An Evaluation of Using Real-time Volumetric Display of 3D Ultrasound Data for Intracardiac Catheter Manipulation Tasks

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Abstract

The enthusiasm for novel, minimally invasive, catheter based intracardiac procedures has highlighted the need to provide accurate, real-time, anatomically based image guidance to decrease complications, improve precision, and decrease fluoroscopy time. The recent development of real-time 3D echocardiography creates the opportunity to greatly improve our ability to guide minimally invasive procedures [Ahm03]. However, the need to present 3D data on a 2D display decreases the utility of 3D echocardiography because echocardiographers cannot readily appreciate 3D perspective on a 2D display without ongoing image manipulation. We evaluated the use of a novel strategy of presenting the data in a true 3D volumetric display, Perspecta Spatial 3D System (Actuality Systems, Inc., Burlington, MA). Two experienced echocardiographers performed the task of identifying the targeted location of a catheter within 6 different phantoms using four display methods. Echocardiographic images were obtained with a SONOS 7500 (Philips Medical Systems, Inc., Andover, MA). Completion of the task was significantly faster with the Perspecta display with no loss in accuracy. Echocardiography in 3D significantly improves the ability of echocardiography for guidance of catheter based procedures [Ahm03]. Further improvement is achieved by using a true 3D volumetric display, which allows for more intuitive assessment of the spatial relationships of catheters in three-dimensional space compared with conventional 2D visualization modalities.

Keywords: 3D echocardiography, cardiac ablation, computer graphics, display technologies, intracardiac catheter procedures, Perspecta display, medical visualization, volume graphics, volumetric display.

1. Background

Advances in imaging technology have usually been readily incorporated into the practice of many medical fields with the assumption that they will lead to better patient care and outcomes. Improvements in medical imaging technology, such as 3D acquisition techniques in MRI and multi-detector CT scanners, are producing images of the body that more closely correspond to volumes rather than 2D tomographic images.

One such advancement in ultrasound technology is the development of 2D matrix transducer arrays which can obtain real-time 3D volumetric imaging. Such devices perform volumetric imaging that allows for viewing volumes from any direction and acquiring any number of true axial, orthogonal, diagonal, and oblique planes. The ability to view the entire volume reduces observer variability because less image reconstruction would have to occur in the user's mind. In contrast, previous 2D echocardiography have allowed sonographers to view only one cross-section and required further manual manipulation of the transducer to capture a different cross-section. Then, the user must stitch the images together mentally.

This 3D imaging capability can potentially be a very useful tool in echocardiography. One obstacle to clinical use of 3D echocardiography is our inability to display the 3D medical data sets in a useful way. The benefits of obtaining volumetric data will not be fully realized until there is a way to quickly visualize and appreciate the entire volumetric image. For example to view the real-time 3D echo data obtained with a SONOS 7500 (Philips Medical Systems, Inc., Andover, MA) the data must be rendered as an image on a 2D display. This process loses much of the valuable spatial information a 3D data set has to offer. In order to assess the entire volume, sonographers consequently need to manually rotate and crop the image to present the desired information. These tedious time-consuming steps often make users prefer the traditional 2D echocardiogram. Thus, to fully realize the potential of 3D echo, we must improve our ability to present the volumetric data to the user.

This paper introduces the idea of presenting 3D data sets in a true 3D volumetric display. To test this concept, we evaluated the use of a real-time volumetric display in assisting intracardiac catheter manipulation tasks where the ability to rapidly assess 3D relationships between objects is most important.

2. Perspecta volumetric display

One strategy for assessing 3D data quickly and intuitively is to present the data in a true three-dimensional volumetric display. One such display system is the Perspecta Spatial 3D System developed by Actuality

Systems, Inc. (Burlington, MA). Perspecta consists of a 20-inch dome that creates spatial 3D imagery by projecting 2D images onto a rotating screen. Each 2D image has a resolution of 768 x 768 pixels, with each image presented at one degree rotational intervals. The serially presented images are fused in the human visual system into a 3D volume. Full-color and full–motion images that float within the dome are created. Neither viewing glasses nor editing of the rendering process is required to visualize the full 3D volume [FNHD*02]. To obtain different perspectives of the image simply requires tilting the head or moving around the display, as if the object were truly there.

We have chosen this display instead of other volumetric displays such as stereoscopic displays and the DepthCube (LightSpace Technologies, Inc.) for several reasons. Stereoscopic displays require viewing goggles, are user dependent, have limited viewing angle, and have fixed perspective. The DepthCube has a limited viewing angle [Lig03]. Recently, Akeley et al. have built a prototype stereo display that comprise of two independent fixed-viewpoint volumetric displays [AWGB04], but the display is a proof of concept and not a practical solution for general purpose viewing yet.

3. Case study

3.1. Study design

Cardiac tissue ablation is performed to destroy abnormal tissue to prevent arrhythmias. Clinicians, guided by ultrasound, need to quickly and accurately assess catheter positioning in order to arrive at target tissue with ablation probe. In order to evaluate the value of presenting 3D echo data on Perspecta's true-volumetric display to enhance the ability to assess catheter positioning, we designed a simplified version of this task. A simplified task was needed because at the time the experiments were conducted the rate of update of volumetric data was limited in Perspecta. The lack of real-time display with Perspecta prevented the task from being an actual intracardiac catheter procedure, but allowed for one that focuses on the user's ability to capture, manipulate, and interpret images during such a procedure. The task consisted of a user determining where on a surface a probe will hit if the probe continued to advance in the direction it was pointing. This task is very relevant to intracardiac catheter procedures because a clinician needs to perform this task continuously during an actual procedure to correct the position of the probe as it is advanced closer to the target in the heart. Though this study is quite simplified, it can at least demonstrate if Perspecta might be a potential benefit in certain aspects of performing a catheter procedure.

3.2. Study procedure/experiment

Two experienced echocardiographers performed the task of identifying the targeted location of a catheter within 6 different phantoms using 4 display methods detailed below: 2D-RT, 3D-RT, 3D-FV, and Perspecta. To create the phantom, a container with a 6x6 cardboard grid placed at the bottom, was filled with water and covered in latex to simulate the human body and its surface. A guide-wire, acting as the ablation probe, was inserted into the container through the latex at six different orientations for the six phantoms. See Figure 1.

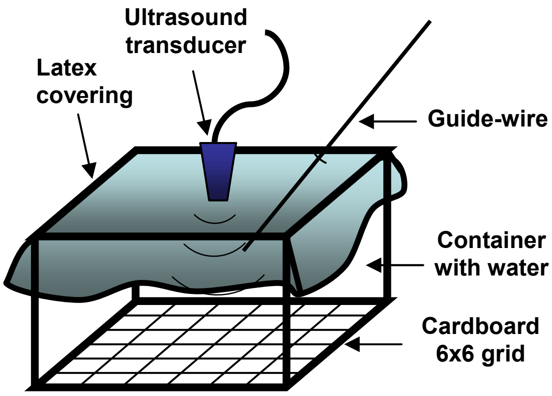

Figure 1: *This schematic is of the phantom setup. The latex-covered container filled with water simulated the body. The grid acted as target points within the body, and the guide-wire represented the catheter ablation probe.*

Using SONOS 7500 (Fig. 2) to obtain the echocardiographic images, the subjects were timed to see how fast they can determine to which cell in the grid the guide-wire was pointing. Their accuracy was recorded. The echocardiographers were accurate if they could determine correctly to which grid the guide-wire was pointing; if they reported a grid other than the correct one, they were inaccurate. Subjects repeated the tasks using four different display methods described below to visualize the wire and grid.

Figure 2: *This photograph is of the SONOS 7500 (Philips Medical Systems, Inc., Andover, MA) with a transducer for obtaining real-time 3D volumetric imaging, onboard CRT display for viewing, and keyboard/mouse for image editing.*

2D-RT: Real-time 2D imaging with echocardiographer scanning of the phantom; The echocardiographer manipulated the ultrasound transducer to get the guide wire and grid into the viewing 2D cross-section. To change views to a different cross-section, the user manipulated the ultrasound transducer as the images are displayed in real-time.

3D-RT: Real-time 3D limited sector size imaging (70ºx20º) with echocardiographer scanning and displaying rendered 2D display; The echocardiographer manipulated the ultrasound transducer to get the guide wire and grid into the

70ºx20º viewing volume. The 3D sector image was rendered on the 2D display using the volume rendering algorithms incorporated into the SONOS 7500. To change views to a different sector, the user further manipulated the transducer as the images are displayed in real-time.

3D-FV: 3D capture of the entire phantom volume (80ºx80º sector) with rendering on a 2D display and echocardiographer manipulation of the rendering process; A bird's-eye view of the entire phantom and wire was captured in a 80ºx80º viewing volume with the ultrasound transducer. Once accomplished, the user viewed the 3D image rendered on the 2D CRT display and then edited the image (rotate, cross-section) with the keyboard and mouse controls to get the desired view. See Figure 3.

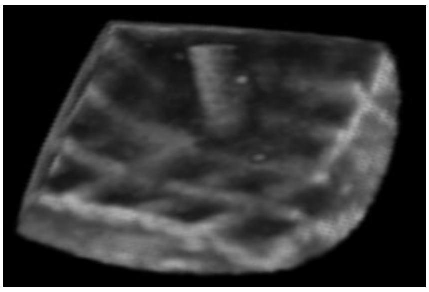

Figure 3: *Above shows the 2D image of the entire grid and guide-wire for 3D-FV rendered on the SONOS 7500's CRT display. Keyboard and mouse were used to change viewing angles. For 2D-RT and 3D-RT, only a 2D slice or a section of the above full-volume sector could be seen, and manipulation of the ultrasound transducer was needed to change viewing angles.*

Perspecta: 3D capture of entire phantom volume (80ºx80º sector) displayed on the 3D volumetric display; Again, a bird's-eye view of the entire phantom and wire was captured in a 80ºx80º viewing volume. The volume was displayed on Perspecta volumetric display as described below. The user can position his head or body about the display to get the desired view. See Figure 4.

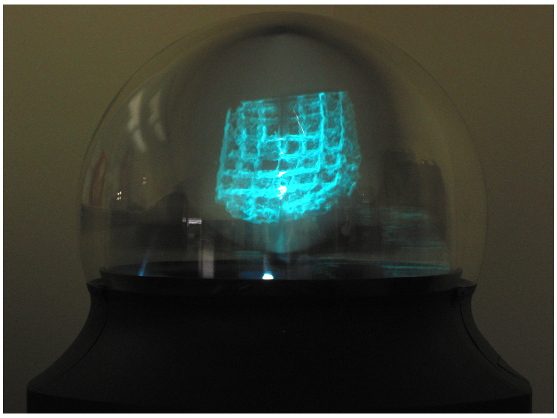

Figure 4: *Perspecta's display of the entire phantom is shown. In most cases, a tilt of the user's head was all that was needed to get desired perspective. Anyone can view the same volume from all around display.*

3D DICOM binary data files were extracted from SONOS 7500 and processed with MATLAB (Mathworks, Natick, MA) and an interactive visualization program written in C++ for display with Perspecta. Three-dimensional geometric meshes were chosen to depict the 3D echo data. The 3D meshes represented the isosurfaces computed from the ultrasound data. Isosurfaces were computed using the classical marching cube algorithm by Lorensen [LC87].

4. 3D interactive visualization program

An interactive graphics program was developed to render the 3D ultrasound data. Isosurfaces were chosen to represent the 3D data at the given threshold level. We chose to represent the data using isosurfaces because they gave the best resemblance of what the echocardiographers would see on the Philips ultrasound system's CRT. See Figure 5. Our program allowed the echocardiographers to interactively set the threshold level of the isosurfaces with simple key strokes on the keyboard. The threshold level corresponded to an intensity value of the 3D echo data. The graphics program was written using Microsoft Visual C++ on a PC running under the Windows 2000 operating system. The program used the Perspecta SDK which allowed the user to easily generate graphics objects using OpenGL function calls. For the frame refresh, Perspecta SDK sent the graphics objects to be rendered to the Perspecta 3D display directly via an SCSI interface card that was installed on the PC.

We have experimented with using various color schemes to shade the isosurfaces. We found that using a single color to render the isosurface best simulates what the echocardiographers would normally see from the 3D ultrasound system's monitor. We found that with gray scale, the structures of the 3D grid were not as easily seen as other colors such as red, cyan, and green. For multiple threshold levels, the echocardiographer could choose to assign a unique color to individual threshold level.

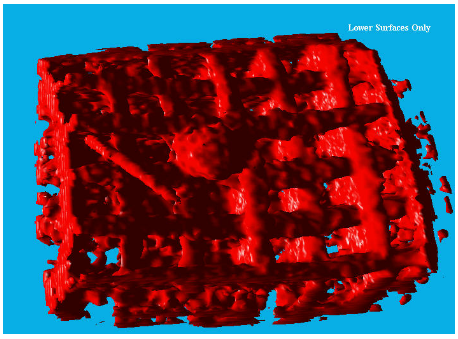

Figure 5: *This is the isosurface of the grid and guide wire displayed on a 2D screen.*

5. Results

This section reports the aggregate results for time to complete the task and for accuracy for both echocardiographers. Though one echocardiographer was overall a bit better than the other (P=0.052 by comparison of proportions), there was no interaction between subject and method. Consequently, the six tests done by each echocardiographer were lumped together as twelve tests done by one echocardiographer for the statistical analysis.

Completion of the tasks was significantly faster with Perspecta, with no loss in accuracy. Times to complete task were compared against Perspecta using a t-test. A summary of the results are reported in the data table below. See Figure 6. Accuracy was analyzed by a comparison of proportions. The only statistically significant comparison was between Perspecta and 2D imaging. Perspecta was more accurate than 2D imaging (95% confidence limits 1.2-155, corrected for subject).

Comparison of accuracy and speed among four different visualization modalities

Method	Accuracy (%)	Time to Complete Task ± SD (sec)	p-value – Time vs Perspecta
2D-RT	50*	63.5 ± 23.9	P < 0.0001
3D-RT	67	55.2 ± 20.2	P < 0.0001
3D-FV	75	22.8 ± 7.1	P = 0.008
Perspecta	92	11.8 ± 6.9	

Figure 6: *Overall, Perspecta provided at least as accurate results in less time. *When compared to 2D-RT, Perspecta was more accurate with statistical significance.*

6. Conclusion and discussion

6.1. Potential of 3D imaging in guidance of intracardiac catheter procedures

The value of 3D visualization in guiding interventions is clear from the data, with a trend toward faster and more accurate completion of the task as we go from 2D image acquisition and 2D display to 3D image acquisition and 2D display and finally to 3D acquisition and 3D display.

Our results show that using a true 3D volumetric display allows for more intuitive and thus more rapid assessment of the spatial relationships of catheters in three-dimensional space when compared with conventional 2D imaging and visualization modalities. For the experimental task designed in this paper, Perspecta Spatial 3D System gave users several advantages that contributed to their ability to perform the task faster and just as accurately. The greatest advantage was that users were able to simply tilt the head to get the desired viewing angle of the object, as if the object were truly there in space. On the other hand, when using a conventional display, the user needed to manipulate the ultrasound transducer and/or rotate the image using the keyboard/mouse to get the desired view.

Usually the best viewing angle is looking directly down the length of the catheter (as if you were aiming the catheter like a rifle). The cell "down the sight" of the catheter would be its target. Perspecta facilitated this task, whereas the conventional display required tedious image or transducer manipulation. Manipulating the transducer effectively requires much previous training and takes getting used to. Perspecta eliminates much of the transducer's involvement in creating a good view, thus would be advantageous for users of all levels.

Another advantage Perspecta offered was that it preserves translucency in its created volumetric images. Since the volumetric image is created by a spinning screen, the image lacks occlusion. Occlusion occurs when an opaque surface prevents another surface behind it from being seen. However, all surfaces on Perspecta are translucent and all surfaces can be seen at once. Thus, unlike conventional displays, no cropping or taking cross-sections is needed to see within the object, reducing procedure time. Lack of occlusion is sometimes labeled as a disadvantage [Ake04], because occlusion contributes to visual clues for depth perception. However, for our application in catheter manipulations within an object, namely the heart, the occlusion becomes a hindrance because we will then not be able to observe the exact position of the catheter and target tissue.

6.2. Advantages of using a true volumetric display such as Perspecta

The impetus for incorporating a true 3D display with the latest in imaging technology, such as 3D echocardiography, derives mostly from its greater diagnostic and therapeutic potential than that of 3D image rendered on a 2D display. Being able to quickly and better appreciate the entire 3D data collected of the heart can lead to a enhanced visualization of the complex anatomic features of the heart and more accurate assessment of tissue and valvular function. Spatial imaging of cardiac structures and better probe visualization in 3D space are especially important in the planning and performance of surgical and catheter interventional procedures, such as cardiac tissue ablation. True volumetric display also offers possibilities of improved quantitative analysis, such as the determination of ventricular size, volume, and function.

Additional benefits are ease and comfort of use. No goggles and image editing are required. Changing angles of view is as natural as adjusting one's head. Usually, the clinician operating the intracardiac catheter or the sonographer obtaining cardiac images is in a fixed position next to the patient or seated next to the ultrasound machine. However, the 360º viewable volume would allow everyone on the operation team and in the room to simultaneously and easily see the exact same volumetric image. Furthermore, in contrast to viewing images on Perspecta, interpreting images on conventional displays requires much training, and maneuvering the ultrasound wand or manipulating images on the screen takes getting used to. Consequently a true 3D display, such as Perspecta, will also help in reducing exam time, decreasing cost, increasing accuracy, reducing patient discomfort, and saving patient lives.

6.3. Challenges for 3D volumetric display

Establishing Perspecta display as part of 3D echocardiography will, however, require further technical improvements in spatial and temporal image resolution. Current equipment limitations limit the ability to update volume data within Perspecta in real-time. Access to raw 3D data in real-time from ultrasound equipment will also be needed to develop systems responsive enough for providing real-time guidance of procedures. Also, the choice of rendering technique needs to be further optimized. The surface-based approach although effective for the relatively simple object used in this task will need to be reevaluated as more complex and noisier data sets from real clinical images are presented.

With a more optimized approach to handle more complex and noisier data sets, this paper's study design could be improved by replacing the 2D grid with a 3D grid and asking the user to determine to which cell in space the guide-wire is pointing. A 3D grid would better represent the 3D spatial complexities in a true catheter procedure. Real-time images on Perspecta would also allow for a better study design that lets users perform an actual catheter procedure instead of a greatly simplified task.

Nevertheless, these initial tests suggest that a true volumetric display, such as Perspecta display holds promise for presenting medical data sets in a way that is intuitive and accurate for guiding the types of minimally invasive procedures that are rapidly developing in many medical fields, such as cardiology, gynecology, and urology etc.

7. Reference

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