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Short Paper: Echocardiography Simulator based on Computer-Simulated Heart

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Abstract

In this paper, we report our approaches to implementing an echocardiography simulator for medical training. The simulator provides experience of diagnosis by echocardiography using normal and endoscope probes; the user interface of the simulator consists of a mannequin and dummy probes that provide a feeling of actual diagnostic operation to the user. The simulator is also equipped with functions that are similar to those of real instruments such as diagnostic view modes and color Doppler imaging. Preliminary evaluation by experiment at a clinic of our university hospital suggested that the simulator is promising for use in practical training.

Categories and Subject Descriptors (according to ACM CCS): Information Interfaces and Presentation [H.5.2]: User Interfaces—Training Computer Graphics [I.3.4]: Graphics Utilities—Virtual device interfaces

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1. Introduction

1.1. Background

Echocardiography is one of most general diagnostic methods for cardiac diseases; it provides a cross-sectional image of the human body using ultrasonic waves, and it poses relatively little harm to the human body. However, the diagnosis of diseases using echocardiography requires considerable skills based on advanced training. Part of the difficulty in what is derived from difficulty in understanding the spatial relationship between the three-dimensional structure of the heart and the two-dimensional image of the heart observed by an echocardiagraph. In addition, training in transesophageal echocardiography is unethical using a real human body because the method is invasive.

1.2. Related research

The idea of an echography training system is not novel, and several systems have been developed and commercialized. MedSim [Med] provides an ultrasound training system and image data from various diseases and pathologies for practical training; the system uses ultrasound volume data of real patients. Heartworks [Hea] has developed a geometric anatomy model of the human heart and ultrasound simulation software. For this model, a transesophageal echocardiography interface is provided, which enables diagnostic simulation.

Some studies have provided the effectivity of ultrasound simulators for diagnostic training. Knudson et al. evaluated the impact of the MedSim simulator in learning diagnosis for trauma and critical care, and reported that effect an equivalent to that of hands-on training is attained with the use of the simulator [KS00]. Maul et al. developed a simulator for obstetric diagnosis and performed an experiment to evaluate the effect of prenatal examination. Their result proved that the simulator significantly improves the skills of doctors and technicians in finding rare fetal anomalies [MSB*04]. Also, Weidenbach et al. have implemented a transesophageal echocardiography simulator and proved the advantage of the simulator through experimental evaluation [WDW*93].

Most of previous echography simulators was present echography images based on ultrasound volume data that have been scanned from real patients. An advantage of echography is that details of abnormalities in the echography image are reproduced in the simulation. However, the approach has a drawbacks in that blood flow information is not included in the data. Similarly, simulation based on a

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geometric model provides no blood flow information. Since information on blood flow, which is visualized by the color Doppler technique, is essential for cardiac diagnosis, lack of such information limits the effectiveness of simulators.

Because of advancements in both computer technology and biomechanics, the numerical simulation of complex biomechanical systems such as the heart has become possible [WSKH04]. Such numerical simulation computes the behavior of the system using a multiphysics model, and provides information on blood flow as well as an structural deformation.

1.3. Our approach

In this paper, we report the use of an echocardiography simulator on the basis of 3D heart data obtained by numerical simulation. The simulator provides experience of diagnosis through a tangible user interface that comprises a mannequin and dummy probes. By taking advantage of the simulation-based data, the functions of color Doppler imaging and other diagnostic view modes related to blood flow have been integrated.

2. Design and Implementation

2.1. Requirement for simulator

Simulators for training must have a similar function to real echocardiographs instruments. Our system was designed to simulate transesophageal echocardiography (TEE) as well as normal echocardiography. Echocardiographs commonly used in clinical practice have several view modes; e.g., B, M, PW, and CW modes (detailed below), and doctors and technicians use these different modes to observe different aspects of the heart and to diagnose diseases.

The above simulators should be capable of providing experience similar to an actual diagnosis. The real-time motion of the heart and real-time imaging by the manipulation of the probe are crucial. In the case of TEE training, the feeling of manipulating an endoscope in relation to the human body is essential, and it is difficult to replace the interface with an intangible virtual interaction.

In addition, some educational functions are considered to be helpful for training. According to experts in echocardiography, the 3D presentation of the relationship between the heart and the imaging plane and the color coding of parts of the heart valves provide effective assistance for traines in interpreting echocardiograms.

2.2. System structure

The interface of the echocardiography system consists of a mannequin, a dummy probe, an endoscope, a rotary control, a small keypad, a trackball, and a monitor display. The mannequin is a dummy human model custom-fabricated for peroral endoscopy; its gular region is has an elaborately crafted gular region and an esophageal tube inside its body. The mannequin is attached to a magnetic sensor, which measures its position and orientation.

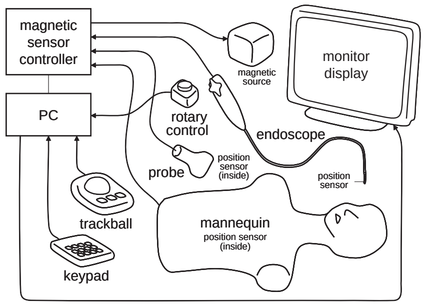
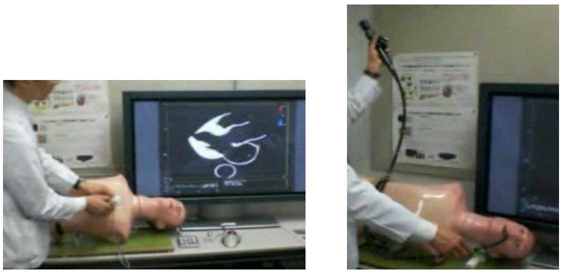


Figure 1: *System diagram*

The dummy probe is shaped similarly to the actual probe and also has a magnetic sensor inside. The endoscope is equivalent to a real one in terms of size and manner of operation except that no ultrasonic transducer is integrated; in place of the transducer, a magnetic sensor is fixed at the tip of the endoscope. A rotary control device is part of the endoscope system; it is used to rotate the cutting surface of the endoscopic probe.



(a) noral probe operation (b) endoscope operation

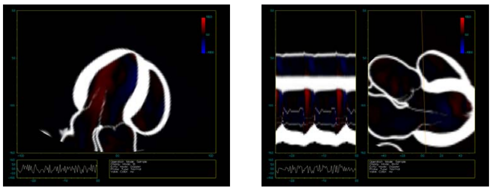
Figure 2: *Dagnostic operation*

The keypad, trackball, and monitor display provide an interface similar to those of dedicated echography instruments. Functions such as mode change, probe selection and sample/hold control are controlled using respective keys.

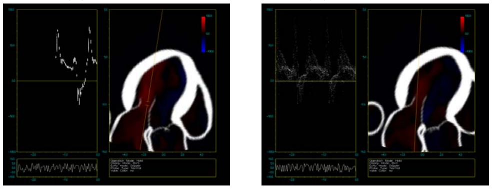
The entire system is controlled by a PC (Core 2 Extreme QX9650 3.00GHz and GeForce 8800GTS graphics card). As stated above, the positions and orientations of the mannequin, probe, and tip of the endoscope are measured using a spatial position sensor (Liberty240, Polhemus).

2.3. Echocardiography interface

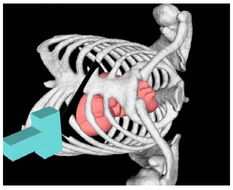
Several commonly used diagnostic viewing modes were implemented. The B mode presents a normal 2D cross-sectional image (Figure 3(a)). The M mode displays a temporal sequence of 1D images on a given line on a B-mode image (Figure 3(b)), which is mainly used to observe the motion of the cardiac wall and valves. The PW and CW modes present temporal changes in blood flow velocity toward or away from the focal point of the probe in a given area of a B-mode image (Figures 3(c, d)). The difference between the PW and CW modes is that the PW mode plots the velocity of flow in a narrow region around a given point in a B-mode image, whereas the CW mode plots the velocity of flow on a given line. In using the M, PW, and CW modes, a B-mode image is essential as a reference; hence, a B-mode image is also provided on the right part of the screen.



(a) B mode (b) B+M mode

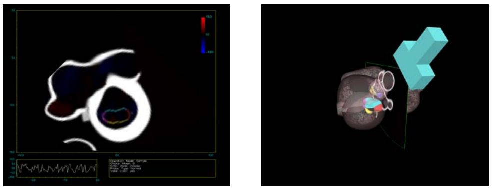


(c) B+PW mode (d) B+CW mode



(e) 3D mode

Figure 3: *Viewing modes*



(a) B mode (b) 3D mode

Figure 4: *Coloring valve regions*

Some additional functions that are also common to real echography instruments, such as color Doppler toggle, sample/hold trigger, measurement cursor on hold image, probe selection function (i.e, normal and endoscopic probe), and adjustment of velocity range in color Doppler mode are implemented.

Also, some educational functions, as stated above, were introduced: The 3D representation mode provides the relationship between the heart and the cutting plane by rendering using a polygon model (Figure 3(e)). The color coding mode presents parts of the heart valves using different colors to make them distinguishable on both echo and 3D images (Figures 4(a, b)).

2.4. Details of implementation

The heart data include both volume data and polygon data; the volume data are used to generate a cross-sectional image on the cutting plane using a 3D texture mapping technique [ASW*05], and the polygon data are used to provide a 3D representation of the heart. In color Doppler imaging,the color of each pixel is determined on the basis of the velocity of flow at the pixel and the orientation vector from the what point to the focal point of the probe. Color is determined on the basis of the inner product of these vectors. The computation of the color of each pixel was performed by a fragment processor of a graphics processing unit (GPU) [FK03].

The original heart data are generated by FEM simulation performed using a tetrahedral mesh structure; the data comprise both the deformation of the heart structure and the distribution of blood speed inside the atrium and chamber of the heart for one cycle of heart beat, which consists of 200 steps of intermediary states. The voxel data were generated from the mesh data by conversion using a rasterizing algorithm. On the other hand, the polygon data were generated by extracting a surface polygon from 3D mesh data.

From the medical viewpoint, the positioning of a heart model in relation to the mannequin requires special care, because it affects the reality of the experience. The fine tuning of the heart position was performed under the supervision of an expert in cardiac surgery. Although the magnetic sensor is operated without calibration, no measurement error has been reported.

Voxel data of the heart structure were represented by a 128x128x128 array of 4 bytes, or by RGBA components. Voxel data of blood flow were also represented by the same structure; each of the x-, y-, and z-components of the velocity vector was encoded into a one-byte format, whose range of values is assumed to be ± 2 m/s. As stated above, one heart cycle consists of 200 steps, and the image of each step must be rendered using different voxel data.

The polygon model of the heart and its valve consists of 205, 882 triangles and 103, 145 nodes. Similarly to voxel data, node position data consist of 200 sets of what corresponding to the number of steps in a heart cycle. Polygon data of breast bone consist of 29, 902 triangles. The visual update rate of the system was higher than 30 Hz in all the diagnostic modes.

A logging function was also embedded in the system. The function records the status of the simulator including the position and orientation of the active probe and the diagnostic modes at 1-sec intervals, and writes the information into a file. Log data are expected to be useful for analyzing how the system is used.

3. Experimental use

As a preparation for evaluation, a preliminary test on the simulator was carried out at our university hospital. The simulator was installed in a conference room of a clinic and opened for use. During the test, the system was used 5 times for approximately 45 minutes.

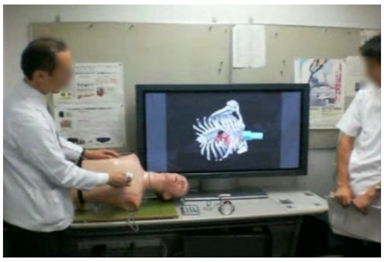


Figure 5: *System in use for training*

Figure 5 shows a photograph of a training session. The person on the left side of the display is the expert, and the person on the right side is the trainee. The expert is explaining the spatial position of the typical cutting plane of standard diagnosis using a 3D view.

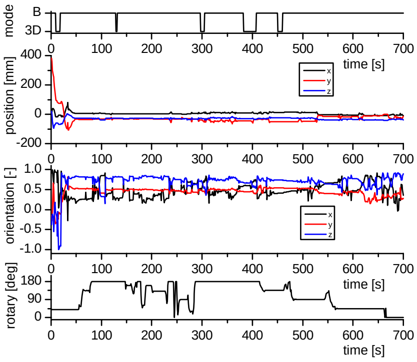


Figure 6: *Operation in esophageal diagnosis*

Another example of operation is shown in Figure 6. The plot shows the change in the system status recorded by the logging function. At the start of the operation, the tip of the endoscope is inserted and the position of the tip is adjusted to a standard position for diagnosis. Once the position is adjusted, probe is kept approximately fixed through out the diagnosis.

In the reset part of the training session, the user is focusing on controlling the orientation of the cutting plane using both the dial of the endoscope and the rotary control device. It is observed that the view mode changes to the 3D mode several times. In particular, at approximately 400 sec into the session, the orientation of the tip of the endoscope is markedly changed while using the 3D view mode, probably to tune the orientation of the tip in order to observe the desired cutting plane.

Although a formal questionnaire has not been sent to users yet, some experts who experienced operating the system had the following comments:

- The system can now be used for teaching fundamental knowledge of echocardiography.
- If simulation data of a diseased heart become available, the system can be used for pathological explanation.
- The color coding of parts of the valve is useful for explaining diagnostic details related to the motion of a valve.

4. Conclusion

In this paper, we discussed an approach to implementing echocardiography using simulation-based heart data. Taking advantage of the fact that the data include blood flow information, the simulation of the function of color Doppler imaging was realized. A user interface using a mannequin, a dummy probe, and an endoscope was implemented to provide an experience similar to that of operating a real instrument. From results of our preliminary test conducted at our clinic, it was suggested that the system is promising for use in practical training.

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