Real-Time, 3-D Ultrasound with Multiple Transducer Arrays

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***Abstract*—Modifications were made to a commercial real-time, three-dimensional (3-D) ultrasound system for near simultaneous 3-D scanning with two matrix array transducers. As a first illustration, a transducer cable assembly was modified to incorporate two independent, 3-D intra-cardiac echo catheters, a 7 Fr (2.3 mm O.D.) side scanning catheter and a 14 Fr (4.7 mm O.D) forward viewing catheter with accessory port, each catheter using 85 channels operating at 5 MHz. For applications in treatment of atrial fibrillation, the goal is to place the side-viewing catheter within the coronary sinus to view the whole left atrium, including a pulmonary vein. Meanwhile, the forward-viewing catheter inserted within the left atrium is directed toward the ostium of a pulmonary vein for therapy using the integrated accessory port. Using preloaded, phasing data, the scanner switches between catheters automatically, at the push of a button, with a delay of about 1 second, so that the clinician can view the therapy catheter with the coronary sinus catheter and vice versa. Preliminary imaging studies in a tissue phantom and in vivo show that our system successfully guided the forward-viewing catheter toward a target while being imaged with the side-viewing catheter. The forward-viewing catheter then was activated to monitor the target while we mimicked therapy delivery. In the future, the system will switch between 3-D probes on a line-by-line basis and display both volumes simultaneously.**

I. Introduction

Atrial fibrillation is the most common sustained arrhythmia observed in clinical practice [1]. A common subtype of atrial fibrillation (AF) arises from one or more of the pulmonary veins (PV). Radio-frequency (RF) ablation can be performed using a catheter to electrically isolate the pulmonary veins from the remainder of the left atrium (LA). This procedure can be curative for these certain types of atrial fibrillation. However, difficulties arise because of the anatomical complexity of the LA and because soft tissue is not visualized by fluoroscopy [2]–[4]. There is also a concern about the exposure levels of ionizing radiation for both the patient and operator [5]. In an attempt to improve the identification of the LA and PVs, and reduce the amount of ionizing radiation, researchers have begun using other imaging modalities, including phased-array intracardiac echocardiography (ICE), to guide the RF catheter into location and monitor the ablation process [2], [3], [5]–[9].

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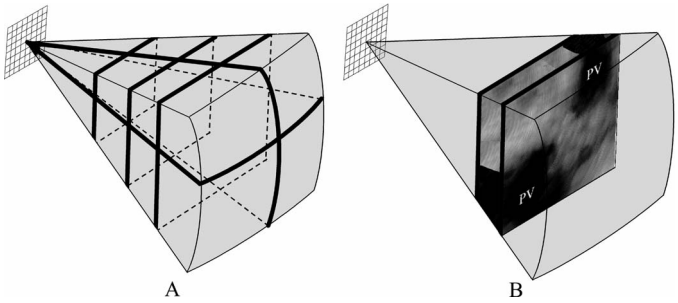

Fig. 1. (a) Schematic showing the five simultaneous image planes. (b) An example of RT3D volume rendering of a face on view of two PV.

Many studies have discussed the use of ICE to aid in intracardiac procedures, including transseptal puncture under ICE guidance [3], [6], [10]. Earing *et al.* investigated using ICE for monitoring the guidance of transcatheter device closure of atrial septal defects and patent foramen ovale [11]. They concluded from their findings that ICE should be considered the preferred imaging technique when performing these procedures in adults and large pediatric patients. Currently, many researchers are describing various benefits of using ICE to aid in the location and monitor the ablation process. Compared with fluoroscopy, ICE guidance and monitoring provides many benefits throughout the entire RF ablation procedure, including visualizing the septal puncture, aiding in catheter guidance, and monitoring the ablation process [5].

Although intracardiac transducers can be used to guide interventional cardiac procedures, they have limitations associated with tracking the ablation device on a monoplanar B-scan image. A real-time, 3-D (RT3D) ultrasound system has been developed in an attempt to address the limitations of imaging techniques such as a conventional 2-D ultrasound system and fluoroscopy. In RT3D ultrasound, a 2-D array transducer is used to steer and focus the ultrasound beam over a pyramidal volume [12], [13]. From this volume of data, the system can display up to five simultaneous image planes [Fig. 1(a)] as well as RT3D rendered images and RT3D pulsed and RT3D color flow Doppler with frame rates up to 30 volumes per second. Various clinical and animal studies using the RT3D system show it is an effective means for monitoring left ventricular function [14], measuring peak left ventricular flow velocities [15], and evaluating congenital cardiac abnormalities

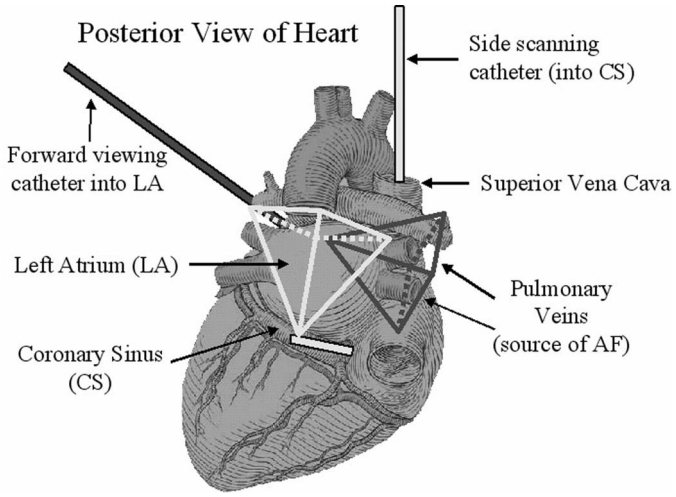

Fig. 2. Visualization of the desired technology using two ICE catheters to localize the PV. Image used and modified with permission of Wesley Norman, Ph.D. http://mywebpages.comcast.net/wnor/heartpostheartchambers.jpg.

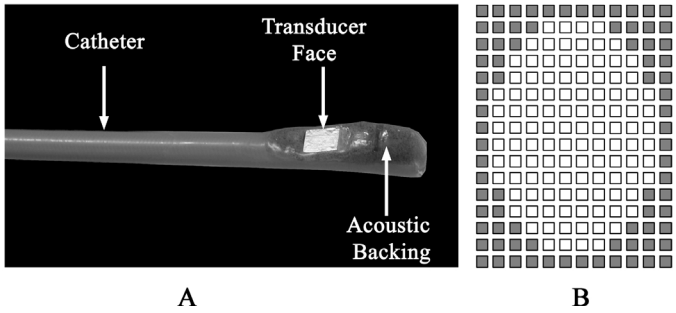

Fig. 3. (a) Side scanning 7-Fr catheter transducer. (b) Schematic of the imaging array showing the available active elements (white squares) and the grounded elements (gray squares).

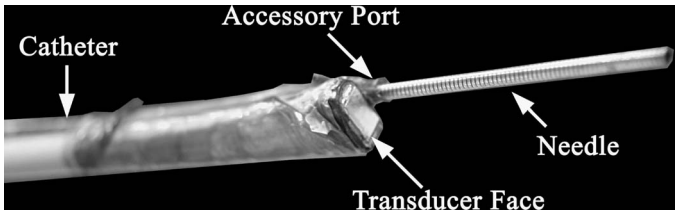

Fig. 4. Forward-viewing catheter with a needle protruding from the accessory port.

[16]. Over the last few years, our lab has reported a series of miniature 2-D array intracardiac transducers that are capable of performing RT3D scanning [17]–[21]. In studies performed in a sheep model using a 7-Fr side-scanning catheter placed within the coronary sinus (CS), we visualized many anatomical landmarks, including the left and right atria, the atrial septum, and the pulmonary veins [20]. Prototype forward viewing catheters (14-Fr and 22-Fr) equipped with accessory ports have been used in an animal model to guide intracardiac therapy tools, including biopsy forceps and a Brockenbrough needle, toward targets within the heart while being monitored by the ultrasound transducer [19]. As an example, Fig. 1(b) shows a 15-mm thick RT3D rendered image of a face on view of two pulmonary veins in the LA of a sheep acquired with our 5-MHz, 12-Fr, 3-D ICE catheter [22].

After using our 3-D ICE catheters, interventional cardiologist colleagues expressed interest in a technology that would provide a panoramic 3-D view of the LA obtained from the coronary sinus with a side viewing catheter combined with a forward viewing catheter to home in on a face on view of the target pulmonary vessels. Fig. 2 illustrates the system with the light-colored, side-scanning, 3-D pyramid inserted into the CS while the dark forward viewing 3-D pyramid scans a pair of pulmonary veins.

It is our hypothesis that simultaneously scanning and displaying images from two 3-D volumes of the same target by using two of the previously reported 3-D ICE catheters may aid in the delivery of RF ablation therapy and could decrease the fluoroscopy exposure to both patients and operators during AF treatment. In this paper, we present the results from initial experiments that show a method for switching between two 3-D ultrasound transducers in 1 second by the push of a button, enabling near simultaneous scanning of the same region with the two separate probes. We describe preliminary results using two 3-D ICE catheter transducers: a side viewing catheter and a forward viewing catheter equipped with an accessory port. We present images obtained in a tissue mimicking phantom as well as in vivo in a canine model to show how this could aid in AF treatment. These results are the first steps toward the goal of simultaneous real-time, 3-D imaging from multiple transducers.

II. Methods

A. Transducers

One transducer used in this study was a 7-Fr (2.3-mm O.D.) side viewing catheter transducer [Fig. 3(a)] developed by Lee *et al.* [20]. The catheter includes a 16×12 2-D phased array with 112 working active elements (white squares) attached to the tip [Fig. 3(b)]. The transducer has an operating frequency of 5.0 MHz, element size of 0.12 mm $\times$ 0.12 mm $\times$ 0.29 mm and interelement spacing of 0.15 mm.

The second transducer used in this study was a 14-Fr (4.7-mm O.D.) forward-viewing catheter transducer (Fig. 4) developed by Lee *et al.* [19]. This transducer's 2-D array has the same physical dimensions and array layout as the side scanning catheter. The catheter also has a 1.3-mm O.D. accessory port that enables cardiac interventional devices to be inserted into the heart while in the field of view of the transducer.

B. Ultrasound System

For the study described here, we used the Model 1 ultrasound system (Volumetrics Medical Imaging, Durham, NC), which is a commercial version of the real-time, 3-D

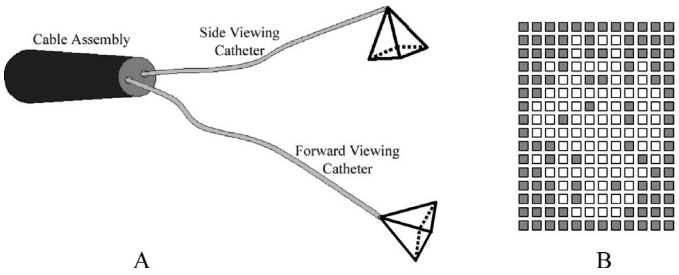

Fig. 5. (a) Schematic depicting two catheters attached to a single cable assembly. (b) Schematic of the active elements (white squares) and the ground elements (gray squares) used during the experiment.

scanner developed at Duke University [12], [13]. The system uses up to 512 transmitters and 256 receive channels with 16:1 receive mode parallel processing to generate a pyramidal volume of 4096 B-mode image lines. From this pyramidal volume, as shown in Fig. 1(a), the scanner can display two simultaneous orthogonal B-mode image planes and up to three C-mode image planes (parallel to the array face) at a rate up to 30 volumes per second. Each image plane can be inclined at any desired angle. By integrating and spatially filtering between two user-selected C-mode planes, the system can display real-time 3-D rendered images [Fig. 1(b)].

Modifications were made to the ultrasound system to allow two 3-D ICE catheters to be attached at the same time as shown in Fig. 5(a). The two transducers, each having two male Precision Interconnect (PI, Wilsonville, OR) PAC connectors, were attached to a PI transducer cable assemble that had seven available female PI PAC connectors. Due to the wiring differences in this cable assembly, compared to the one with which the catheters were designed to be used, each of the transducers had 85 active channels available shown by the white squares in Fig. 5(b).

Once the transducers were attached, phasing data were generated for each element on both of the 2-D arrays. The Volumetrics system is capable of storing in memory three different sets of 3-D phasing data that are accessed by software when a transducer is attached. Under normal use, the system recognizes each transducer by reading a unique identification value that is stored in programmable read-only memory (PROM) located within the transducer cable assembly. By modifying the system's software, we are able to bypass the PROM and assign a static ID value to each catheter transducer. The scanner's touch screen software then was modified to include two buttons to control which transducer was active. When a button was depressed, the system started using the preloaded phase delay data, transmit frequency, and transmit cycles associated with the assigned catheter with a delay of about 1 second. Such a switching feature is standard on conventional 2-D scanners, but to our knowledge it has not been used to image the same structure from multiple views with near simultaneous scanning. As an example, the Siemens Antares system (Siemens Medical Solutions, Ultrasound Group, Issaquah, WA) delays approximately 4 seconds when switching between probes. The time difference between the two

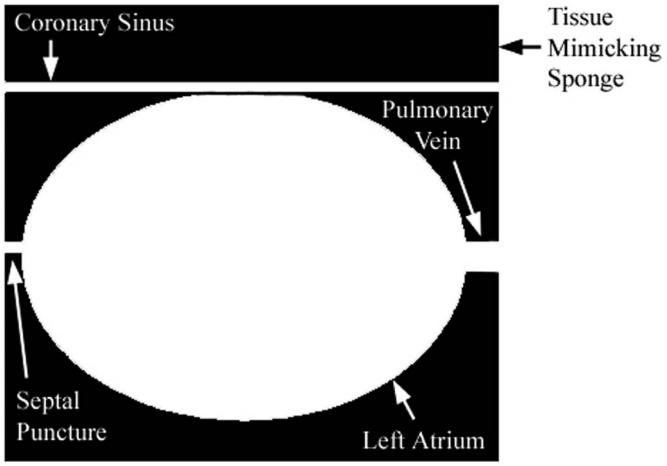

Fig. 6. Schematic of the tissue-mimicking phantom, including the LA, CS, PV, and septal puncture.

ultrasound systems is due to the way the phasing data are stored. The Volumetrics system can store in memory three different sets of phasing data. Once this data is written, it can be accessed quickly during transducer switching. The Siemens system, however, must rewrite the phase delays every time the transducers are switched, accounting for the longer time delay.

Currently, we assign two buttons on the touch screen to two different identification values associated with the catheter transducers. However, we also could use any combination of transthoracic, transabdominal, endoscopic, catheter, and ultrasound therapy probes of annular, linear and 2-D array transducers, limited only by the 3-D system's total available number of transmitters (512) and receivers (256).

C. In Vitro Phantom

A tissue-mimicking phantom was constructed to imitate the LA of the heart (Fig. 6). A cavity was created in the middle of a sponge to imitate the LA with a hole in the chamber wall to emulate the ostium of a PV. A smaller hole was created opposite the PV to give the forward-viewing catheter access to the LA as in an atrial septal puncture. The side-viewing catheter was inserted into a channel created adjacent to the cavity that imitated the coronary sinus. The experiment was conducted by using the side-viewing catheter to track the forward-viewing catheter as it entered and crossed the LA. Once the forward-viewing catheter was near the PV ostium, a button was pressed to activate the forward-viewing transducer. The display planes then were realigned, and the forward-viewing catheter was manipulated to center the PV ostium within the 3-D scan. A needle then was inserted through the accessory port into the lumen to mimic therapy delivery to the region surrounding the PV.

D. Animal Model

The in vivo images in this study were acquired using a canine model. The study was approved by the Institutional Animal Care and Use Committee at Duke University and

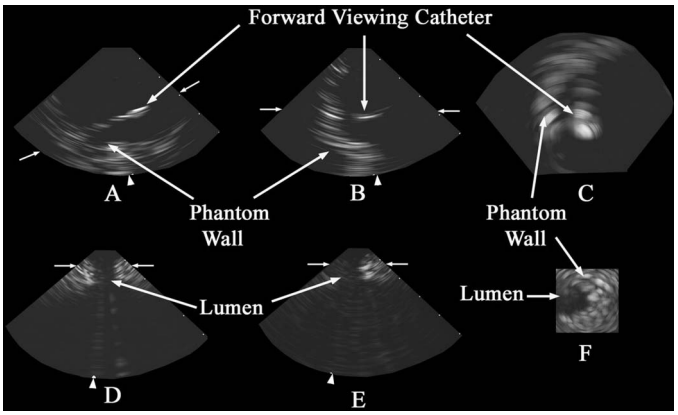

Fig. 7. Image slices from a volume acquired by the side-viewing catheter showing the forward viewing catheter (A–C). Image slices from a volume acquired by the forward-viewing catheter show of the PV (D–F).

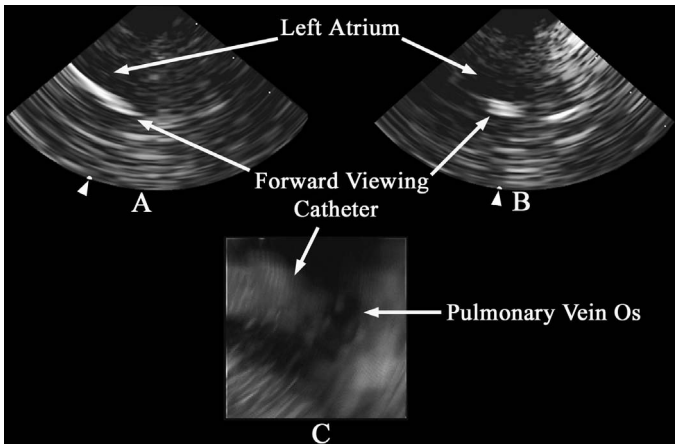

Fig. 8. In vivo side-scanning RT3D rendered view of the PV and forward-viewing catheter.

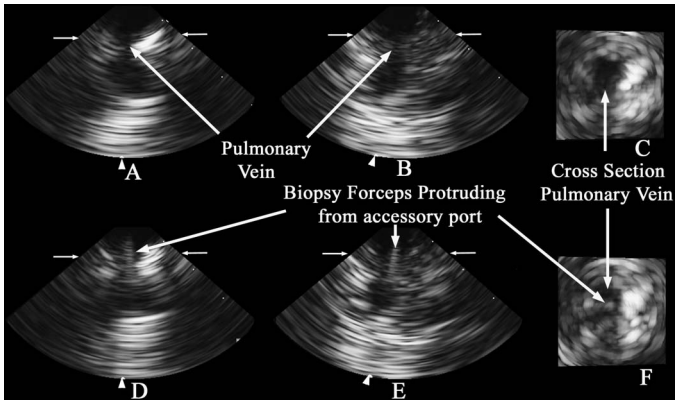

Fig. 9. Forward-viewing catheter images of pulmonary vein before (A–C) and after (D–F) biopsy forceps were inserted into the PV.

conformed to the Research Animal Use Guidelines of the American Heart Association. For this open chest procedure, the heart was exposed by left thoracotomy. The side-viewing catheter then was inserted into the jugular vein and advanced through the superior vena cava and right atrium and directed into the coronary sinus. This transducer provided a 3-D view of the LA and one of the PV. After this view was obtained, the forward-viewing catheter was advanced through a small incision in the left atrial appendage of the LA and directed toward the ostium of the PV while being monitored by the side-viewing transducer. Once in place, we pressed a button on the touch screen to switch to the forward-viewing catheter. After a few adjustments to get the PV into the center of the 3-D scan, closed biopsy forceps were inserted into the PV to mimic therapy delivery.

III. Results

Illustrative images from 5-cm deep 3-D scans of the tissue mimicking phantom are shown in Fig. 7. A volume of data obtained by the side-viewing catheter looking into the LA where the forward-viewing catheter was located is shown in the top three images [Figs. 7(A), (B), (C)]. Fig. 7(A) shows a long axis view of the forward-viewing catheter. Fig. 7(B) shows a short-axis view. Fig. 7(C) is a tilted C-scan showing the forward-viewing catheter in another long-axis view. Once we switched the transducers, we were able to obtain the bottom three images in Fig. 7 while the forward-viewing transducer was about 1 cm away from the PV ostium. The first two views [Figs. 7(D) and (E)] are oblique cuts of the PV lumen in the sponge wall. The third view [Fig. 7(F)] shows a C-scan cross section of the lumen. In each of the B-scan images, the location of the C-scan is shown by the small horizontal arrows. The blunt arrowheads at the base of each B-scan indicate the position of the corresponding orthogonal B-scan.

The in vivo images obtained from the canine study are shown in Fig. 8. The set of images shows a view of the LA obtained from the coronary sinus by the side-viewing catheter. In the top two images, the forward viewing catheter is observed in the LA in long axis [Fig. 8(A)] and in short axis [Fig. 8(B)]. The third image [Fig. 8(C)] shows a RT3D volume rendered view of the forward-viewing catheter within the opening of one of the PV.

The next series of images was obtained within the LA by the forward-viewing catheter. The top series of images show a pulmonary vein in oblique views [Fig. 9(A) and (B)] as well as a cross section of the vein [Fig. 9(C)]. A lumen is clearly visible in these images. The lower series of images [Figs. 9(D)–(F)] are views of the same anatomy with the same orientation described here. These images show biopsy forceps as they were delivered to the target site. The biopsy forceps can be seen in all three views.

IV. Discussion

In this paper, we presented a method for near simultaneous 3-D scanning using multiple 2-D array transducers. Multiple transducers were connected to the scanner and were selected by a specific button on the touch screen of the scanner. This system was used to guide a forward-viewing catheter through the LA toward a PV. The PV ostium then was imaged with the forward-viewing catheter

and biopsy forceps guided to the vein to imitate a therapy delivery device. The ability to switch between a view of the entire LA from the CS and a close-up view of the vein was instrumental to guiding the forward-viewing catheter into place. These results suggest that a system displaying multiple simultaneous volumes could improve catheter guidance within the heart.

Future work on this project may yield improved results that are more clinically relevant. Currently, attempts are being made to alternate scanning between the 3-D probes on a line-by-line basis. We first plan to transmit a single line on one of the catheter probes, then receive on the same probe. The received signal will then be processed and will be stored in an associated volume-storage location. The second probe will then be activated, transmit and receive a line, and store the data in a separate volume-storage location. By separating the receive lines in this manner, we will be able to generate two pyramidal volumes simultaneously. Slices from these volumes will then be displayed using the dual play mode on the Volumetrics Model 1 ultrasound system. This option was originally intended to be used by clinicians to compare resting versus exercise segments collected during a stress echo exam. We hope to modify this dual play mode to update every time new volumes are available in the memory and display either two orthogonal B-scan slices or one B-scan and one C-scan slice from each volume. Such a method would increase the information provided to the clinician.

Another improvement more specific to the images presented would be to improve the image resolution. The transducer cable assembly used during these experiments limited us to only 85 elements in each catheter array, despite the fact that more channels were available on each transducer. We also will consider designing and building new side- and forward-viewing catheters, at different center frequencies, using different proximal connectors and a cable assembly that would increase the number of channels. These changes should improve our ability to resolve the LA and PV.

We have shown in this paper an ability to guide a wire into a 1-cm lumen. To further validate our system, there are two methods we could pursue. The first experiment would require performing our in vitro experiments again, this time guiding a wire into a smaller diameter lumen. A second experiment would involve guiding the forward-viewing catheter into place, inserting an ablation wire down the tool port, creating four lesions around the lumen with the wire, excising the heart, then measuring the difference between lesions location and the desired location.

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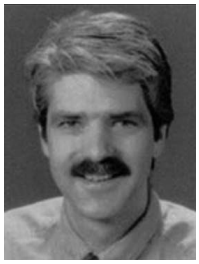

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Dr. Smith is cofounder of Volumetrics Medical Imaging. He has served on the education committee of the American Institute of Ultrasound in Medicine, the executive board of the American Registry of Diagnostic Medical Sonographers, the editorial board of *Ultrasonic Imaging*, and the Technical Program Committee of IEEE-UFFC. He was corecipient of the American Institute of Ultrasound in Medicine Matzuk Award in 1988 and 1990 and corecipient of the IEEE-UFFC Outstanding Paper Award in 1983 and 1994.