Real-Time Sonography Simulation for Medical Training

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Abstract — With the increasing role played by ultrasound in clinical diagnostics, ultrasound training in medical education has been becoming very important. The clinical routine is for ultrasound to be trained on real patients; therefore, monitored and guided examinations involving medical students are quite time constrained. To be realistically effective, a computerized ultrasound simulation would provide ample time and opportunity for sonograph training. We have investigated a real time ultrasound simulation methodology based on 3-dimentional (3-D) mesh model of the organ. A virtual echocardiogram displays various sonograph orientation in real time according to the placement of a virtual transducer without the need of an actual patient.

Keyword — Biomedical imaging, ultrasound simulation, image synthesis, medical training.

I. INTRODUCTION

Ultrasound has become a very useful diagnostic tool in almost every medical field after it was introduced in the late 1950's. Ultrasound beams scan the region of interest on the human body in thin slices and are reflected back into a continuous 2-dimensional (2-D) picture of medical structures on a monitor screen. The information obtained from different reflections is recomposed into a sequence of pictures and shows the dynamic motion of human organs.

Although ultrasound plays an important role in clinical diagnostics, there are still some major drawbacks associated with this technique for medical training. The clinical routine is for ultrasound to be trained on real patients; therefore monitored and guided examinations involving medical students are quite time constrained. Köhn's [1] research shows, after completing one-year training course, students will still have seen only up to 80 % of the possible findings. Consequently, sub-optimally trained medical personnel currently in every day clinical practice is asked to diagnose ultrasound images without appropriate ultrasound training. Therefore, computerized education without real symptomatic patients in ultrasound training will become particularly important especially with the increasing role played by sonography.

Furthermore, Standardized Patients (SPs), individuals trained to realistically portray patients, are commonly used in medical school to teach and assess medical students in three areas: communicating with a patient, eliciting patient history, and performing the physical exam. To become clinically competent physicians, medical students must develop knowledge and skills in both the art and science of medicine in their early clinical training. Working with SPs provides students the opportunity to learn these and other clinical skills in a safe setting. SPs also provide a way to reliably test students' clinical skills in a realistic setting by interacting with a person. The range of clinical problems that an SP can portray, however, is limited. They are typically healthy individuals with few or no abnormal findings. For these reasons, we have developed a prototype based on augmented reality to expand the abnormality that a SP could perform. As the role of ultrasound in clinical diagnostics has increased, using ultrasound simulation technology to augment healthy SPs is the other emergent issue for this research.

We have investigated and developed a real-time sonography simulation methodology based on virtual 3-D mesh model. Our approach is to use a 3-D model slicing technique to generate structure with dynamic motion and combine with an ultrasound pattern simulation technique [2] to translate structure into gray-scale representations of sonography. Our research on sonography simulation has shown promising results. A virtual echocardiogram based on this technology displays an infinite variety of oriented sonography views in real time according to the placement of a virtual transducer. This virtual echocardiogram totally avoids the need for an actual patient. It provides immediate and unlimited use for critical ultrasound training by showing both common and rare pathologies.

In this paper, we will detail the overall methodology, present its first prototype application—the virtual echocardiogram. Finally, we describe our validation experiments and report the results.

II. RELATED WORK

Current research in ultrasound simulation relies on reproducing videos of real patient data such as from CT volumes [3][4][5] and ultrasound images [6] and others focus on still ultrasound B-scan image simulation [2] [7]. The problem with these research are that video reproducing represents limited real situations due to finite amount of data in each case, and furthermore, constructing real patient data volume like CT volume and ultrasound volume needs lots of pre-processing work. On the other hand still ultrasound image simulation does not provide any of dynamic motion of internal organs, which is very important information for diagnosing pathologies.

The core of ultrasound simulation is the capability to generate image frames in real-time that resemble the movement of the organ during sonography. Real-time imaging means a frame rate of at least 12 Hz to reach a relatively smooth video, 30 Hz is optimal. Song's research [8] is a good approach for simulating the physical mechanism of the ultrasound apparatus; however this method does not provide a real-time effect due to the computationally expensive procedures of incorporating effects of reflection, scattering and attenuation. It would be extremely difficult to produce the very characteristic ultrasound imaging in real-time.

A simple and apparently effective alternative is to slice a 2D anatomical plane from a 3D model of the organ, then synthesize it into the ultrasound image. We have developed a real-time sonography simulator using computer generated 3-D mesh model. In this paper, we describe the unique simulation methodology and the development of an echocardiogram simulator.

III. Methods

The main research issue for ultrasound simulation based on a virtual 3D model is how to form a simulated ultrasound image in real time so that smooth sonography can be produced for training purposes. Our target is to use this technique on Standardized Patients so that medical students can learn how to use ultrasound to diagnose abnormal conditions on these healthy adult actors. However, this technique obviously has applicability as a stand-alone training device. In this research we focus on investigating a real-time dynamic ultrasound simulation methodology using virtual 3-D mesh organs. The overall method is able to produce dynamic ultrasound for the purpose of medical training and assessment.

The simulation consists in following steps:

1. Virtual 3D Organ Model Creation
2. 2D Anatomical Image Generation
3. Ultrasound Image Synthesis
4. Dynamic Ultrasound Production

Figure 1 shows the process that follows to carry out the construction of dynamic ultrasound and the method is described as follows:

First, the 3-D model is sliced to generate a 2-D anatomical image. The intent is to generate a slice according to the orientation of a transducer held by a trainee. Subsequently, a pre-computed artificial ultrasound texture is mapped to the anatomical image within the boundaries of the tissue structure, and then the image is combined with model noise to synthesize the sonograph. In the last procedure, 12 anatomical image frames showing different motions are sliced within one animation cycle, and then processed into the ultrasound images. In the mean time, the slices are refreshed inside computer memory to build a dynamic ultrasound. Our display rate is approximately 24 frames per second.

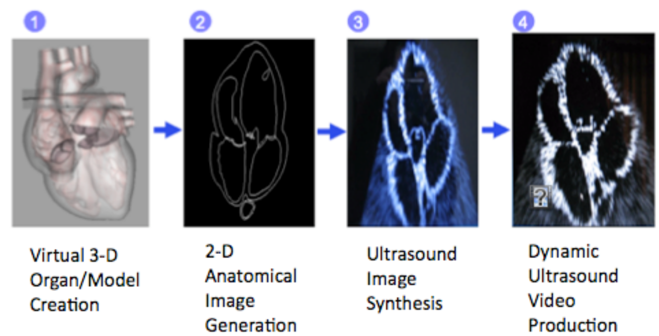

Fig. 1 Ultrasound Simulation Method

The simulation method is intended to benefit sonography training. Figure 2 shows the system diagram.

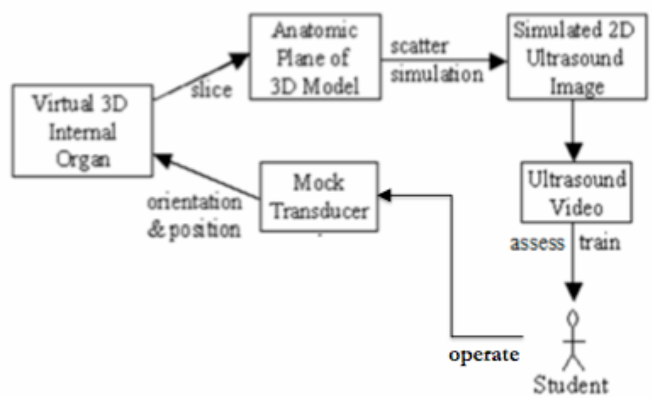

Fig. 2. Ultrasound simulation system diagram

To ensure the accuracy of the simulation, a computer generated 3-D mesh model of a heart is developed based on the structure of real human heart. The corresponding organ motion, heart pumping is also animated in the virtual environment. Many virtual 3-D organs, such as the heart model we used in the research, are already used in medical school to demonstrate human anatomy. Unlike simulations based on real patient data [2][3][4][5][6][7][8], virtual 3-D organs can provide the textbook pathology case with accurate internal structures; also it offers an easier motion simulation environment than 2-D images [2], therefore, accurate motion simulation of 3-D organs can be achieved with the guidance of medical practitioners; and comparing with other 3-D models such as CT volumes, virtual 3-D model requires much less pre-processing work. This uniqueness allows us to overcome the shortcomings of current ultrasound simulations for realistic real-time application.

We have utilized three major algorithms to accomplish the real-time requirement, which includes a clipping algorithm, texture mapping algorithm and sonography texture simulation algorithm. We will detail these three algorithms in the following sections:

A. Clipping Algorithm

A virtual 3-D model is generally constructed into external and internal surfaces using a polygonal mesh structure. To be able to generate the anatomic plane image of the 3-D model analogous to the plane of the transducer in real time, we have utilized a highly efficient clipping algorithm. The algorithm slices the 3-D model and calculates clipped lines between each polygon and the plane of interest. Then, all the intersected lines are drawn to construct the 2-D anatomic plane image.

To calculate the clipping line between a polygon and the plane of interest, the algorithm uses E_1, E_2, and E_3 to identify three edges (segments) of each polygon (triangle). Each edge is tested to see if it is intersected with the plane. To test if an edge is intersected with a plane, we use an algorithm that calculates clipping points by solving simultaneous equations [10]. Then the clipped segments are stored and drawn. The pseudo code of this clipping line algorithm against a polygon and a plane is showed below:

```
PL = plane of interest;
Se = Segment;
Se.P1 =  start point; Se.P2 = end point;
If (E1 interact with PL ) {
      Record the intersection Point P1;
      If (E2 interact with PL )
         Record the intersection Point P2
      Else if (E3 interact with PL )
        Record the intersection Point P2
}
Else { if (E2 interact with PL )
             Record the intersection Point P1
        if (E3 interact with PL )
             Record the intersection Point P2
     }
     Se.P1 = P1; Se.P2 = P2;
     Draw Se;
     If ((E1 lies on PL )
             Draw E1;
     If ((E2 lies on PL )
             Draw E2;
     If ((E3 lies on PL )
             Draw E3;
```

Using the clipping line algorithm described above, we go through each polygon in the 3-D heart model to generate the anatomical image. The result of applying our algorithm to the 3-D heart model at a four-chamber long axis view is shown in figure 3.

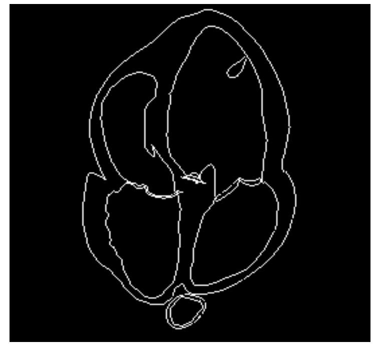

Fig. 3 Anatomic Plane Image using Clipping Algorithm

The overall method generates non-degenerate polygons and demonstrates the real-time effect.

B. Sonography Texture Simulation Algorithm

We synthesized the ultrasound texture in this research using the method proposed by Bamber and Dickinson [2]. In their method, an image is described as (1):

$$I(x,y) = H(x,y) \otimes T(x,y) \qquad (1)$$

where H is a point spread function (PSF), and T is a continuous distribution function of point scatters. For obtaining the value of T, the impulse response of the tissue or object, a Fourier domain synthesis of the tissue model, which permits convenient specification of some statistical properties of a randomly inhomogeneous scattering medium [7], is designed and given by (2):

$$T(x,y) = \nabla^2 \beta(x,y) \qquad (2)$$

where ∇^2 represents the Laplacian operator (the sum of all the unmixed second partial derivatives), and β is the compressibility of tissue. Then the spatially isotropic structures of the tissues are given by a relatively simple form [7]:

$$N(R) = e^{-\frac{R^2}{a^2}} \qquad (3)$$

R is a scalar quantity, and represents x^2+y^2 and a is correlation length. Its Fourier transform is calculated as:

$$G(s) = \pi a^2 e^{-\pi^2 a^2 s^2} \qquad (4)$$

where s is spatial frequency ($s^2 = s_x^2+s_y^2$). The task now becomes that of synthesising a random distribution whose power spectrum is *G(s)*. This can be done by defining the spatial frequency spectrum $\Gamma(s_x, s_y)$ of the compressibility matrix, $\beta(s_x, s_y)$, in terms of a magnitude spectrum $M(s_x, s_y)$ and a phase spectrum $P(s_x, s_y)$, i.e.

$$\Gamma = M\cos P + iM\sin P \qquad (5)$$

The magnitude spectrum acts as an isotropic weighting function, given by $(G(s))^{1/2}$, which is combined with random phases, $P(s_x, s_y)$, according to (5).

Based on the above equations, we computed the impulse response of synthesized tissue structures, T, using MatLab, in which the correlation length, *a,* is set to 2 for the best realistic result. Figure 4 shows one of the examples that we computed, which is enlarged to demonstrate the tissue structure. This part of the computation is an off-line process.

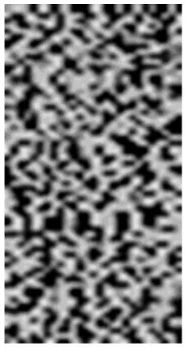

Fig. 4. Impulse response of synthesized tissue structures texture

Fig. 5. Applied and blurred artificial ultrasound texture

The PSF spreads each individual synthesized tissue pixel in order to produce the texture with blurring effects in the ultrasound image. In our simulation, the impulse response texture (Figure 4) is directly filled into the 2-D anatomical image, and the blurring effect is added in our real-time simulation using OpenGL. After applying the synthesized tissue structures, our simulation generates the artificial ultrasound pattern, showed in Figure 5. Figure 5 is enlarged to demonstrate the tissue structure.

Following equation 4, we are able to synthesize various tissue densities (compressibility) by adjusting the correlation length. However, in our simulation only one type of tissue compressibility (β) is utilized. H is applied to the heart tissue, including the arteries and chamber walls.

C. Texture Mapping Algorithm

In order to fill the artificial ultrasound texture into the tissue area of the anatomical image, a texture-mapping algorithm is developed. The core component of this mapping method is based on a basic scan-fill algorithm [10].

The 3-D heart model is constructed by two surfaces including the internal and external walls, so the gap between these two walls represents the tissues of the heart. Rays are generated vertically and go through the anatomical image. The intersected points split the ray into several segments. Employing the odd/even parity concept, the basic concept of the scan-line algorithm is to draw points from edges of odd parity to even parity on each scan-line. Moreover, knowing the property (representation) of the components (the lines) in the anatomical plane image , the computer can easily exclude exceptional cases by checking if the segment lies inside the tissue area. The segment inside the tissue will be drawn with the simulated texture and others are kept un-textured as figure 6 shows. The algorithm of the texture mapping method is illustrated in figure 7.

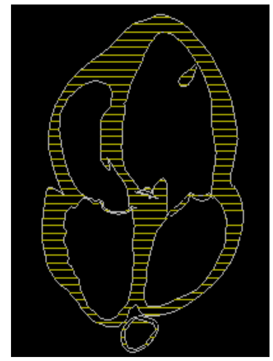

Fig. 6. Texture mapping method

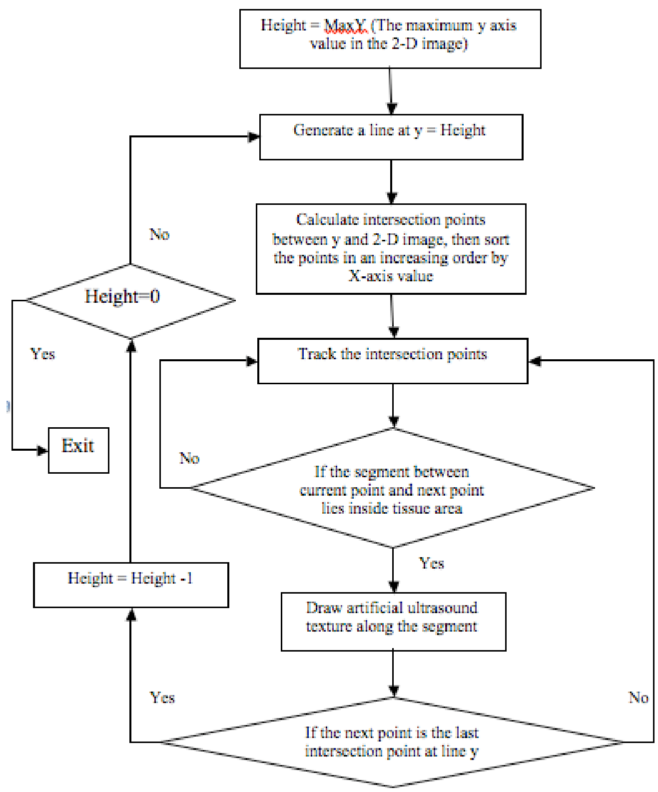

Fig. 7. Algorithm of texture filling method

To check if the segments lie inside the tissue area of the anatomical image, we need to know the representation of the lines (used to construct 2-D image) that are computed from the clipping algorithm. The 3-D heart model includes internal surfaces of left and right ventricles, left and right atriums, tricuspid valve, pulmonic valve, mitral valve and aortic valve and the external surfaces of these eight anatomic parts. Correspondingly, each polygon is identified by one of these components. When the interaction lines were computed from the clipping algorithm, the algorithm records the anatomic representation with the lines intersecting the 3-D model. Then when the ray traces the sliced 2-D image, the intersection points inherit the representation of the polygon that the ray interacted with. Therefore, we are able to tell whether a segment lies inside tissue or heart chamber by checking the representation of its two end-points. For example, if the initial point of a segment is an external surface and the destination point is internal surface, the segment has a good chance to be inside the tissue; if both end-points of a segment are an internal surface, it is most likely to lie inside the chambers. Furthermore, based on the odd/even parity concept of the scan-line fill algorithm [10], odd segments fall into the tissue area, while the even segments lie inside the chambers.

Based on above information, firstly, the textures are drawn along the odd segments, and then the representation of two end-points is used to filter the exceptions. Also, the same texture coordinate is applied to the even segments with different length. This may cause a single pixel on the screen corresponding to anything from a tiny portion of a texel (magnification) to a large collection of texels (minification). Thus, the texture will be blurred, which makes our artificial ultrasound pattern more realistic. So far, our filling algorithm cannot discern edges that overlap other edges. Further research is needed on this tissue.

In the last step, the simulated ultrasound image is finalized with background noise representing the scatters of blood and other tissue, which is randomly added for enhanced realism.

IV. Echocardiogram Simulator

This real-time ultrasound simulation methodology is intended to apply to an ultrasound simulator for medical training and assessment. We built two versions of the simulator to utilize the overall simulation methodology.

The first simulator is virtual environment-based. It works as follows: First, a 3-D virtual heart and a virtual transducer are loaded into a window screen and then the user is able to manipulate the position and orientation of the transducer in 3-D using a keyboard. As the orientation of the transducer is updated, the corresponding sonography in this orientation is generated and displayed. Figure 8 is one of these virtual echocardiogram scenes.

Fig. 8. Virtual Echocardiogram

This system will help students to improve their sonography reading skills based on the heart anatomy. Additionally, the system may be configured to be used with SPs for medical assessment.

The second simulation system is tracker-based. This Echocardiogram Simulator is constructed by a computer, a magnetic tracker and a non-functional transducer as shown in Figure 9. The magnetic tracker we used is the 3SPACE FASTRAK from POLHEMUS and the tracked Application Programmer's Interface (API) from VRCO® is used as the PC interface to obtain real time 6 DoF updates of position (X, Y, and Z Cartesian coordinates) and orientation (azimuth, elevation, and roll). There are two movable magnetic sensors from the tracker. One is attached to the head of the transducer for real-time tracking of the position and orientation of the transducer; the other is glued to the back of the SP/mannequin to locate the center of the SP's/mannequin's heart.

In this simulator, a sensor attached to a non-functional transducer indicates orientation and position regarding the patient's body, which corresponds to the same orientation of the virtual heart. Based on the sliced anatomical image of this orientation, an ultrasound image is synthesized in real-time using the technology described above.

Essentially, the simulator operates as follows. Medical students place the transducer against the SP/mannequin and perform an ultrasound examination. As the student places the mock transducer (1), its position and orientation is tracked via the Polhemus FASTRAK (2) using the movement of the attached sensor (3). When the computerized ultrasound simulation running on the PC (4) detects that the sensor/transducer is placed within an appropriate location, the technology generates the corresponding dynamic echocardiography that is displayed on the monitor (5). Everything occurs in real time, and the image is produced according to the "Echo Windows" marked on the mannequin.

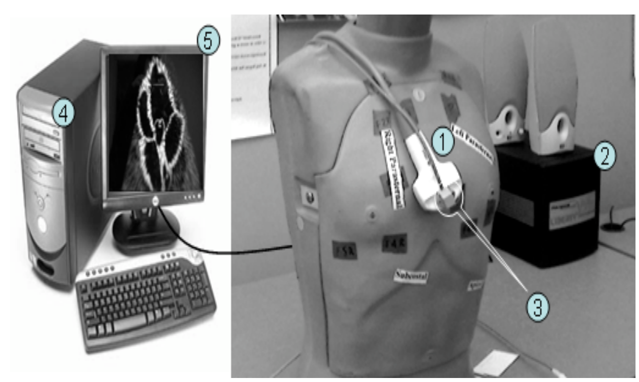

Fig. 9. Tracker-based Echocardiogram Simulator

Our target is to use tracker-based simulator to augment Standardized Patients for medical assessment. Therefore, we are still researching an effective calibration method to map the orientation of the virtual heart to different size of human bodies.

V. Evaluation Results

For ultrasound simulation, image quality is the most important parameter that needs to be validated. Its appearance directly affects applicability for the training. Therefore, we had both a subjective measurement and an objective measurement method for validation.

A. Objective Measurement (Computerized Validation)

The objective measurement we designed was to analyze the image in term of two properties of the ultrasound wave, scattering and attenuation.

Based on the method purposed by Makela [11], the mean values of gray levels of an ultrasound image in the referenced tissue area indicate the tissue scattering property. Their result shows that the mean values calculated in the experiment comply with the known scattering properties as shown in figure 10. The heart tissue has a range from 45 to 90, and its average is around 69.

Using this method, we calculated the mean values of several simulated images. The synthesis image is screen-captured from the generated dynamic video. The background noise is removed to obtain an accurate gray level. Then we utilized MatLab for calculating the image gray scale.

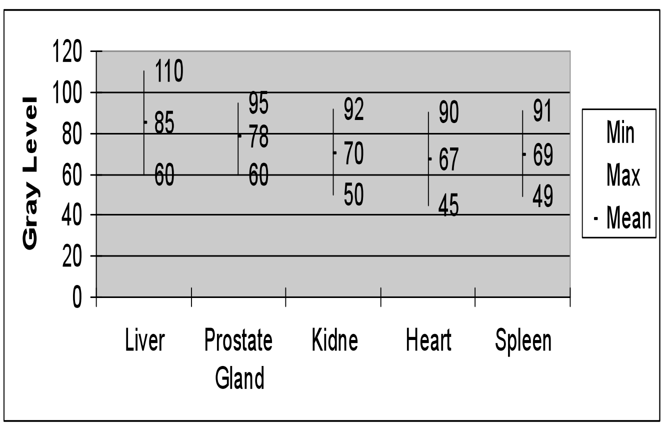

Fig. 10. Standardized Mean Levels of tissue samples [8]

We randomly picked five different-oriented images from our virtual echocardiogram for the scattering measurements as in figure 11. The mean values of their gray scale are 84.5048, 81.7304, 82.3108, 90.3945 and 82.4407 respectively.

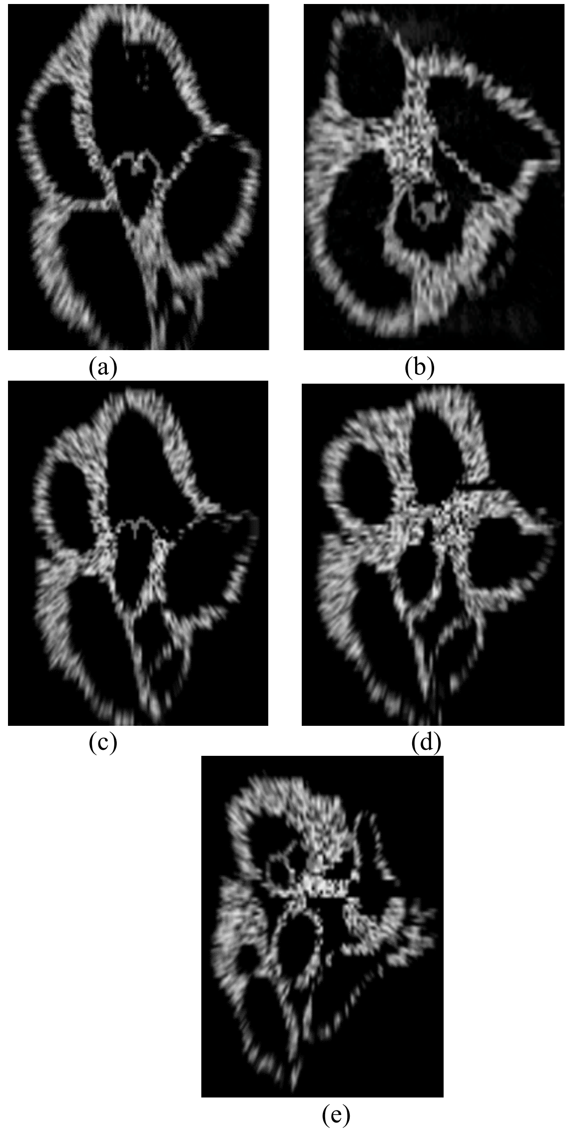

Fig. 11. Scattering property of heart tissue: (a) 84.5048 (b) 81.7304 (c) 82.3108 (d) 90.3945 (e) 82.4407

The scattering properties of our simulated images are almost within the range of the heart tissue scattering value. The average of the images' scattering value is 84.2762. Therefore, our simulated echocardiography is representative of the scattering properties of heart tissue.

Heart tissues have various attenuation coefficients depending on the type of pathologies. For example, attenuation coefficients in the myocardium specimens are 1.3 decibel (dB)/MHz*cm for infarction and 1.2 dB/MHz*cm for dilated cardiomyopathy, while attenuation coefficient is 1.6 dB/MHz*cm for normal myocardium [12]. To measure attenuation property in ultrasound, we have investigated many methods [11, 13, 14]. However, this property cannot be estimated in our simulated images using these existing methods because some of the data needed from an ultrasound probe such as signal strength and distance from probe to phantom is not available in our simulation. Figure 12, generated from a real ultrasound, shows the data from a homogeneous calibration phantom with known attenuation. The ultrasound strength drops about 8 dB through 2.5

centimeters. We can perceive an increase in grey level intensity of the image from top to bottom. However, for a normal myocardium, the ultrasound will drop 4 dB (1.6 * 2.5 = 4) through 2.5 centimeters using the worst-case attenuation coefficient above. This is equivalent to about half the signal loss showed in figure 12. It is probably not a perceptible difference.

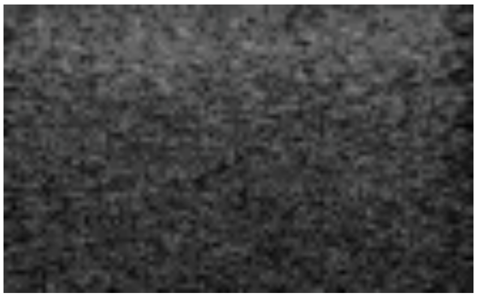

Fig. 12. Attenuation of a homogeneous calibration phantom with known attenuation [15]

We do not utilize an attenuation property in this research other than to specify tissue density coefficients in calculating the general texture for a given tissue, and given the above analysis, it may not be a useful endeavor for certain types of tissue. Nevertheless, future work may include presentation of attenuation in the simulated ultrasound image.

B. Subjective Measurement

Four radiologists from Sentara Heart Hospital were invited to evaluate the image quality of the simulation. Since the tracker-based simulator is still under development, we ask them to operate virtual echocardiogram individually and fill an evaluation survey after operating. We sum their comments in Table 1.

TABLE I
Results of the Subjective Evaluation
Virtual Echocardiogram

Personals	Comments
Professional A	The simulated image looks almost same as the real one; the image showed a normal heart. There are some landmarks we use in echo that I did not see such as papillary muscles, the chordae tendonae, which anchor the mitral, and tricuspid valve into place.
Professional B	Good wall texture; the image showed a normal heart, but aortic valve leaflets open into left ventricle (LV) too much
Professional C	3-D model was very good and very accurate; the image showed a normal heart, but aortic valve (AoV) doesn't look correct on live video.
Professional D	Yes, this has great potential to be used for training especially in the identification of cardiac view and basic anatomy. It looks like a heart with pathology, because the aortic valve is misplaced. This has great potential with views in place

The overall comments on image quality are promising: "the tissue texture is very realistic"; "the video simulation shows basic anatomical structure of heart and movement of valves". We also received comments that (1) our simulated sonographies did not present chordae tendinae, compared to a real ultrasound image; (2) also the aortic valve was misrepresented because leaflets open into left ventricle too much. The synthetic sonography is generated based on the anatomical image of the virtual model. Therefore, the misrepresentation in the ultrasound image is caused by the same problem inherent in the virtual model. For example, the heart model does not have chordae tendinae, so the simulated echocardiogram won't be able to present this component. On the other hand, we think that this is one of advantages in using the virtual model because we can easily modify the structure of the model to produce a pathological image.

VI. Conclusion

Our research was successful in developing technology to generate synthetic sonography based on a virtual 3-D model in real time. The objective measurements in terms of scattering property comply with the known literature. The subjective evaluation we received from professionals indicates that synthesized sonographies provide the basic anatomical information and represent the ultrasound image texture. Our virtual echocardiogram demonstrated its usefulness in real-time SP-based training as well as in its function to be a general sonography-training tool.

Acknowledgment

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