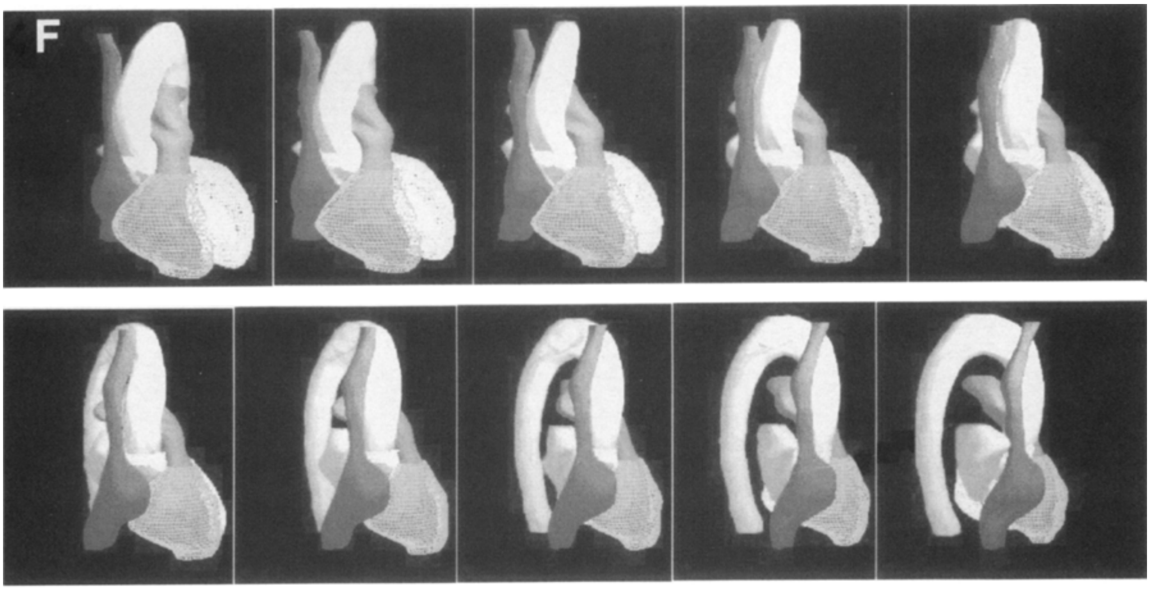
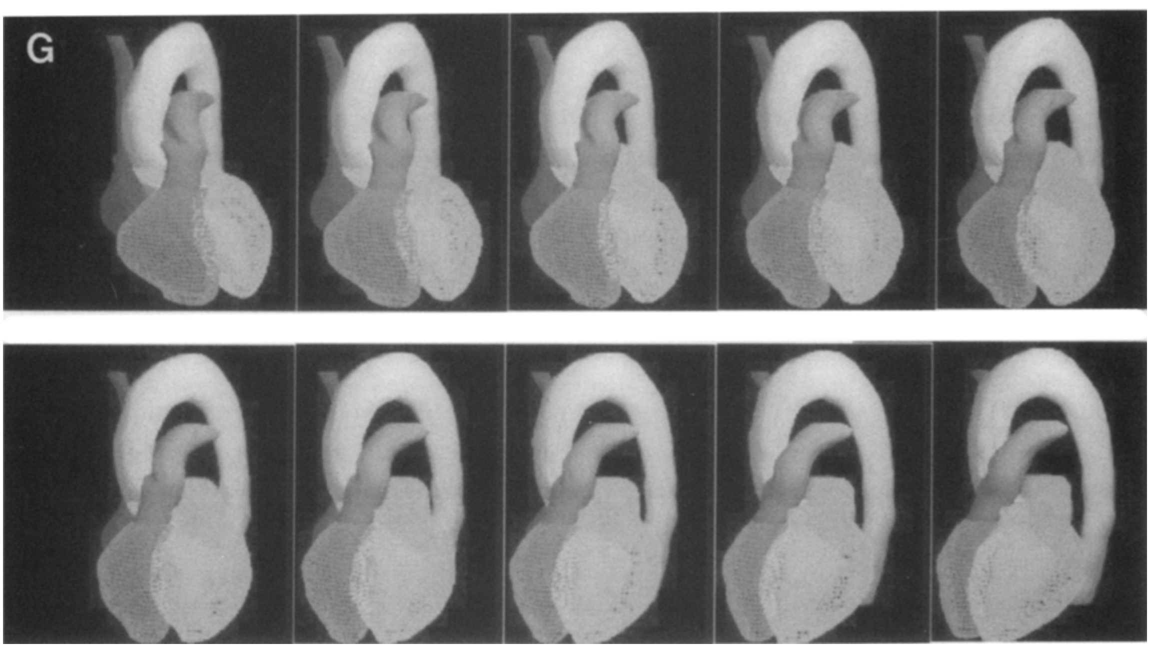


Fig 4. The standard four projection of the normal subject is shown. (A) PA projection of the plain chest roentogenogram; (B) 3D-reconstructed image of A; (C) lateral projection of the plain chest roentgenogram; (D) 3D-reconstructed image of C; and (E) RAO projection of the plain chest roentgenogram.

3D-reconstructed images, plain chest radiographs, and text files that describe the disease and the finding of the images (Fig 3). The 3D modeling was performed by the following steps: (1) First, in trimming (Fig 1A), the original images were enlarged to 512 × 512 pixels and then, using the region of interest (ROI) box, the images were reduced to half size with a 256- × 256-pixel matrix (Fig 1B). Thus, a ROI containing the heart and great vessels was chosen by an operator to reduce the need for computer memory space and to speed manipulation. (2) In thresholding (Fig 1C), the program converted 8-bit gray depth images to 2-bit gray depth images. (3) In image correction (Fig 1D), the structures of interest had to be delineated by an operator knowledgeable in cardiac anatomy. This segmentation was accomplished by using interactive thresholding and line erasing and line drawing. (4) Next, we input the starting point for the tracer program that detects the edge of the target chamber. Color-coded starting points are shown in Fig 1E. From the starting point, the tracer started to detect the edge of the target structure. (5) Lastly, the tracer detected the edge of the target chamber, as shown in Fig 1F. Stacks of contours were stored on the disk for the next rendering process.

The 3D surface-rendering program performed interpolating and smoothing of the contour data, surface rendering with hidden surface removal, shading of the visible parts of the surface, and changing of viewpoints by rotation of the surfaces (Fig 2). Combining the surface rendering of the inner structures and wire-frame representation of the outer structures of the cardiac chamber showed the size and shape of the cardiac chamber. (In our color figures, the left ventricle and the aorta are colored vermeil, the right ventricle and the pulmonary artery, sky blue; the right atrium and the superior vena cava (SVC), blue; and the left atrium, red.) A series of reconstructions rotating around





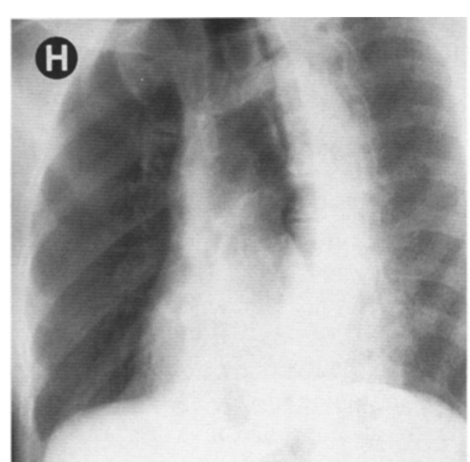


Fig 4 (cont'd). (F) 3D-reconstructed images from frontal to right lateral projection (see the color figures on page 110); (G) 3D-reconstructed images from frontal to left lateral projection; and (H) LAO projection of the plain chest roentgenogram.

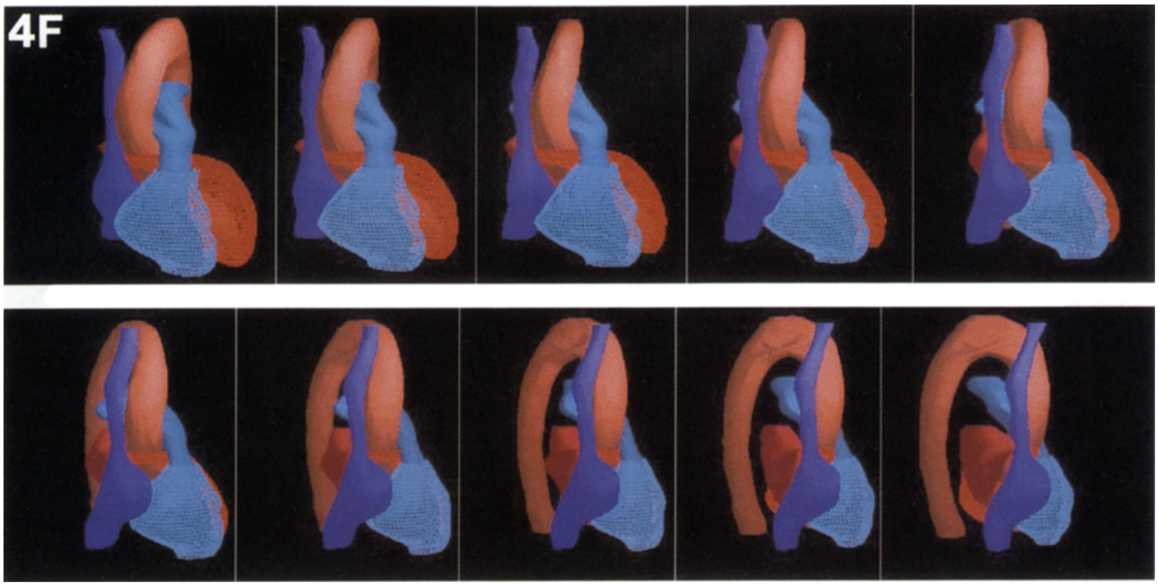


Fig 4F.

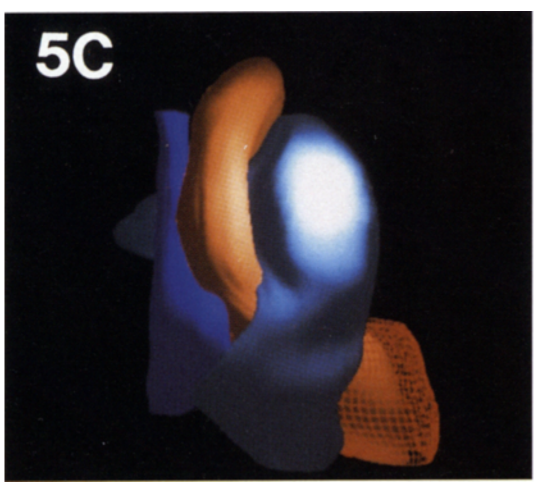


Fig 5C.

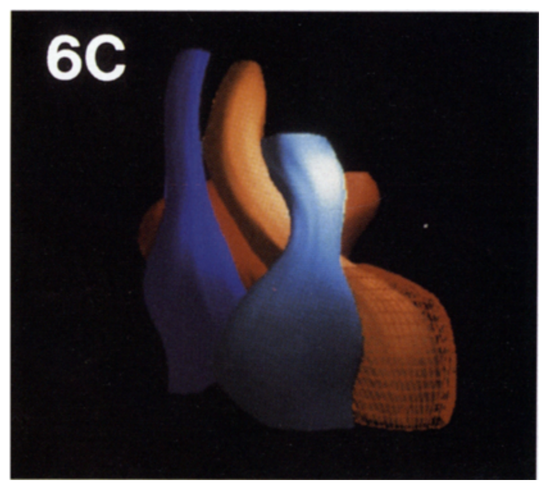


Fig 6C.

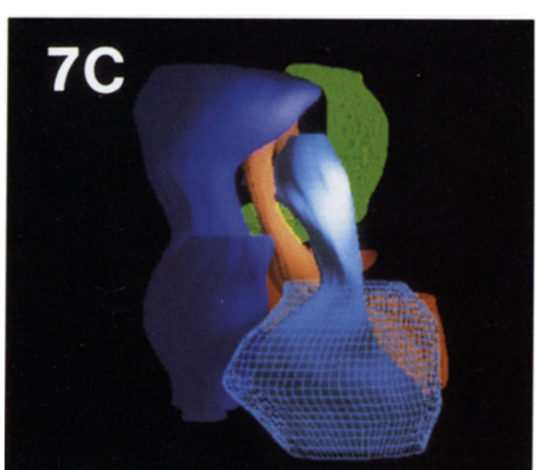


Fig 7C.

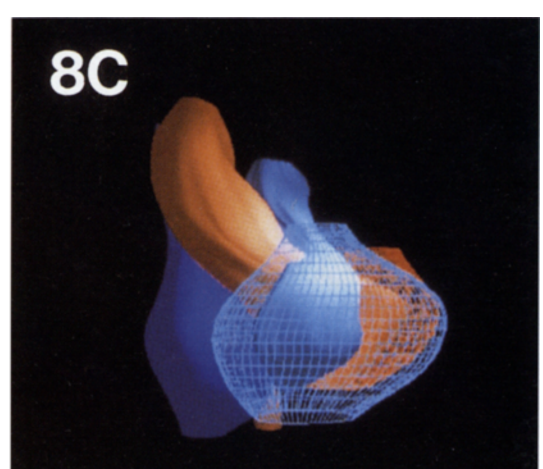
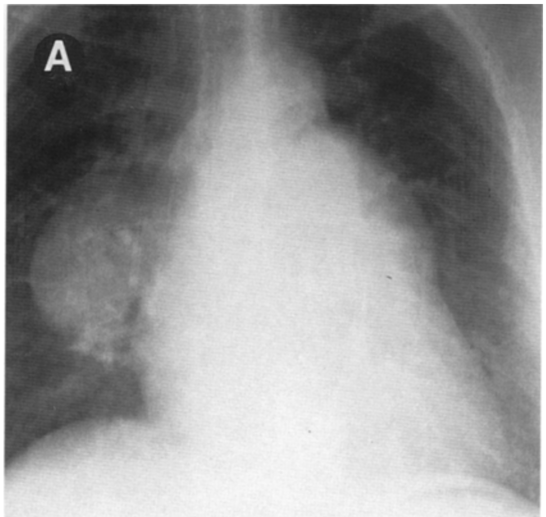
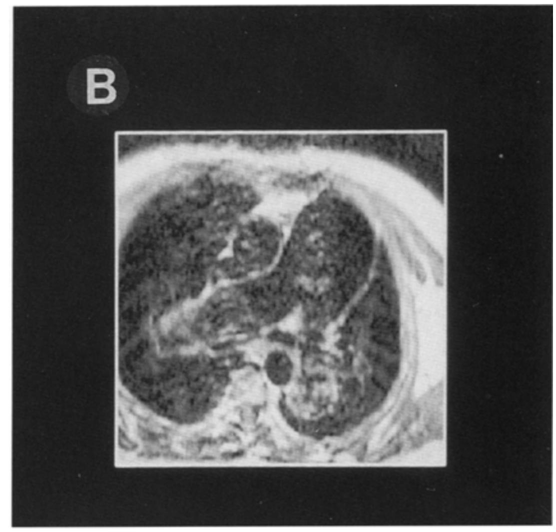


Fig 8C.





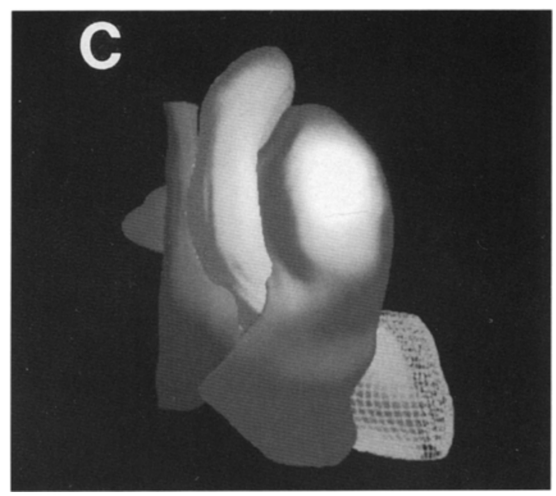


Fig 5. PDA is shown. (A) Plain chest roentgenogram; (B) MRI shows the marked enlargement of the pulmonary artery; and (C) 3D-reconstructed image (see the color figures on page 110; note the enlarged pulmonary artery in sky blue).

one axis can be stored on a disk and later redisplayed as a movie with a demonstration program. The demonstration program has a function of selection list that lets the user select a name from the list and shows text data instantly. The program also shows the plain chest radiographs and 3D-reconstructed images (Fig 3). After approximately 20 seconds for loading the 32 projections of the 3D images, the program can show a movie display and also show the images frame by frame. The movie display of the rotation of 3D images provides an easily-recognizable projection of the complicated cardiovascular anatomy.

Comparison of 3D images and plain chest radiographs in cardiac diseases. 3D reconstruction was performed for 15 patients with cardiac diseases and the 3D-reconstructed images were compared with the plain chest films of each patient. Delineations about the size and shape of the individual cardiac chambers from plain chest radiographs can only be presumptive. However, using the present 3D reconstruction system, color-coded, sectionable, rotatable 3D MR reconstructions of the heart, great vessels and mediastinal structures can be produced for the evaluation of cardiovascular anomalies.

Generally, in the posterior-anterior (PA) projection of the normal heart, the two arches of the right cardiac border correspond to the SVC and the right atrium, whereas four arches of the left cardiac border correspond to the aortic knob, the pulmonary artery, the auricle of the left atrium, and the left ventricle, and the third

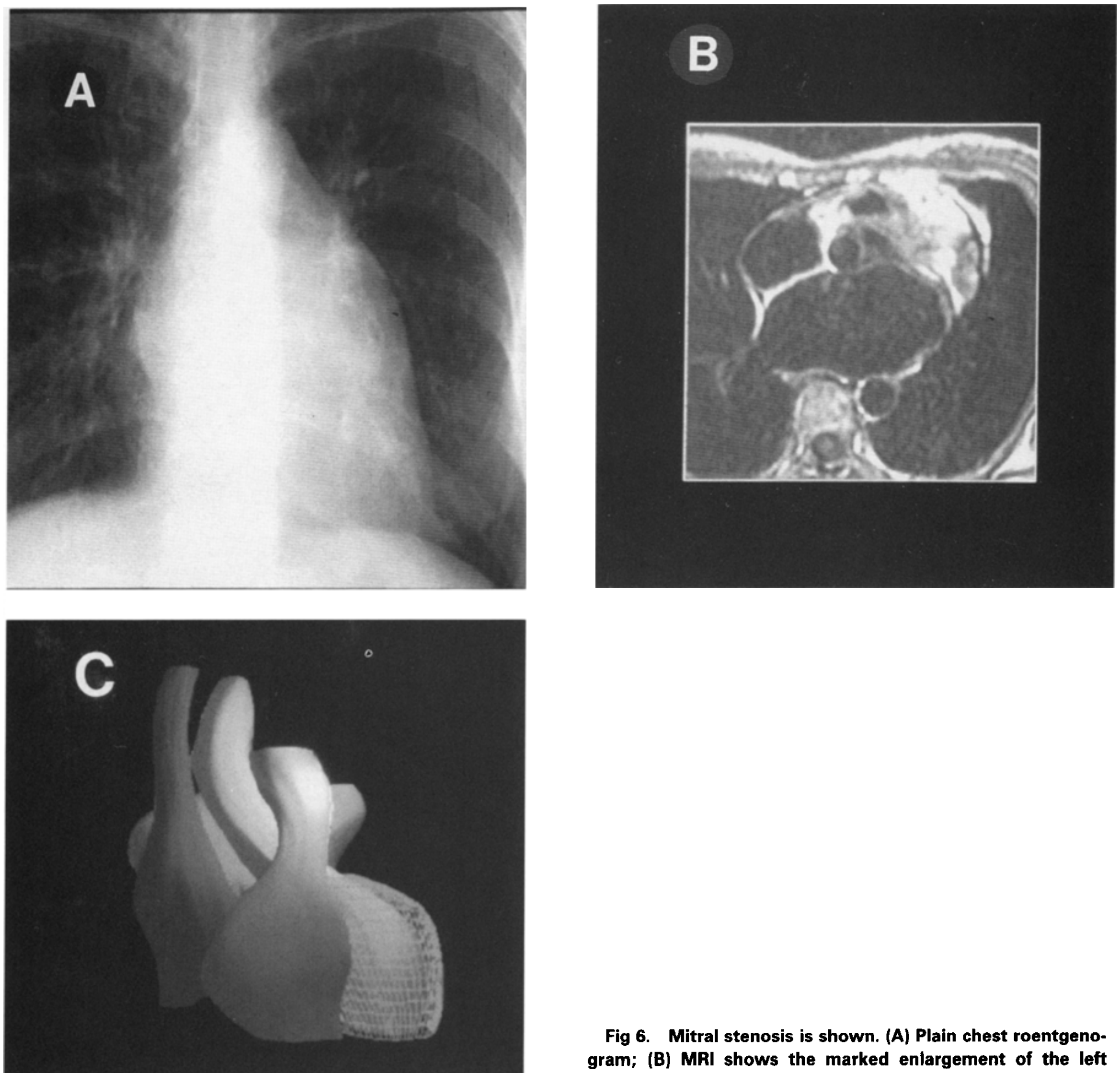


Fig 6. Mitral stenosis is shown. (A) Plain chest roentgenogram; (B) MRI shows the marked enlargement of the left atrium; and (C) 3D-reconstructed image (see the color figures on page 110; note the enlarged left atrium in red).

arch of the appendage of the left atrium is not present. However, in practice, minor variations are seen in individual cases. The left second arch is also not seen in a normal patient in PA projection of plain chest radiograph (Fig 4A). The 3D-reconstructed image (Fig 4B) shows the slight anticlockwise rotation of the heart, which is the cause of nonvisualization. Figure 4C is a lateral radiograph and Fig 4D is the lateral 3D-reconstructed image, which shows that the anterior border of the heart is the right ventricle, the most superior position is the left atrium, and the most inferior part is the floor of the right ventricle.

The standard cardiac series consists of frontal, lateral, right anterior oblique view (RAO), and left anterior oblique view (LAO). Because only two of the cardiac borders are seen in any one view, it is necessary to obtain several projections for complete study. Although the RAO projection is used to evaluate the outflow tract of the right ventricle and the LAO is used for evaluation of the configuration of both ventricles, it is not easy to decide the best angulation of the oblique projection. Figure 4E is RAO projection of the plain chest roentgenogram. Figure 4F shows the 3D-reconstructed image of the MRI of the same patient with a normal heart. From the extreme left image of the top row to the extreme right image of the

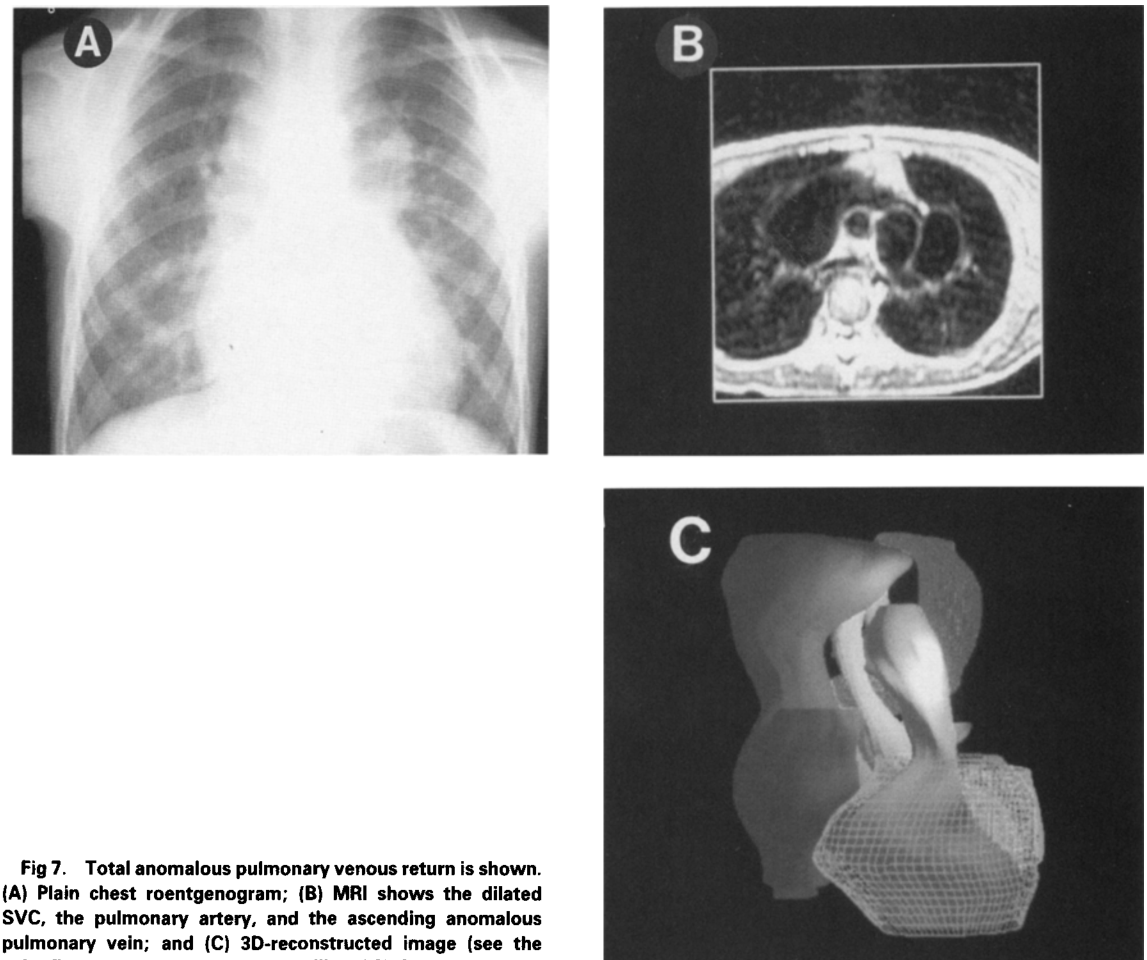
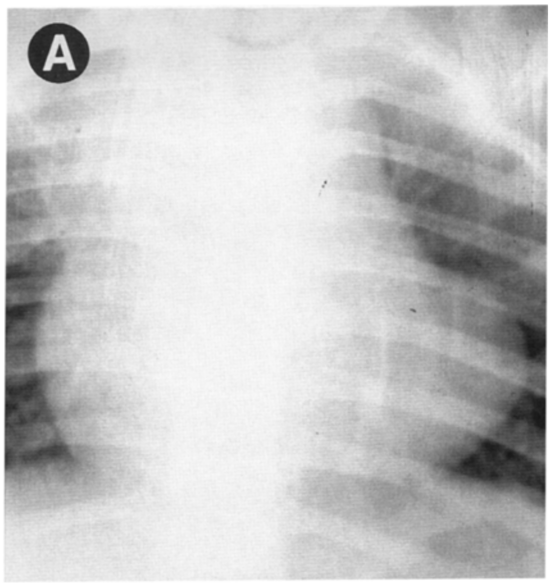


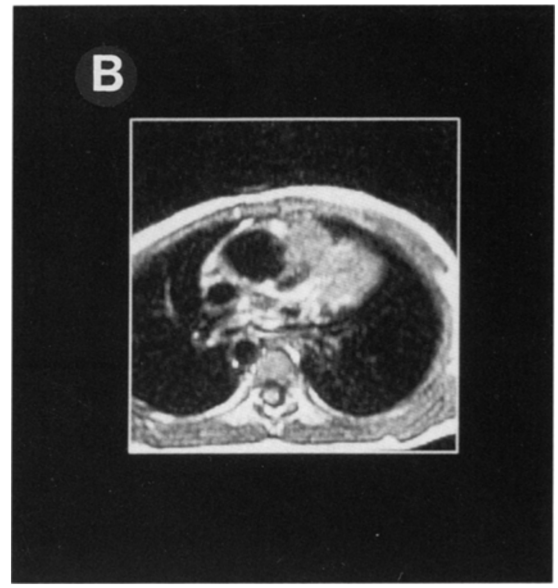
Fig 7. Total anomalous pulmonary venous return is shown. (A) Plain chest roentgenogram; (B) MRI shows the dilated SVC, the pulmonary artery, and the ascending anomalous pulmonary vein; and (C) 3D-reconstructed image (see the color figures on page 110; note the dilated SVC in blue and the enlarged pulmonary artery in sky blue).

bottom row, each consecutive image rotates 10 degrees. The second left image of the bottom row, at an angulation of 60 degrees, is the best to show the outflow tract of the right ventricle. Figure 4H is the RAO projection of the plain chest roentgenogram. Figure 4G shows the 3D series for the same normal heart using the opposite rotation. Because two or three images of the top row clearly show the size and shape of both ventricles, approximately 45 degrees less angulation is recommended for an LAO projection.

Figure 5A shows the plain chest film of a patent ductus arteriosus (PDA) with marked protrusion of the left second arch. PDA results from the persistence of the distal aspect of the left sixth branchial aortic arch. This structure normally closes soon after the birth with the onset of spontaneous respiration. MRI (Fig 5B) shows the marked enlargement of the pulmonary artery. The 3D-reconstructed image (Fig 5C) shows that the marked enlargement of the main pulmonary artery is the cause of the marked protrusion of the left second arch.

A plain chest radiograph of a patient with mitral stenosis (Fig 6A) shows marked protrusion of the third arch of the left cardiac border and also shows the double density of the right heart border. The characteristic roentgen findings of pure mitral stenosis are enlargement of the left atrium and left appendage, signs of pulmonary venous hypertension, and evidence of right ventricular hypertrophy. Most commonly, the etiology for mitral stenosis is rheumatic fever in childhood or adolescence causing an inflammation of the mitral valve. It takes several years for the inflammatory process and subsequent reparatory changes to lead to the scarring and diminished orifice of the mitral valve. MRI (Fig 6B) shows the marked enlarge-





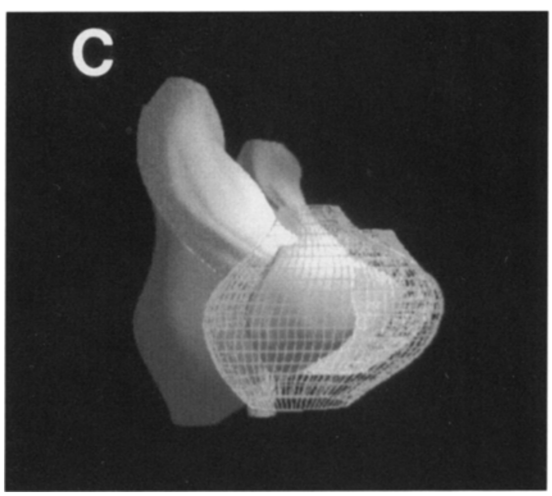


Fig 8. The tetralogy of Fallot is shown. (A) Plain chest roentgenogram; (B) MRI shows the severe narrowing of the outflow tract of the right ventricle; and (C) 3D-reconstructed image (see the color figures on page 110).

ment of the left atrium. A 3D-reconstructed image (Fig 6C) shows marked enlargement of the left atrium, which causes the abnormality of the radiograph.

A plain chest radiograph of a patient with total anomalous pulmonary venous return (Fig 7A) shows marked protrusion of the first and second arches of the right cardiac border and also marked abnormal bulging of the left superior cardiac border. The pulmonary venous return in this rare condition is anomalously directed into the right side of the heart instead of the left. MRI (Fig 7B) shows the anomalous vein entering the SVC. A 3D-reconstructed image (Fig 7C) shows the vascular structure of the abnormal venous return, which corresponds to protrusion of the left superior cardiac border and also an enlarged SVC and right ventricle. These abnormalities cause the findings in the chest radiograph, the so-called "snowman's heart" or "figure of eight."

A plain chest radiograph of a patient with the tetralogy of Fallot (Fig 8A) shows another well-known abnormal configuration, "*coeur en sabot.*" The anatomy components in the tetralogy of Fallot are a right ventricle outflow into the aorta, a pulmonary artery obstruction, or both, a large ventricular septal defect, right ventricular hypertrophy, and the aorta overiding the ventricular septal defect. MRI (Fig 8B) shows the severe narrowing of the outflow tract of the right ventricle. A 3D-reconstructed image (Fig 8C) shows marked hypertrophy of the right ventricle, which causes an upward shift in the

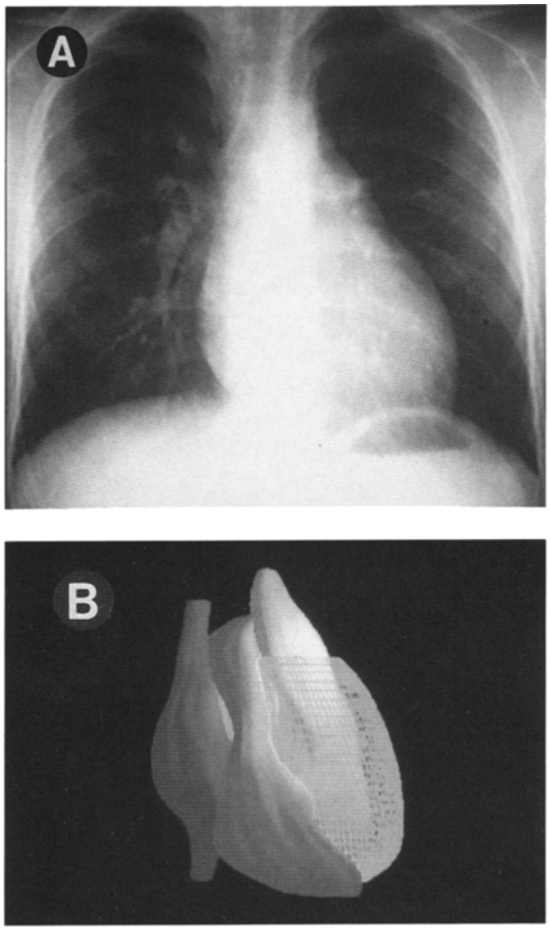


Fig 9. TGA is shown. (A) Plain chest roentgenogram; and (B) 3D-reconstructed image.

position of the hypoplastic left ventricle and resultant elevation of the cardiac apex.

A plain chest radiograph of the patient with corrected transposition of the great arteries (TGA) (Fig 9A) appears normal. In cases of corrected TGA, there is atrioventricular discordance in addition to ventriculoarterial discordance. Although a series of MRI shows the congenital anomaly of the TGA, it is difficult to image the anomaly of the systemic and pulmonary arterial connection of the entire heart. However, an overview image of the 3D-reconstructed image (Fig 9B) clearly shows the abnormality.

Our system of 3D modeling, 3D surface rendering, and the demonstration program is completed. The demonstration program is presently used to educate medical students.

DISCUSSION

A major benefit of our system is that 3D images of the normal heart and various cardiac diseases allow improved evaluation of the anatomic relationships between the cardiac chambers and the mediastinal great vessels and have promoted a better understanding of what is seen on conventional radiographs.[2,3]

Another advantage is the low cost of the hardware of our system. 3D reconstruction systems in radiology are still expensive. Most of the manufactures of radiologic modalities such as computed tomography or MR developed their own 3D-reconstruction software systems that work only on their own products. With the availability of greater computing power at reasonable prices, there is a resurgence of interest in 3D-reconstruction techniques. The total cost of our PC-based system, including the software development system with a 3D kit, is less than $10,000.

The present use of our 3D images is to educate medical students and beginners in radiology in the anatomy of cardiovascular diseases. The 3D images could be viewed at an individual pace with plain radiographs, MR images, and legends. Complex anatomy of congenital heart diseases can be easily understood with computer graphics. 3D images generated with spiral computed tomography is reported to be useful for clinical practice and education in radiology.[4] We speculate our 3D images might be also helpful for surgery planning by clearly depicting the 3D relationships. In conclusion, our method is a low-cost way to delineate complex cardiac anatomy and has proven computer graphics to be useful in this field.

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