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Computerized Medical Imaging and Graphics 23 (1999) 173–179

Computerized Medical Imaging and Graphics

www.elsevier.com/locate/compmedimag

Computer system for four-dimensional transesophageal echocardiographic image reconstruction

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Abstract

This paper presents a system for reconstructing a four-dimensional (4D) heart-beating image from transesophageal echocardiographic (TEE) data acquired with a rotational approach. The system consists of the necessary processing modules for two-dimensional (2D) echocardiogram reformation and 3D/4D-image reconstruction. These include the modules of image decoding, image re-coordinating, and three-dimensional (3D) volume rendering. The system is implemented under PC platform with Windows 95 operating system (with Intel Pentium-166 CPU, 64 MB RAM on board, and 2.0 GB hard disk capacity). It takes 6 min to reconstruct a 4D echocardiographic data set. The resultant 2D/3D/4D echocardiographic image provide the tools for investigating the phenomenon of heart beating, exploring the heart structure, and reformatting the 2D echocardiograms in an arbitrary plane. The functions provided by the system can be applied for further studies, such as 3D cardiac shape analysis, cardiac function measurement, and so forth.

Keywords: Four-dimensional echocardiography; Transesophageal echocardiography; Image reconstruction; Volume rendering; Image re-coordination; Image reformation; Concentric interpolation

1. Introduction

Medical ultrasonic imaging can be performed in a short period of time and at the bedside if necessary. It allows real-time imaging and is relatively inexpensive when compared to other imaging methods. Ultrasound has therefore been paid much attention in clinical diagnoses and researches. With the advances in image processing techniques, it has become one of the most important tools for routine clinical services. It has now been applied not only to the assessment of cardiac functions [1–3], but also to the basic study of the morphology and dynamic alternation of the heart [4–6].

Although two-dimensional (2D) echocardiography reveals the spatial relationships between cardiac structures, an experienced examiner must mentally synthesize three-dimensional (3D) relationships during studies. It is impossible to present the heart objectively using this technique. However, progress in 3D imaging techniques has encouraged the study of 3D and 4D (four-dimensional) echocardiogram reconstruction and related applications. In the work of Fine et al. [7], interactive computer techniques were used to reconstruct the 3D shell of the endocardium and epicardium during the end-diastolic and end-systolic phases, respectively. The volumes and indices of left ventricular function can be calculated using their system. In the study of Deng et al. [8], 2D echocardiographic images were acquired and reconstructed to show the 3D structure of fetal hearts. This approach was developed to diagnose the prenatal cardiac malformations and malfunctions for the purpose of in utero cardiac surgery and fetal cardiology instruction. In the study of Pai et al. [9], the 3D reconstruction of the left ventricle was performed using an echo-computed tomographic (CT) method based on a serial pull-back parallel slice imaging technique in both in vitro and in vivo settings. The volumes of the left ventricle were then calculated by summing the volumes of each slice. This was demonstrated to be an accurate method for deriving the left ventricular volume for the further applications. The study of Gotteiner et al. [10] assessed the effect of nonlinear myocardial deformation by use of finite element analysis and 3D echocardiographic reconstruction. The work provided a detailed measurement of non-homogeneous regional deformation using a sophisticated imaging technique. 3D or 4D echocardiographic imaging techniques have since been widely used in research and the diagnosis of cardiac function and diseases.

In this paper we have tried to devise a simple, inexpensive,

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0895-6111/99/$ - see front matter
PII: S0895-6111(99)00016-6

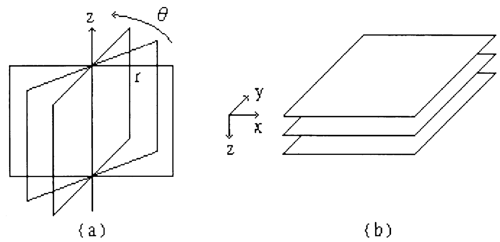

Fig. 1. Sketches of the transformation from the rotating set of slice into a *Z*-series of slices. (a) Schematic diagram of a set of slices acquired in the rotational approach respects to the *Z*-axis. (b) Schematic diagram of a set of *Z*-slices.

and clinically useful system which provides the functions to reconstruct 3D and 4D echocardiograms from time-evolving 3D transesophageal echocardiographic (TEE) images on a PC platform. Our system has been sought to: (a) re-coordinate the TEE images from the rotational data set to the cubic one; (b) reconstruct static or dynamic 3D/4D echocardiography; and (c) reformat 2D echocardiograms from an arbitrary angle using the re-coordinated cubic data set. In addition, we integrated the necessary processing modules, such as image decoding, image re-coordinating, image reformatting, 3D image reconstruction and image display modules, into an integrated software program with a user-friendly operating interface. The following sections will describe the processing modules in detail, with several experimental results given at the end to illustrate the functions of the developed system.

2. Image re-coordination

The subject to be discussed in this paper is 3D transesophageal echocardiography, which is performed using a multiplane transesophageal probe and a commercially available ultrasound system (HP Sonos 2500, Hewlett-Packard, Andover, USA) in the 3D/4D protocol. In this imaging method a rotational technique of data acquisition has been used to obtain a 3D time-evolving echocardiographic image data set [11,12]. The transducer is held stable at one point, and the transducer probe itself or the transducer element within the probe is rotated around a pivot point, which is always located at the tip of the imaging probe. Generally, this pivot point is fixed and the relative motion between the transducer and heart is negligible, it can be the reference point to stack and reconstruct the time-evolving 3D image set. A computer-controlled motor advances the sectors 2–10° over a span of 180° and generates a conical 3D data set. At each imaging position, the ECG-gated imaging technique is used to enable the image acquisition from the *R*-wave detected. Many time frames, commonly 21 frames, can be acquired during a cardiac cycle. The frame rate is dependent upon the length of cardiac cycle of the patient. Then the transducer is rotated to the next imaging position and waiting for the next triggering signal.

As the image data set is acquired with rotational approach and is natively the conical form, it is necessary to convert the acquired 3D image data set from conical form to cubic for the further processing. That is, a transformation is required to convert the image data set from the polar coordinate system (r, θ, z) to the Cartesian one (x, y, z). This re-coordinates a set of slices rotated along a common axis to a set of *z*-slices. The relationship between the transformed 3D cubic volume data set and the rotational image data set is given by:

$$G(x,y,z) = g(r,\theta,z),$$
$$x = r\cos(\theta), \quad (1)$$
$$y = r\sin(\theta)$$
$$z = z,$$

where G is the gray level of the voxel at position (x, y, z) in the *z*-series of slices, and g represents the gray level of the voxel at position (r, θ, z) in the rotating slices. r is the distance from the position of transducer to the projected point of the voxel onto the x–y plane. θ is determined by the slice number that corresponds to the degree of rotation of the transducer. In this approach, we calculate the r- and θ-components of the voxel in polar coordinates, which correspond to the x- and y-components of the same voxel in Cartesian coordinate; and find the gray level of the voxel at position (r, θ, z) in the original image data set (in polar coordinate). The transformation of a rotating set of slices to a *Z*-series of slices is shown in Fig. 1 [13].

In addition, the converted cubic volume undergoes interpolation to fill in the gray level of the extra voxels that are generated during the re-coordination process and lose on the other hand a specified gray level. As the rotational approach is used to acquire echocardiographic images, some voxels lose a gray level when the original image data set is converted to the cubic volumetric data set. For the example of a volume data set with size $240 \times 240 \times 108$, the gap in the outermost circle between two adjoining rotational slices acquired every 2° is more than four voxels ($120 \times \sin 2°$). It is necessary to calculate the gray level of these extra voxels by interpolation processes. For that purpose, concentric interpolation is used to perform the necessary interpolation. The gray level of the extra voxel is calculated by linear interpolation using the neighborhood voxels with the same concentric distance as the extra voxel. For instance, by calculating the radius and angle of the voxel to be transformed with Eq. (1), we obtain the coordinate of the calculated voxel in the rotating image data set (r, θ) corresponding to that in 3D cubic volume data set (x, y). If the derived angle cannot be found in the conical data set, it means that there is no gray level attributed to this calculated voxel. Therefore, the voxels in the original image data set with the same radius as the calculated voxel but with the angle after and prior to that of the calculated voxel are averaged to estimate its gray level. This method is called "concentric interpolation".

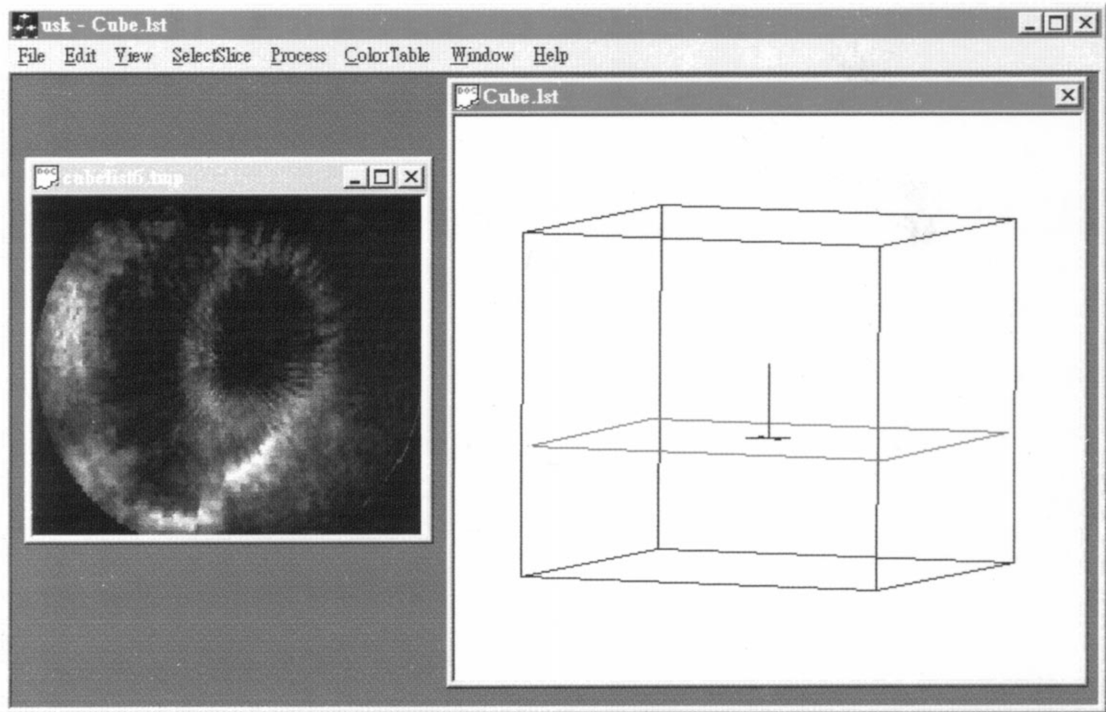

Fig. 2. The reformation of 2D echocardiogram. On the right panel, the cube shows the recoordinated cubic echocardiographic image data, the frame inside the cube and with a arrow attached on it is the resampled 2D frame, and the arrow displays the direction to resample the 2D echocardiograms. On the left panel, it displays the resultant 2D echocardiogram in the short-axis cutting plane.

3. 3D echocardiogram reformation

Image reformation is used to extract a 2D echocardiogram in an arbitrary cut plane from the 3D cubic volume data set. To achieve this, a user-friendly interface must be implemented to allow users to select the correct image plane as easily as possible. In our system, a computer-generated cubic wire frame containing rectangle is used as a slice locator (Fig. 2). The cubic wire frame is analogous to the re-coordinated 3D cubic volume data. The rectangular plane inside the cubic wire frame is used to represent the position of the image plane that is extracted from the 3D cubic volume data.

There is a small arrow called reformation pointer at the center of the rectangular plane. It is used to indicate the direction of projection from the 3D cubic volume data to the scene or viewers. That is, it points out the side of the image plane that will be displayed. Along the direction specified by the reformation pointer, a series of slices can be collected to form another *z*-series slices (Fig. 2). In order to define the direction of the reformation pointer, the degree of rotation of the reformation pointer respective to the *x*-, *y*-, and *z*-axis can be assigned by using the mouse (left to decrease and right to increase the angle). The rectangular plane can also be moved freely in the *x*-, *y*-, and *z*-axis to determine the position to start reformation. However, in order to retain the rectangular shape of the reformatted slices, the coordinates of the four corners are recalculated according to the position and direction of the reformation pointer and the size of the reformatted image slice (e.g. 240×240).

After the direction and position of the slice locator have been determined, the coordinates of every pixel inside the reformatted slice are evaluated. The recreated 2D echocardiogram is generated by checking the gray level of the voxels in the 3D cubic volume data set. Moreover, the direction of the reformation pointer of the slice locator can also be referred to as the direction of central projection for 3D/4D-image reconstruction.

4. 3D/4D echocardiographic image reconstruction

In our approach, several procedures are integrated to reconstruct 3D/4D echocardiographic images. These consist of selection of viewing angle, image smoothing by masking, selecting a color palette from a look-up table, volume rendering and hidden surface removal by the use of a *z*-buffer algorithm, as well as shading. In the process of viewing angle selection, the slice locator is used to define the direction of projection from object to scene or viewer. After the direction of viewing angle has been determined, the 3D cubic volume data is smoothed by either a $3 \times 3 \times 3$ or $5 \times 5 \times 5$ averaging mask, depending on the image quality of the original echocardiography, to obtain a volumetric image data set with a more

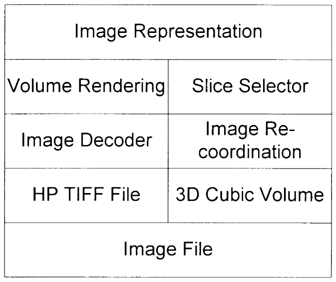

Fig. 3. The software structure of the developed 4D echocardiographic reconstruction system. It consists of: one image decoder (HP TIFF image); one image encoder (3D cubic volume data); and five image processing modules.

homogeneous distribution of gray level. If the smoothed 3D cubic volume data are too dark to display, a suitable color table may be chosen to increase the gray level. Later the 3D cubic volume data undergo 3D reconstruction with simple volume rendering and shading. In our system, parallel projection is used to speed up the process of 3D reconstruction. To eliminate the invisible front faces surviving the back-face removal algorithm, which are obscured by some object close to the scene or viewer, the *z*-buffer or depth-buffer algorithm is used in our system. It is considered a pixelwise bubble sort of the *z*-depth of all polygons pierced by the projector ray to the pixel. The results of the *z*-buffering process are then lightened with a single light source and shaded by Gouraud shading to complete the 3D reconstruction [14,15].

5. Experimental results

The system for 4D echocardiographic image reconstruction was implemented according to the description in the previous sections. Fig. 3 shows the software structure of the system. The system consists of five necessary components for 4D echocardiographic image reconstruction. These were the HP TIFF image decoder, image re-coordination, slice locator, volume rendering, and image representation modules.

As the raw data acquired by the HP Sonos 2500 ultrasound imager were encoded in the TIFF image file format, it was necessary to decompress the raw data to obtain the whole data set in four dimensions. After the raw image data files had been decoded, the image re-coordination process was performed to convert the original image data set in rotational format into that in 3D cubic format. The system also provides the option of storing the 3D cubic volume data in the storage device for further processing. Using the 3D cubic volume data, the slice locator can be used to reformat a 2D echocardiogram in an arbitrary cut plane, and the volume rendering routine can be used to build a 3D static image. Further, the resultant images obtained by every process can be displayed by the image presentation module. These functions are all integrated in a single program to provide the user with a comprehensive perception of dynamic heart activity and structure by means of TEE images. The system is extremely suitable not only for functional research of the heart but also for both static and dynamic structural studies.

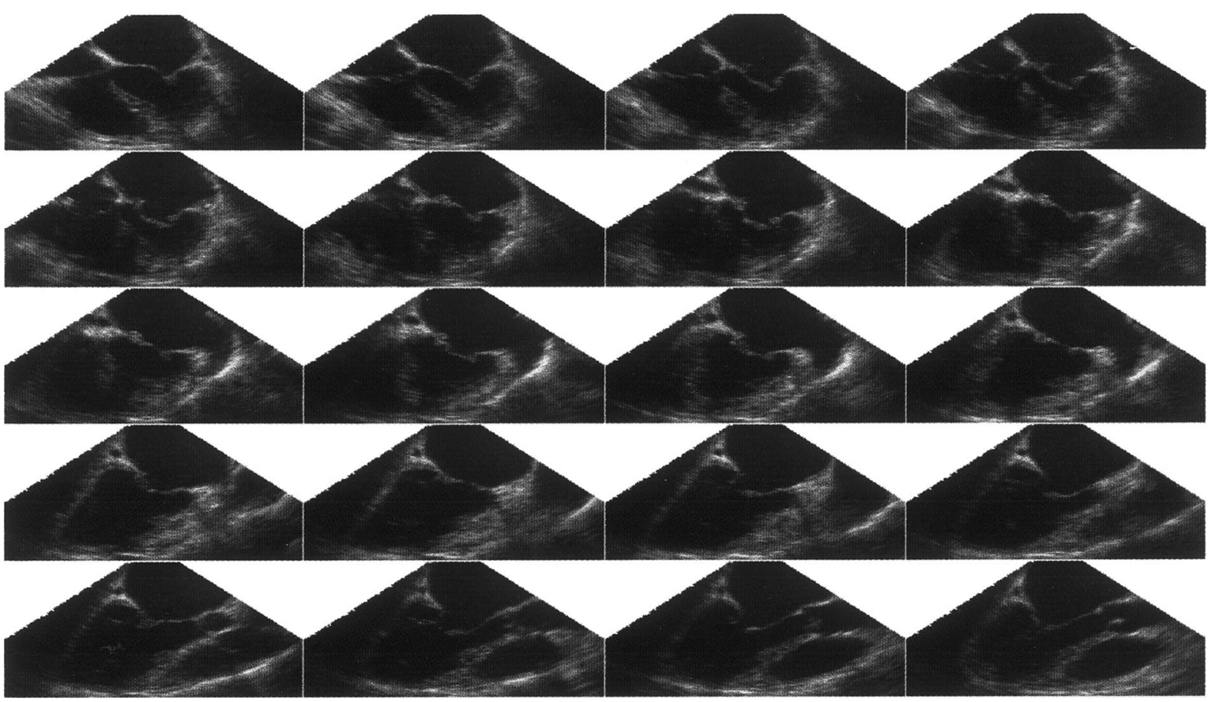

Fig. 4. Multiplane transesophageal echocardiography acquired in the rotational approach. From left to right and top to down, it shows the sequence of acquisition from 0 to 80° and with 4° for each frame.

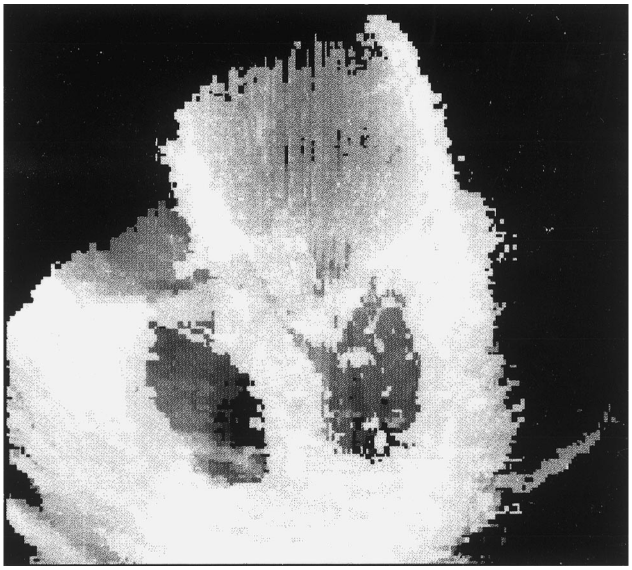

Fig. 5. Static 3D echocardiography with volume rendering and shading.

The system software was written in Microsoft Visual C++ version 5.0 programming language and MFC class library version 4.2 under Windows environment and ran on a personal computer with an Intel Pentium-166 CPU, 64 MB RAM on board, and 2.0 GB hard disk capacity. As the TEE images used were acquired in rotational approach from 0 to 180° with 2° increments, there were 91 frames for every time phase. Generally, the *R–R* interval was divided into 42 time frames, that is, there were 3822 frames generated in one examination. When considering the size and resolution of single frames of the echocardiographic images, the resultant data volume was more than 260 MB ($240 \times 240 \times 108 \times 42$), which was too large to store in the hard disk of the working system. An auxiliary CD-recorder was therefore connected to store the re-coordinated 3D cubic volume data and reduce the workload of the system storage device so that enough storage capacity could be reserved for other processes.

In Fig. 4 a series of TEE images acquired in the rotational approach are displayed as an example of 4D echocardiographic image reconstruction. From left to right and top to bottom, Fig. 4 shows the TEE images from 0 to 80° with a 4° increment for each image frame. These frames were chosen from the rotational image data set with 91 image frames. The original image data set underwent image re-coordination and concentric interpolation to generate 3D cubic volume data. All other functions were derived from the 3D cubic volume data. The reformatted 2D echocardiogram accompanied by the slice locator is shown in Fig. 2. From the sketch of slice locator, we can see the position of the reformatted 2D echocardiogram relative to the 3D cubic volume data. Fig. 5 shows the resultant 3D echocardiography reconstructed with the processes of volume rendering and shading. The resultant dynamic 4D echocardiographic images changing through the cardiac cycle are shown in Fig. 6.

As for execution time, to transform the rotating slices to cubic *z*-series slices with the system on the PC platform, it takes about 30 s with the smoothing process on the 3D cubic volume data and 25 s without. For reconstructing the 3D echocardiography for all time frames after the slice position and the threshold have been determined, the system should take only 6 min. That is, all processes needed to reconstruct the 4D echocardiography from the TEE image data set would take less than half an hour to complete.

6. Summary

By using transesophageal echocardiography (TEE), a 4D image data set can be obtained with ECG triggering and a rotating ultrasound transducer. According to the characteristics of the acquired data set, we developed an integrated system to perform 4D echocardiographic image reconstruction and display in this paper. This system provides several functions for 3D echocardiographic image reconstruction, 3D echocardiographic image reconstruction with time evolution (4D echocardiography), 2D echocardiogram reformation in any arbitrary cut plane, and other necessary processes for TEE images. The 2D, 3D and 4D echocardiography can be easily reconstructed within the integrated system running on inexpensive and commonly available hardware and software. Moreover, the results show the feasibility of the 4D echocardiographic image reconstruction system.

In reconstructing 3D or 4D images from 2D data, limitations are encountered at each stage of the process. In the stage of image acquisition, poor quality echocardiography affects the results of 4D image reconstruction most. During 3D image reconstruction, a threshold must be determined for volume rendering. Poor image quality always makes this determination difficult. In addition, motion of the patient may also complicate the process of image reconstruction. As the acquisition of TEE images is performed during multiple cardiac cycles, the results of echocardiography often deteriorate due to patient movement. This may cause the artifact of shifts in some slices within the 3D cubic volume data, and deform the resultant 3D/4D echocardiography.

Lack of a global positioning system for image acquisition is another problem of 3D image reconstruction in echocardiography. An in vivo or in vitro landmark is needed for the image alignment process when the series of images are acquired at different times. Artifacts caused by patient movement can also be corrected by using such a landmark. Therefore, an inexpensive and clinically feasible locator serving as a landmark would be an important auxiliary facility needed for TEE image acquisition in the future to make 3D/4D echocardiographic image reconstruction more precise and accurate.

In the stage of 3D reconstruction, the most intensive computations are performed during image re-coordination.

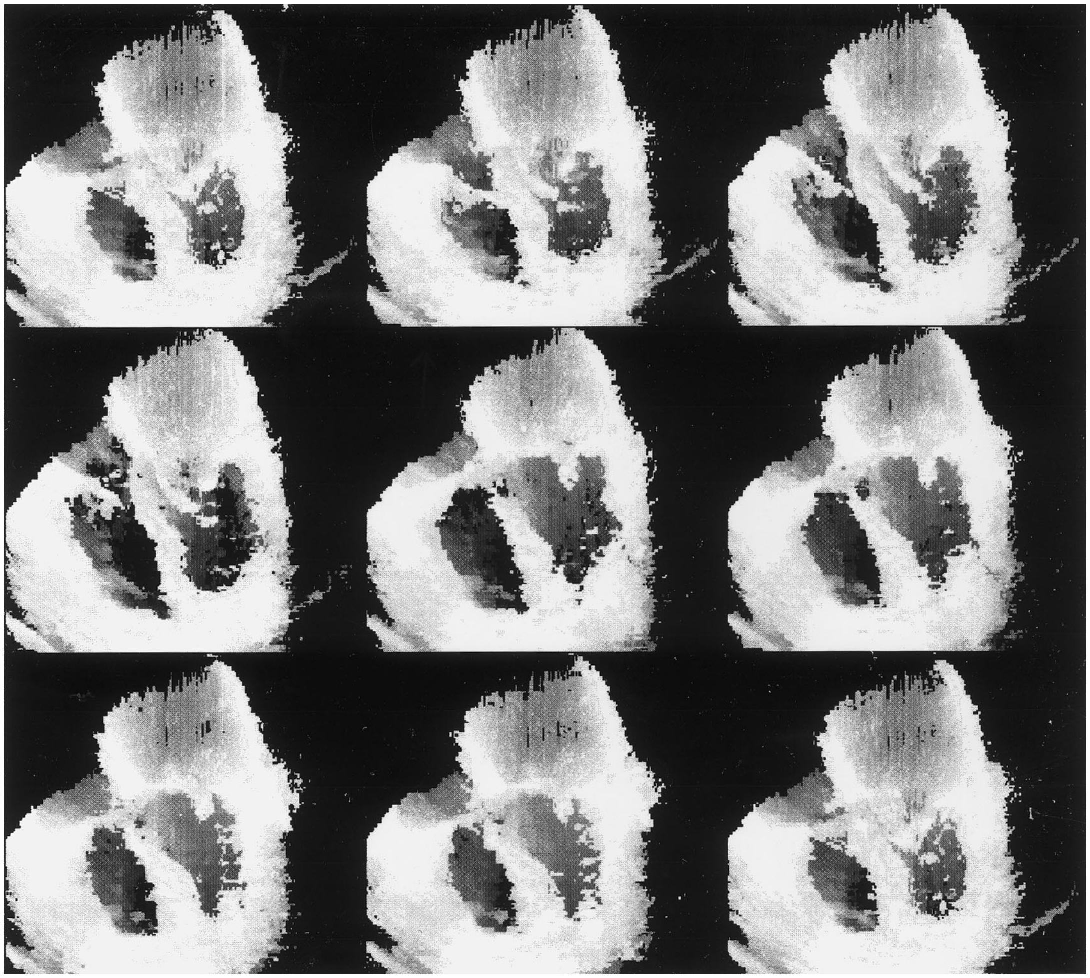

Fig. 6. Contiguous image frames extracted from the 4D echocardiography reconstructed by the developed system. The activity of the mitral valve can easily be observed in the dynamic 4D echocardiography.

It is very time-consuming to calculate the sine–cosine pair for converting a location represented by polar coordinating system (r, θ, z) to that represented by the Cartesian coordinating system (x, y, z). In order to reduce the computation time, some accelerating mechanism should be introduced. Considering the data structure of the TEE image data set and the transformation in Eq. (1), only the coordinates of r and θ (or x and y) are needed to convert the coordinate system within the same slice. That is, the data set is independent in the z-axis. Thus, the sine and cosine calculations for transforming the coordinated are estimated in advance and constructed as a looking-up-table. While the image re-coordinating process is performed, the complex calculation can be massively reduced. It can efficiently accelerate the 4D reconstruction as the image re-coordination is the bottleneck of the whole process. Besides, the interface between the computing hardware and the ultrasound imager is also included to transfer the rotating z-slice image data set directly to the auxiliary computing hardware. The purpose is to link the ultrasound imager with self-designed computing hardware and to generate output in the 3D cubic volumetric format which will make processing easier for further research work.

Acknowledgements

I wish to thank Dr Tsui-Lieh Hsu, Director of Echo Room, Department of Cardiology, Veterans General Hospital, Taipei, for having provided plenty of material to validate our system, and also to the anonymous reviewers, who give us the most helpful suggestion to revise our manuscripts. I also greatly appreciate Shan-Hui Hsu, PhD scholar in the Department of Chemical Engineering of National Chung Hsin University who revised this manuscript for us.

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