4D-ECHOCARDIOGRAPHIC SYSTEM FOR WALL MOTION AND CARDIAC PARAMETERS QUANTIFICATION

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Abstract *- We propose a system for 4D reconstruction, visualization, measurements and quantification of cardiac parameters. The system is connected with a conventional 2D ultrasound machine via video signal. Images are acquired and registered with electromagnetic position sensor readings and ECG signal readings. Volume reconstruction and volume visualization of the heart is done after acquisition. 4D cardiac parameters are calculated after segmentation of the desired cardiac ventricle such as left ventricle chamber. Cardiac parameters such as 3D surface area, 3D maximum area, 3D minimum area, 3D average volume and ejection fraction ratio are quantified along ECG cycles. Cardiac wall motion deformation measurements are quantified and color mapped to show the contractility of different wall segments which indicate cardiac abnormality.*

I. INTRODUCTION

3D Ultrasound systems proved its importance over 2D Ultrasound during the past decade in accurate volumetric measurements, visualization of abnormal structures or anatomy, and arbitrary image slicing. Event recognition for determining ischemia based on automatically detected left ventricular contour was investigated in [1]. 3D Dynamics Echocardiography workstation for the acquisition, reconstruction and visualization of 4D Images of the heart were designed and introduced for clinical implementation and is shown in details in [2]. Tracking the left ventricle in real time Echocardiographic images by learning heart dynamics were studied and reported in [3]. Three-Dimensional motion display of human heart using ultrasonic images was analyzed in the Master's Thesis of [4, 5]. Volumetric reconstruction and visualization in three-dimensional Echocardiography were investigated in vitro in [6]. Segmentation and VRML visualization of left ventricle images using 3D deformable models and superqudrics were done in [7]. Application of continuum theory and multi-grid methods to motion evaluation from 3D Echocardiography was introduced in [8]. Assessment of normal and ischaemic myocardium by quantitative M-MODE tissue Doppler imaging were done in [9] Registration of 3D Ultrasound images to surface models of the heart were introduced and discussed as in [10]. Model of Probe motion in transthoracic 3D-echocardiography for assessing the precision in left ventricular cavity volume measurement were presented in details as in [11]. Quantification of LV volumes with 4D real-time Echocardiography was obtained in [12]. Modeling, analysis, and visualization of left ventricle shape and motion by hierarchical decomposition were investigated [13]. Cross correlation for aligning 3D Ultrasound derived endocardial surface were computed and analyzed as in [14]. A prototype for 3D Ultrasound scanning and reconstruction based on mechanical and electromagnetic locators were designed and proposed in [15]. Three-dimensional Ultrasound echocardiography were introduced and described in [16]. In this paper we propose a system for 4D reconstruction, visualization, measurements, and quantification of cardiac parameters.

II. 4D ECHOCARDIOGRAPHIC SYSTEM DESCRIPTION

The system consists of 4 modules. The first one is the video grabber card (Matrox Meteor II) connected to the video-out port of the conventional 2D-ultrasound system and can acquires 25 fps for PAL format and 30 fps for NTSC format. The second one is the electromagnetic sensor which is a six-degree-of-freedom sensor mounted on the transducer to measure the position and orientation of the ultrasound transducer. The third one is the ECG trigger module that detects the R wave within the ECG cycle. The fourth one is a PC with 512 MB memory connected with the previous 3 modules. Figure 1 shows a block diagram for our proposed 4D Echocardiography system.

III. 4D ECHOCARDIOGRAPHIC SYSTEM DATA ACQUISITION

Three parallel threads were designed to simultaneously acquire images, locations, and ECG data.

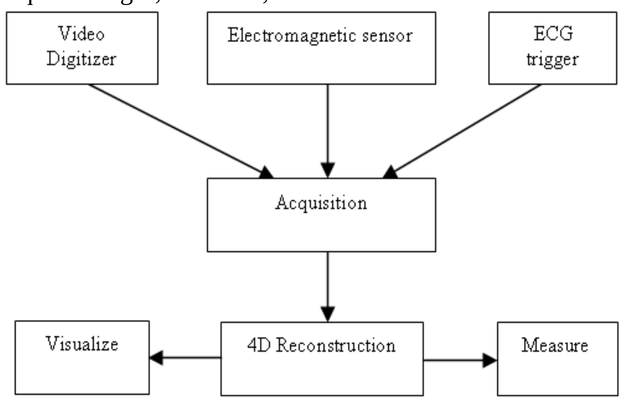

Figure 1
4D-Echocardiographic system block diagram.

Scanning duration depends on volume size, frame rate, and number of volumes. Frame rate was fixed to 25 fps even if the scanner shows higher frame rate (PAL video format limitation). Number of Volumes was also fixed to 12 Volumes per ECG cycle. A volume of 128^3 requires a minimum of 100 to 128 images to fill it. Scanning duration can be calculated as shown in (1).

$$T = \frac{NOV \times IPV}{FPS} \quad (1)$$

Where *NOV* is number of volumes, *IPV* is images per volume, and *FPS* is frames per second.

IV. 4D ECHOCARDIOGRAPHIC RECONSTRUCTION

After scanning, we have 3 arrays of images, locations, and ECG signals. Each image frame was associated with its location frame. R-R periods within the entire acquired ECG cycles were automatically detected [19]. Each period is then divided into 12 equal intervals each representing an individual volume. Each image frame was then associated with its corresponding volume. The 12 volumes were then reconstructed. Nearest neighbor interpolation was applied for each volume to fill the resulted gaps. Figure 2 shows images registration and reconstruction with ECG cycle for number of N 3D volumes.

V. 4D ECHOCARDIOGRAPHIC VISUALIZATION

The major benefits of 3D Ultrasound are its powerful tools used for visualization that help in better understanding of anatomy and diagnosis [16]. These tools are 3D rendering, rotation, cropping, arbitrary plane slicing, and image enhancement. Figure 3 shows one of the 12 rendered volumes.

VI. LEFT VENTRICLE SEGMENTATION

3D segmentation is performed on the volume of interest (VOI) for calculating volumetric measurements. Segmentation is done by 2 methods:

1. Manual segmentation

Rotational contours that define the border of the VOI were selected manually. Manual segmentation is fast and suitable in a case of noisy volume as in figure 4.

2. Semi-automatic segmentation

Gradient Vector Flow active contour model (GVF) [17] was used. Active contour model is suitable for well bounded and less noisy objects.

VII. 3D MEASUREMENTS

After segmentation of left ventricle (LV) for the whole number of volumes, 3D volume as given in (3) and 3D surface area as in (2) [16], were calculated as follows:

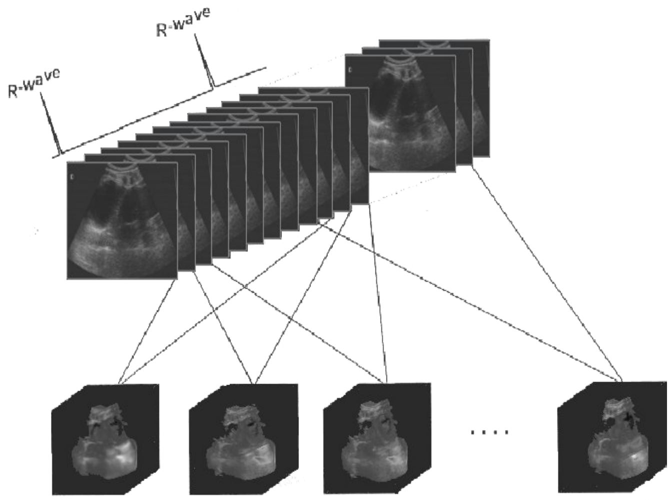

Figure 2
Images registration and reconstruction with ECG cycle.

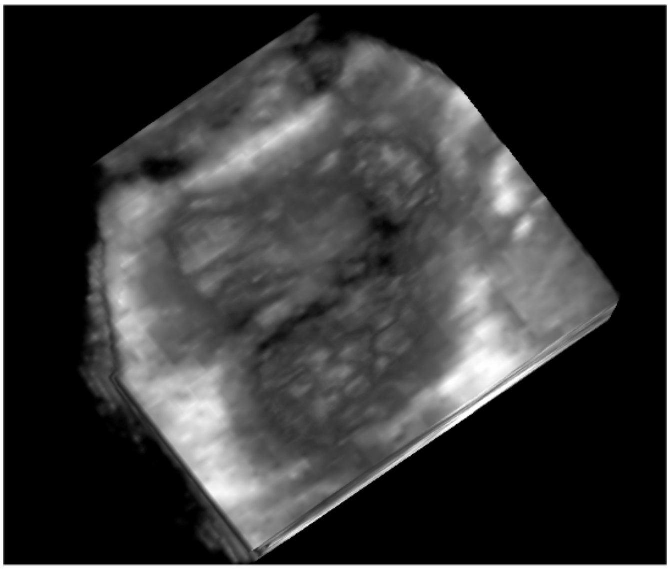

Figure 3
3D Visualization of a heart showing chambers and valves

1. Surface area Measurement

$$SurfaceArea = \sum_{j=0}^{C-1}\sum_{i=0}^{N-1}\left[\sqrt{(X_{i+1}-X_i)^2+(Y_{i+1}-Y_i)^2}\right]\times D \quad (2)$$

Where *C* is the number of contours, *N* is the number of points in the contour, *(X, Y)* is the coordinates of the point, and *D* is the distance between each contour.

2. Volume Measurement

Measuring the volume is calculated by summing the cross-section area of all contours and multiplying the result by the spacing between 2 successive contours.

$$Volume = \sum_{j=0}^{C-1}\sum_{i=0}^{N-1} A_i \times D,$$

$$A_i = \frac{1}{2}\times\left[(X_i Y_{i+1}) - (X_{i+1} Y_i)\right] \quad (3)$$

Where *C* is the number of contours, *N* is the number of points in the contour, *(X, Y)* is the coordinates of the point, *D* is the distance between each contour, and A is the cross-section area of contour.

VIII. 4D MEASUREMENTS

Four volumetric parameters were calculated. These parameters are maximum volume, minimum volume, average volume, and ejection fraction ratio. These parameters were calculated for each of the 12 volumes that represent the full ECG cycle. Figure 5 shows a graph for the volume versus time over the ECG cycle. Ejection flow ratio as one of the most important measurement parameter in cardiology was calculated as in (4).

$$EFR = \frac{Max.L.V.volume - Min.L.V.volume}{Max.L.V.volume} \times 100 \qquad (4)$$

Where *EFR* is the ejection fraction ratio.

IX. 4D CARDIAC DEFORMATION MEASUREMENTS

Another useful measurement for the cardiologist is the elasticity measurement of the cardiac muscles. It gives an indication of how healthy the cardiac muscle is. It is calculated by tracing the motion of the cardiac wall. It is the total distance covered by every part of the heart during one cycle. Free form deformation model was assumed. First the desired wall chamber is segmented is each volume and its contours were generated. The strain can be calculated by 2 methods: *Step Strain Method* or *Accumulated Strain Method.*

X. STEP STRAIN METHOD

Starting from the last volume in the heart cycle. step strain can be calculated by getting the minimum Euclidean distance between every point in the contour of the current volume and points within a mask of size (n x n) in the previous volume within the ECG cycle as in (5).

$$D = \sqrt{(X_t - X_{t-1})^2 + (Y_t - Y_{t-1})^2 + (Z_t - Z_{t-1})^2} \qquad (5)$$

Where *D* is the Euclidian distance between two points.

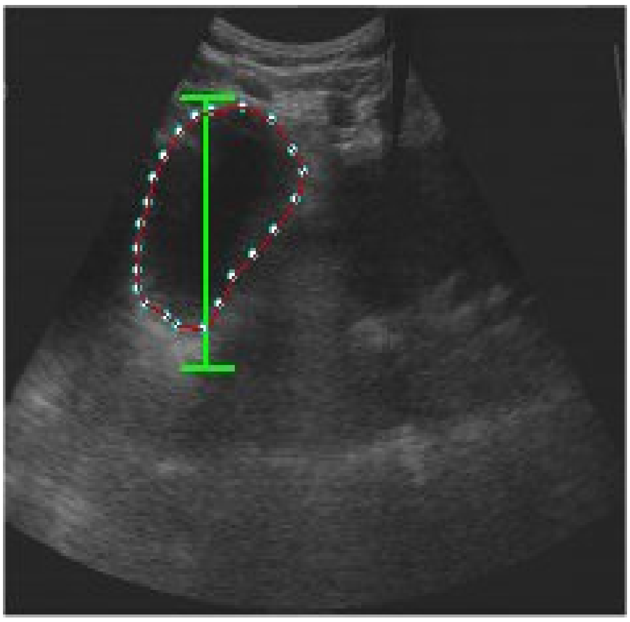

Figure 4
Contour drawn around an object.

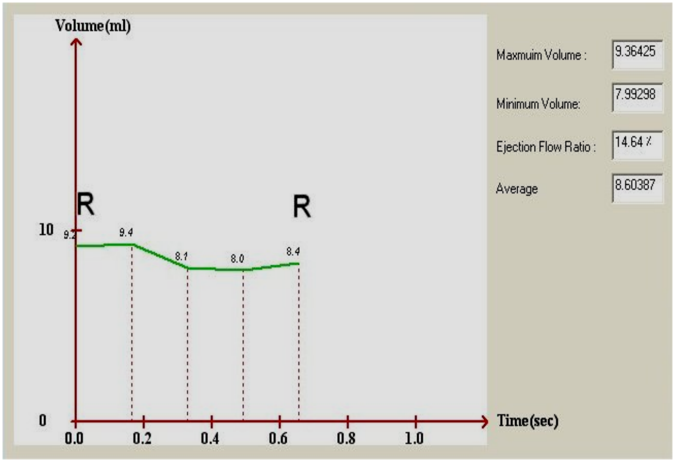

Figure 5
4D volume parameters measured during one ECG cycle.

This minimum distance is used as a code for this voxel. This minimum distance calculation process is repeated over all the volumes to get the associated code for all the voxels within each volume. Each voxel was then assigned a color code calculated as shown in (6).

$$Step = (Max. - Min.)/256$$

$$ColorCode = (Displacement - Min.)/Step \qquad (6)$$

Where Max. and Min. are the maximum and minimum displacement in all the points. Figure 6 shows a 4D deformation of the L.V. using step strain method. The image is color displayed where red color indicates regions of highest strain (motility) during the cardiac cycle. Yellow, green, and light blue colors indicate moderate strain while dark blue colors are those segments of wall chamber that have the least strain (motility) values. It is clear that the regions at the valves border have a higher strain during cardiac cycle.

XI. ACCUMULATED STRAIN METHOD

Accumulated stain can be calculated by getting the minimum Euclidean distance between each point in the contour of the current volume and points within a mask of size (n x n) in all the previous volumes within the ECG cycle the calculated distances for each point is then summed and used as a code for the voxel. Each voxel was then assigned a color code calculated as shown in (6). Figure 7 shows 4D deformation of the L.V. using accumulated strain method. The image is color displayed where yellow color indicates regions of highest strain (motility) during the cardiac cycle. Orange, red, and green colors indicate moderate strain while dark blue colors are those segments of wall chamber that have the lowest strain (motility). It is clear that the regions at the valves border have a higher strain during cardiac cycle.

XII. CONCLUSIONS

We proposed a system for 4D reconstruction, visualization, measurements and quantification of cardiac parameters. Volume reconstruction and volume visualization of the heart is done after acquisition. 4D

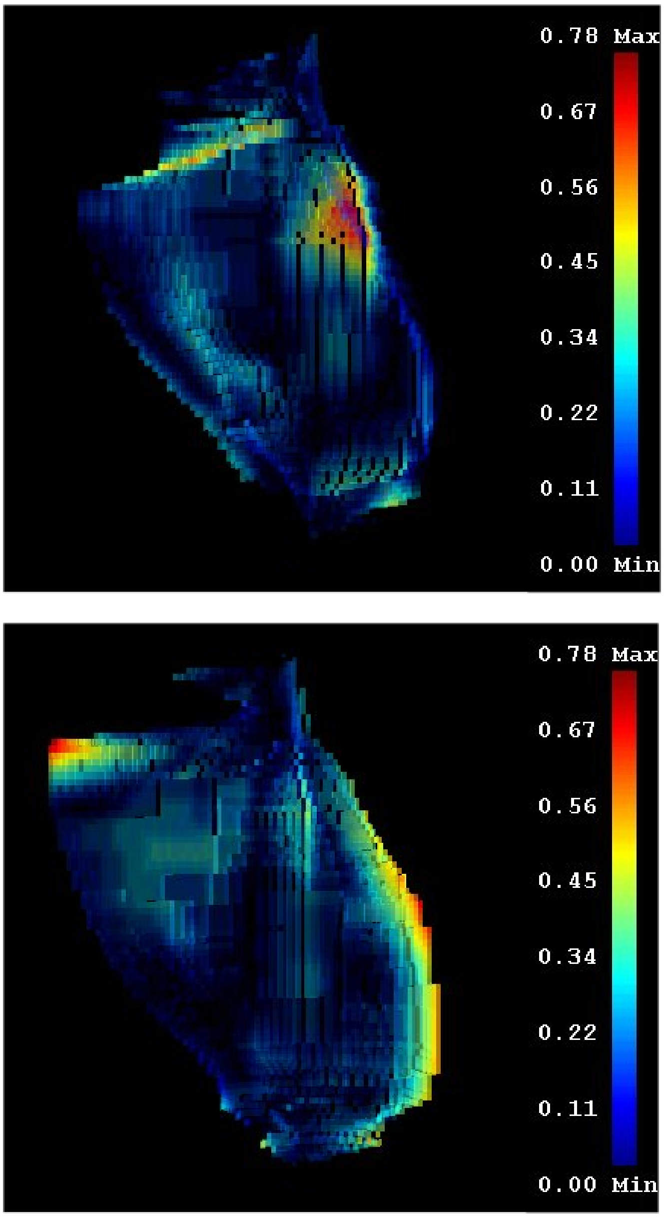

Figure 6
4D deformation of the L.V. using Step Strain Method

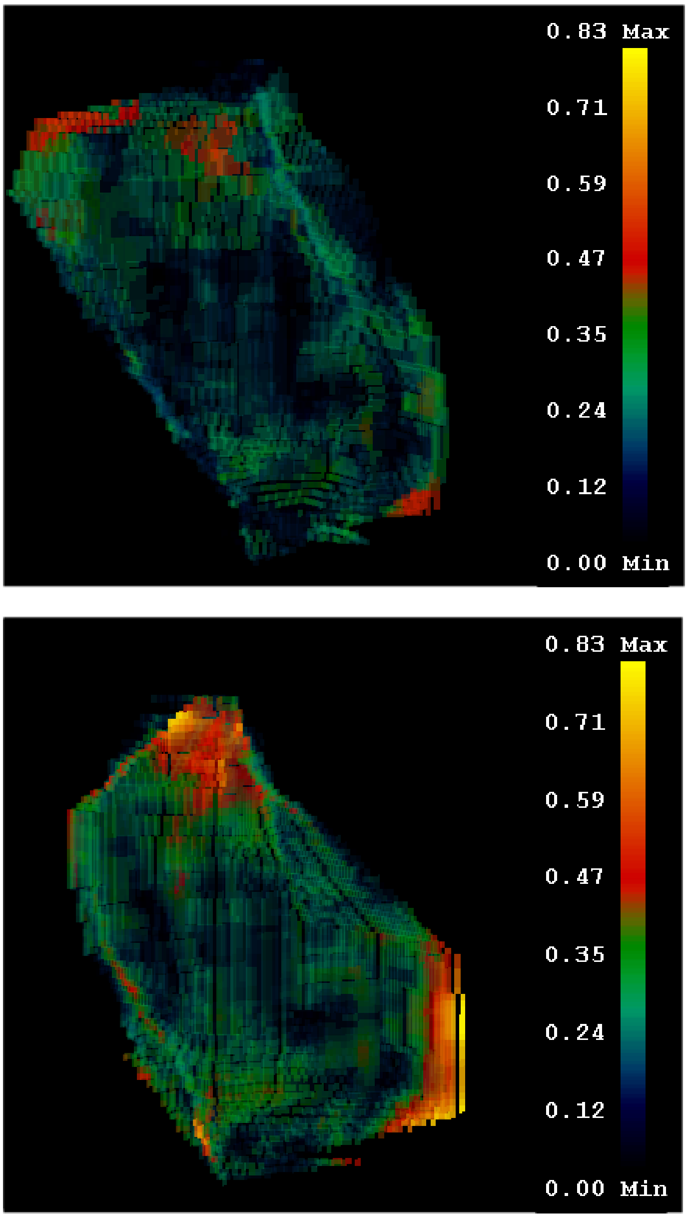

Figure 7
4D deformation of the L.V. using Accumulated Strain Method

cardiac parameters measurements were calculated after segmentation for the desired cardiac ventricle. Cardiac parameters such as 3D surface area, 3D maximum area, 3D minimum area, 3D average volume and ejection fraction ratio were quantified over ECG cycles. Cardiac wall motion deformation measurements were quantified and color mapped to show the contractility of different wall segments. The overall computation time for 4Dscanning, reconstruction, segmentation, visualization, cardiac parameters quantification for the 12 different volumes of size 128^3 was in the order of 10 minutes.

XIII. Future Work

Clinical investigation on large dataset is to be performed using the proposed system. Correlation of cardiac parameters with cardiac diseases is to be performed for the diagnosis of cardiac wall abnormalities.

XIV. Acknowledgments

The authors are acknowledged to Prof. Dr. Abou-Bakr M. Youssef and International Electronics Co., Biomedical Division for their partial support.

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