Fast Interactive Real-time Volume Rendering of Real-time Three-dimensional Echocardiography: an Implementation for Low-end Computers

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Abstract

Real-time three-dimensional echocardiography (RT3DE) is an innovative cardiac imaging modality. However, partly due to lack of user-friendly software, RT3DE has not been widely accepted as a clinical tool. The object of this study was to develop and implement a fast and interactive volume renderer of RT3DE datasets designed for a clinical environment where speed and simplicity are no secondary factor to accuracy. Thirty-six patients (20 regurgitation, 8 normal, 8 cardiomyopathy) were imaged using RT3DE. Using our newly developed software, all 3D data sets were rendered in real-time throughout the cardiac cycle and assessment of cardiac function and pathology was performed for each case. The real-time interactive volume visualization system is user friendly and instantly provides consistent and reliable 3D images without expensive workstations or dedicated hardware. We believe that this novel tool can be used clinically for dynamic visualization of cardiac anatomy.

1. Introduction

Real-time three-dimensional echocardiography (RT3DE) is an innovative modality for imaging the heart in 3D space. Since it was first introduced, the usage RT3DE in clinical procedures has increased.

3DRTE has several advantages over other imaging modality such as conventional echocardiography (2DE) and Magnetic Resonance Imaging (MRI). The capability of displaying 3D images without respiratory-gated acquisition or post-acquisition elaboration renders RT3DE the ideal method for capturing all the heart's complexities in one view[1]. The possibility to evaluate the real geometry of cardiac structures removes limitations of 2D ultrasound in the assessment of cardiac function; because it is possible to visualize the imaged heart during the acquisition, RT3DE has and edge over MRI.

Intensive computational power is generally required to visualize RT3DE data. For this reason, review of RT3DE is possible by utilizing dedicated hardware such as the commercial RT3DE system, or expensive workstations. The availability of these resources in a clinical environment is limited because of their high cost of acquisition and/or maintenance, and it represents a bottleneck for the broad clinical acceptance of this innovative modality. Even though we acknowledge that computational power of processing units is exponentially increasing with an overall reduction of costs, we belief that the user-friendly visualization of RT3DE on low-end PC will contribute to dramatically spread diagnostic usage of RT3DE.

The aim of this study is to apply advanced and fast visualization and rendering computer technique in order to provide highly optimized software that pushes the actual PC hardware architecture and visualizes volumetric data on conventional computers for diagnostic purposes.

2. Methods

2.1. Population

The population for this study consisted of thirty-six (36) subjects whose heart was both in physiologic (n=8) and pathologic (n=28) condition. Pathologies of selected cases included mitral regurgitation (MR, n=20) and hypertrophic obstructive cardiomyopathy (HOCM, n=8). This study included cases where the visualization of structures not completely visible in a single planar section had a relevant role in the qualification and quantification of dysfunctions. Physiologic cases played the role of reference in the evaluation of dysfunctions by using the volume rendering.

2.2. RT3DE

For the acquisition, we employed a real-time 3D echocardiograph by Volumetrics with a 3.5 MHz transducer [13]. Volumetric data is available as samples distributed uniformly in the (ρ,θ,φ) coordinate system. Each sample is addressed by a triple of integers and represent the brightness of the anisotropic sub-volume, known in literature as voxel[7].

All subjects were imaged by RT3DE. 3D data was

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analyzed by using software designed in our lab. Initially two orthogonal B-Planes are displayed. The user can sweep each plane throughout the acquired volume. One B-plane shows original data from RT3DE system and works as guideline. Taking it as reference, adjacent B-planes, orthogonal to the former, have been selected outlining the volume of interest. Then, original dataset was filtered in order to eliminate noise contained in the cavities that would obstruct visualization of anatomic structures. By using a lighting model, filtered data has been rendered in real-time in three-dimensional space.

The user could interactively change point of view and the position of the light source in order to be able too see the part of interest from a desired perspective and to enhance contrast in the visualization of specific details [7][9].

2.3. Volume rendering

The selected volume is subdivided into several two-dimensional slides. The volumetric visualization of the selected data is obtained superimposing and shading the two-dimensional slides. The slides are compounded by a grid of points. Each point of the slide, determined in the (x,y,z) coordinate system, has a gray shade. The brightness of shade of gray is proportional to the intensity of the echo signal received from that point, and is obtained applying the reconstruction formula. A transparency index Ti is assigned to each point, as well. Transparency of each point enables us to see through voxels that are not representative of cardiac structures (Ti=0) and renders cardiac structure opaque (Ti=1). Each slide is drawn following a back-to-front order. This means that the farthest slide is drawn first and each transparent point will leave preciously drawn voxels visible to the observer; opaque points, by contrast, will completely cover previously rendered points.

The technique described above can render and shade a three-dimensional scene taking full advantage of power available in any hardware 3D accelerated video card. In fact, it is possible to add a semi-transparent object to a previously rendered scene by simply blending the previous scene with the new rendered object. Blending is controlled by a blending function that describes how the added object will blend with the previously drawn scene. This process is sensitive to the order used to draw objects. Thus, to obtain the correct visual effect, this implementation sorts the 2D slides and draws transparent object from back to front [11][13].

2.3.1 Scan conversion and reconstruction

Extraction of each 2D slice of the volume is obtained by reconstructing the echocardiographic signal in the (x,y,z) coordinate system from samples in the (ρ,θ,φ) coordinate system. Any signal that has been sampled following Shannon's theorem can be exactly reconstructed from its samples [5].

A continuous function f(t): $R \rightarrow R$ is completely defined by its samples if the distance between two adjacent samples is $t_s=1/f_s$; where f_s is the Nyquist frequency[3][4][5]

In fact, if x(k) are samples of f(t) every 1\fs, hypothesizing that the sampling theorem has been satisfied, then

$$f(t)=\sum_{k=-\infty}^{k=+\infty} x(k)\operatorname{sinc}(t * fs-k)$$

where:

$$\operatorname{sinc}(x)=\frac{\sin(\pi x)}{\pi x};$$

Extending this formula to a three-dimensional domain, it is possible to reconstruct the continuous function $f(\rho_c,\vartheta_c,\varphi_c):R^3 \rightarrow R)$ from RT3DE samples $x(k_1,k_2,k_3)$ in the (ρ,θ,φ) coordinate system by using the following formula:

$$f(\rho_c,\vartheta_c,\varphi_c)=\sum_{k=-\infty}^{k=+\infty}\sum_{k=-\infty}^{k=+\infty}\sum_{k=-\infty}^{k=+\infty} x(k_1,k_2,k_3)\cdot \operatorname{sinc}(\rho_c \cdot fs_1-k_1)\cdot$$
$$\cdot \operatorname{sinc}(\rho_c \cdot fs_2-k_2)\cdot$$
$$\cdot \operatorname{sinc}(\rho_c \cdot fs_3-k_3);$$

where f_{s1},f_{s2},f_{s3} are sampling frequencies in (ρ,θ,φ) coordinate system.

By using a scan-conversion formula, it is possible to obtain a triple $(\rho_c,\vartheta_c,\varphi_c)$ given any triple (x,y,z). The above-described reconstruction function has been used to retrieve the brightness from samples.

The bandwidth-limited interpolation has given superior results in image brightness and contrast (Figure 1) over tri-linear interpolation.

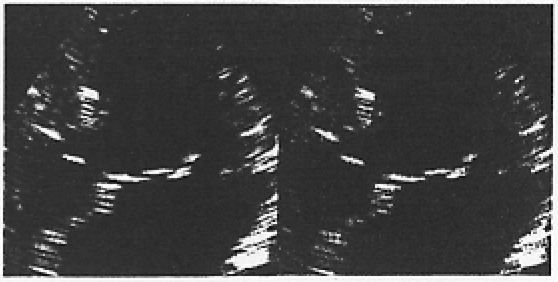

Figure 1: Comparison between tri-linear interpolation from samples (right) and band-limited reconstruction (left).

2.3.2 Noise removal

RT3DE has a lower ratio signal-to-noise ratio compared to conventional 2D echo. For this reason, particular attention must be paid to noise. In our specific study, noise contained in the cavities would obstruct the vision of inner cardiac structures. To prevent this phenomenon we adopted a special filter. The function of this filter is to render noise semi-transparent rather than removing it completely. This is to prevent that low intensity signal associated to fast moving or thin anatomies, such as valve leaflets is cut off, as well. An added function of this filter is to assure that the correct opacity is assigned to samples (Figure 2).

The following equation describes the function that our volume rendering employs to assign transparency index to a given point (x,y,z) in three-dimensional space.

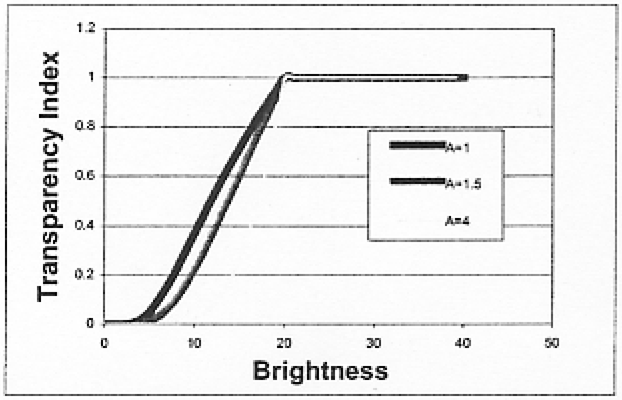

Figure 2: Examples of mapping transparency to brightness with different parameters (trigger value = 20, A=1, 1.5, 4).

If P(x,y,z) is point in (x,y,z) coordinate system and f_p is the value of the reconstructed function, which represents the brightness, calculated in P(x,y,z), the assigned transparency index $T_i(f_p)$ is:

$$T_i(f_p) = \min\left\{\exp(A \cdot \frac{f_p - Tv}{f_p});1\right\}$$

where Tv is the trigger value; brightness higher than the trigger value is rendered opaque. The parameter A says how fast will the signal get transparent as its brightness approaches the zero value (Figure 2).

3. Results

All patient data was reviewed using our custom-made software. It was easy to identify and quantify cardiac pathologies. Particular attention was paid to visualize cardiac structures that are not visible in one plane such as mitral valve leaflets (Figures 3-5) and papillary muscles. Only several seconds were necessary to visualize patient data on a 400 MHz computer with 128 MB RAM.

Figure 3: Mitral valve during diastole displayed in the volume renderer

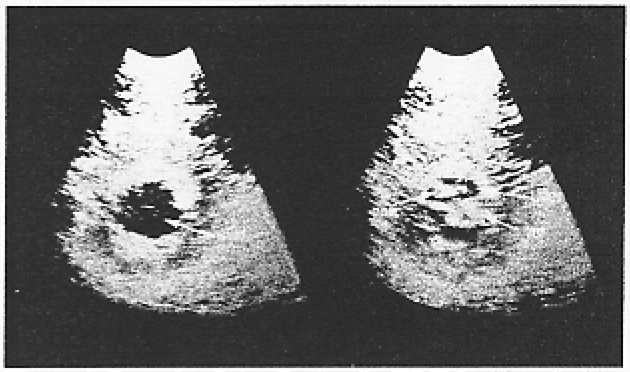

Figure 4: Example of visualization for HOCM subject: looking from the ventricle, mitral valve (MV) is open during diastole (left) and closed during systole (right). Narrowed left ventricular outflow tract due to the systolic anterior motion (SAM) of mitral leaflets is clearly visible (right).

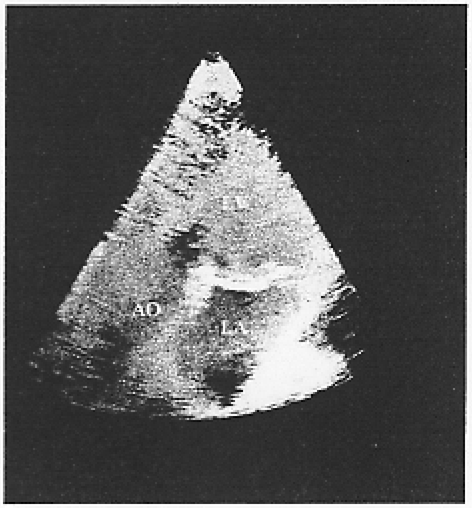

Figure 5: Volume rendering of mitral valve prolapse at end-diastole

4. Discussion

This paper illustrates the implementation of technique that enables low-end computers to provide, in real-time, reliable and consistent volume rendering of three-dimensional echocardiographic data. The innovation presented here is the optimized code that enables us to implement scan conversion, bandwidth-limited interpolation and noise removal in real-time. Image quality is dramatically improved by the bandwidth-limited interpolation that we implemented. Furthermore, real-time computation enables our volume rendering system to work directly with not-scan-converted files. This allows us not only to save time but also to efficiently use storage space on the computer as raw-data files occupy less media space than scan-converted ones. This implementation of volume rendering for low-end PC reached an excellent compromise between speed and quality of rendering. Even with noisy RT3DE dataset our system was able to feasibly provide quick three-dimensional views of the imaged hearts employing low-end computers which are commercially available for less than 300US$.

5. Conclusion

By enabling low-end computers to immediately display RT3DE data through a user-friendly interface, our real-time volume visualization system introduces a low-cost tool to be clinically used for dynamic visualization of complex anatomies of human heart. This technology may broaden utilization of computers for clinical purposes in cardiology; furthermore, it might widen clinical acceptance of RT3DE by addressing limitations due to the high cost of workstations and long elaboration time.

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