Real Time 3D Laparoscopic Ultrasonography

Edward D. Light[1], Salim F. Idriss[2], Kathryn F. Sullivan[1], Patrick D. Wolf[1] and Stephen W. Smith[1]
[1]Department of Biomedical Engineering, Duke University, Durham, NC 27708
[2]Department of Pediatrics, Duke University med Center, Durham, NC 27708

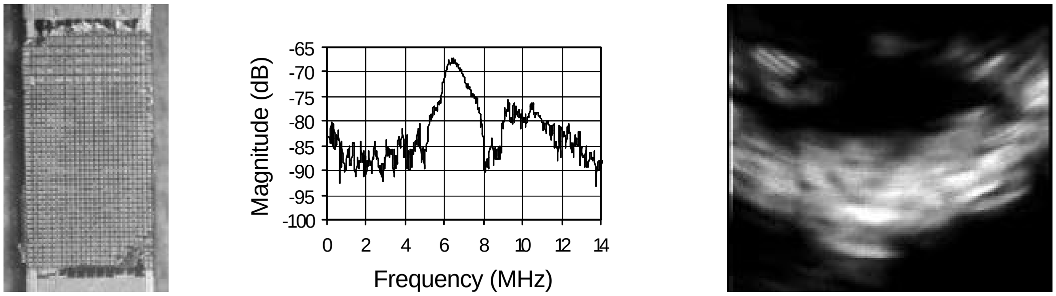
We have previously described 2D array ultrasound transducers operating up to 10 MHz for applications including real time 3D transthoracic imaging, real time volumetric intracardiac echocardiography (ICE), real time 3D intravascular ultrasound (IVUS) imaging. We have recently built a pair of 2D array transducers for real time 3D laparoscopic ultrasonography (3D LUS), and real time 3D transesophageal echocardiography (TEE). These transducers are intended to be placed down a trocar during minimally invasive surgery. The first is a forward viewing 5 MHz, 11 x 19 array with 198 operating elements. It was built on an 8 layer multi-layer flex circuit. The interelement spacing is 0.20 mm yielding an aperture that is 2.2 mm x 3.8 mm. The O.D. of the completed transducer is 10.2 mm , and includes a 2 mm tool port. The average measured center frequency is 4.5 MHz, and the -6 dB bandwidth ranges from 15% to 30%. The 50 Ohm insertion loss, including Gore MicroFlat cabling, is -81.2 dB. The second transducer is a 7 MHz, 36 x 36 array with 504 operating elements. It was built upon a 10 layer multi-layer flex circuit. This transducer is in the forward viewing configuration, and the interelement spacing is 0.18 mm. The total aperture size is 6.48 mm x 6.48 mm. The O.D. of the completed transducer is 11.4 mm. The average measured center frequency is 7.2 MHz, and the -6 dB bandwidth ranges from 18% to 33%. The 50 Ohm insertion loss is -79.5 dB, including Gore MicroFlat cable. Real time *in vivo* 3D images of canine hearts have been made including an apical 4 chamber view from a substernal access with the first transducer to monitor cardiac function. In addition we produced real time 3D rendered images of the right pulmonary veins from a right parasternal access with the second transducer which would be valuable in the guidance of cardiac ablation catheters for treatment of atrial fibrillation.

Key Words: Laparoscopic Ultrasonography, Real Time 3D Imaging, 2D Array Transducer, Trocar

Introduction

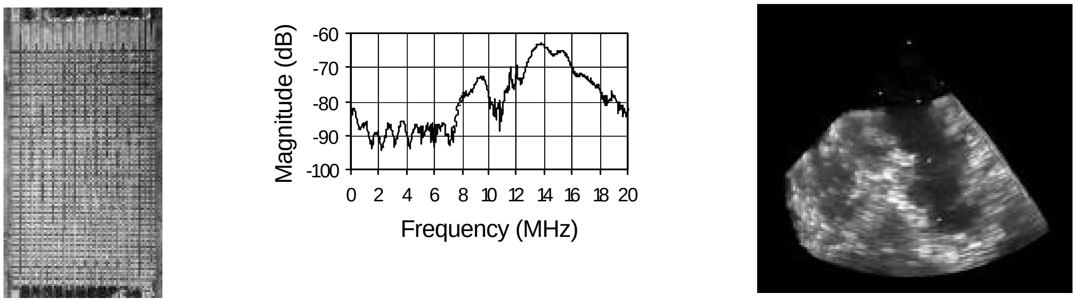
We have been developing 2D arrays for real time 3D ultrasound for many years. From our humble beginnings with 63 element array transducers operating below 2 MHz[1,2], we have grown to develop 200 element arrays operating up to 14.5 MHz that fit into a 10 Fr catheter.[3] Figures 1 and 2 show our recent efforts in developing higher frequency catheter transducers for intracardiac ultrasound. Figure 1A shows a diced 7 MHz transducer. The interelement spacing is 0.20 mm, but the elements have been subdiced at 0.10 mm to suppress lateral vibrations. Figure 1B shows a typical spectrum from this transducer centered at 6.5 MHz with a –6 dB bandwidth of 20%. Figure 1C shows a real time rendered view of the ostium of the coronary sinus (CS) of a canine. The display dynamic range is 48 dB, and the rendered image is about 2 cm x 2 cm. Figure 2A shows the diced array elements of a 14.5 MHz 2D array transducer. The interelement spacing is 0.20 mm, and it has also been subdiced at 0.10 mm. Figure 2B shows a typical spectrum from this transducer. It is centered at 14.5 MHz and has a – 6dB BW of 22% . Figure 2C shows a 4 cm deep real time rendered image of a 1 cm wide and 1 cm deep channel cut out of the surface of a tissue mimicking phantom. The display dynamic range is 48 dB.

Laparoscopic ultrasound (LUS) was developed to help the surgeon regain the information lost due to the use of laparoscopic surgery techniques.[4,5] Typical optical laparoscopes only provide a view of the outer surfaces of the organs. The surgeons lost their tactile feedback and the information they got from their haptic sense. By using ultrasound, surgeons can see beyond the tissue boundaries, giving them feedback into areas that an optical laparoscope cannot. By placing the transducer in direct contact with the organ of interest, higher frequency probes can be used to improve resolution. Commercial LUS systems are all based upon linear arrays of transducer elements in a side scanning configuration. The use of LUS has found acceptance during minimally invasive surgery and cancer staging in the liver[4] and in urological applications. [5]



A B C

Figure 1. A diced 7 MHz 200 channel transducer for intracardiac imaging. Figure 1B shows a typical spectrum centered at 6.5 MHz with a –6 dB bandwidth of 20%. Figure 1C shows a real time rendered view of the ostium of the coronary sinus (CS) of a canine as imaged from the right atrium.



A B C

Figure 2. A diced 15 MHz 200 channel transducer for intracardiac imaging. Figure 1B shows a typical spectrum with a center frequency of 14.5 MHz and a –6 dB bandwidth of 22 %. Figure 2C is the real time rendered view of a tissue mimicking phantom with a 1 cm deep by 1 cm wide groove cut in the top surface. The depth of the scan is 4 cm.

Several recent trends in medicine have given rise to a strong movement to develop minimally invasive surgical procedures in the field of cardiac surgery. [6,7] Minimally invasive surgical procedures have been developed for coronary artery bypass grafts, aortic and mitral valve surgery and repair of atrial septal defects. A frequently described ultimate goal of minimally invasive cardiac surgery is coronary artery revascularization requiring only minimal incisions under video endoscopic guidance performed without the need for cardiopulmonary bypass, without general anesthesia and on an outpatient basis. [6,7] During all of these procedures, it will be important to monitor and evaluate cardiac function. This is typically done with 2D transesophageal echocardiography (TEE) requiring the use of general anesthesia. One goal is to minimize and remove the use of general anesthesia. [8] Also, TEE can be contraindicated in patients with esophageal disease or in patients where the position of the heart has been altered. [9]

There has also been interest in substernal epicardial echocardiography (SEE) where a transducer is placed in a mediastinal drainage tube to image and monitor the heart in post cardiac operation patients. [9] This technique can have advantages over transthoracic echocardiography (TTE) in the case of hyperinflated lungs, difficulty in positioning the patient or if the patient is unable to comply with directions.[9] While transesophageal echocardiography (TEE) can be used in these cases, it cannot be used for prolonged monitoring, is uncomfortable for repeated applications and can be contraindicated as described above.[9]

A real time 3D laparoscopic system can be used in a thoracoscopic application to give feedback on procedures such as bi-ventricular pacing lead placement where small shifts in the location of the pacing leads within the RV or LV have a significant effect on the activation pattern and the cardiac output.[10] Clinical trials indicate the value of minimally invasive surgical placement of epicardial pacing leads for such bi-ventricular pacemakers[11] in a portion of the patient population. A real time 3-D ultrasound laparoscope for measurement of cardiac function would allow immediate feedback during surgery to evaluate the effectiveness of the site of bi-ventricular pacemaker lead placement.

To meet the needs of emerging techniques for minimally invasive heart surgery, new thoracoscopic transducers need to be developed. We have previously described preliminary efforts in this area.[12] In this paper we will describe two new transducers for real time 3D laparoscopic ultrasound. The first is a 5 MHz, 198 channel laparoscopic transducer, the second is a 7 MHz, 504 channel device. While these transducers were initially designed for laparoscopic applications, we have applied them to thoracoscopic procedures to take advantage of our previous expertise in real time 3D cardiac echocardiography.

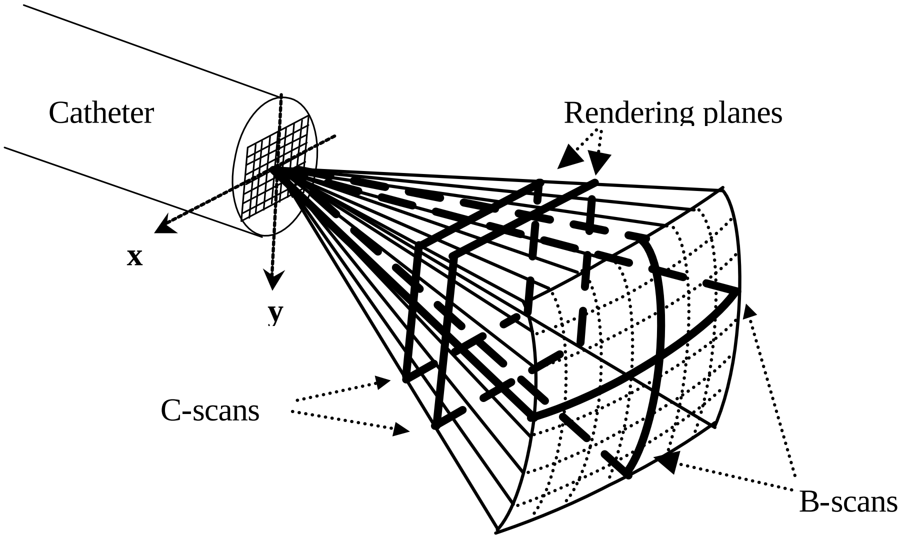


Figure 3. Schematic of the pyramidal scan from catheter 2D array transducer. Bold lines indicate possible display planes. By integrating and spatially filtering between two user selected planes, real time 3D rendered images are displayed.

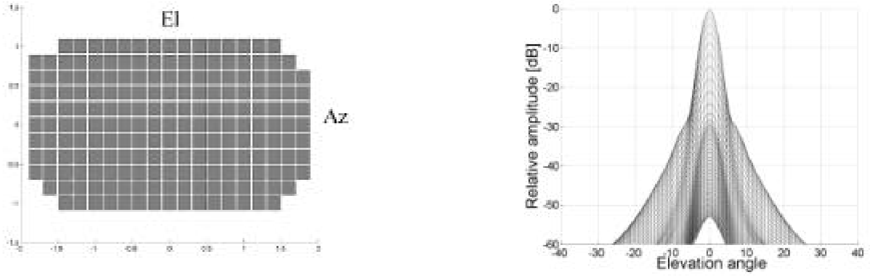
Methods

Volumetric Scanner System

We have previously described our work in real time three dimensional ultrasound imaging.[2,13] We have modified the Duke/Volumetrics 3D scanner as the system platform for imaging with our transducers. The commercial Volumetrics Medical Imaging ultrasound scanner generates a real time 3D pyramidal scan using as many as 512 transmitters and up to 256 receive channels. The scanner uses 16:1 receive mode parallel receive processing to generate 4100 B-mode image lines at up to 30 volumes per second. Figure 3 shows a schematic of image planes (perpendicular to the transducer array) and two C-scan planes (parallel to the array). Each image plane can also be inclined at any desired angle. By integrating and spatially filtering between two user selected planes, e.g. the C-scan planes, the system also displays real time 3D rendered images.[12,14,15] The pyramid angle is typically set at 65 degrees, but we have modified the system to produce up to a 120 degree pyramidal scan for a larger field of view up close to the transducer.[16]

Transducer Design

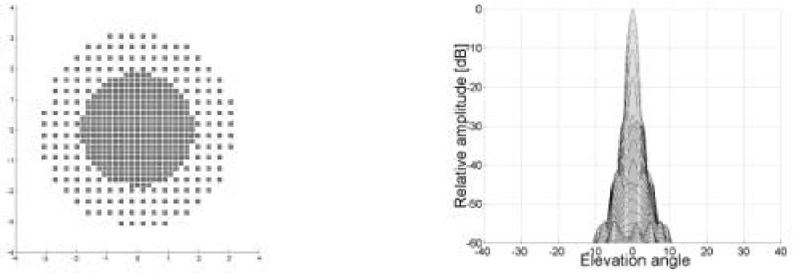
For the 5 MHz laparoscope, we adapted a design we have previously used for a side viewing intracardiac catheter transducer. The transducer was designed to fit into a 10 French catheter and has 198 active elements. Because it was designed to fit into a 10 French catheter, there was a limit to the width dimension of 2.2 mm. To take full advantage of the 198 channels, the device is longer in the elevation dimension. The pattern is shown in figure 4A, and the resulting Field II[17] simulated beam plot yielding a –6 dB beamwidth of 2.4 mm at a depth of 30 mm in figure 4B.



A B

Figure 4. The 2D array pattern for the 5 MHz laparoscope (fig. 4A) and the corresponding Field II simulated elevation beam plot (fig. 4B). The beam plot predicts a –6dB beamwidth of 2.4 mm at a depth of 30 mm.

For the 7 MHz laparoscope, we adapted a design we have previously used for a side viewing transesophageal endoscope.[18] This transducer was designed for 504 active channels to fit into a typical endoscope. The aperture size is limited to 6.5 mm to fit into the ID of the endoscope. The pattern can be seen in figure 5A, and the resulting 7 MHz Field II simulated beam plot in figure 5B. The beam plot predicts a –6dB beamwidth of 2.5 mm at a depth of 60 mm.



A B

Figure 5. The 2D array pattern for the 7 MHz laparoscope (fig. 5A) and the corresponding Field II simulated beam plot (fig. 5B). The beam plot predicts a –6dB beamwidth of 2.5 mm at a depth of 60 mm.

Transducer fabrication, 5 MHz

We built the 5 MHz transducer on an eight layer custom flexible circuit from MicroConnex (Seattle, WA). There are 198 transducer element pads set into the 11 x 19 pattern. The interelement spacing is 0.20 mm. Through vias and traces on the various layers connect the element pads to solder pads arrayed along the length of the flex circuit, shown in figure 6. To build the transducer, 0.29 mm thick PZT-5H from TRS Ceramics, Inc.

(College Park, PA) was attached to the flex circuit with silver epoxy (Chomerics, Billerica, MA). The transducer was then diced with a diamond wheel dicing saw with a 0.025 mm kerf. A 0.012 mm thick layer of liquid crystal polymer (LCP) was attached to the top. The LCP was metallized on both top and bottom to provide an electrical ground return to the top of the elements and an isolated shield ground to cover the front of the transducer. At this point, the flex circuit was bent so that the transducer would be in the forward viewing configuration. A backing was applied and the MicroFlat cables (W.L. Gore, Germany) were soldered to the flex circuit and to the proximal boards for connecting to our system cable. Since the transducer aperture is asymmetric, we added a 2 mm tool port to the side of the transducer to fill in the extra space.

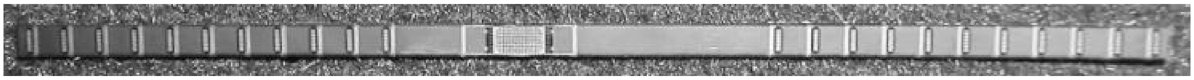


Figure 6. The eight layer flexible circuit used to build the 5 MHz laparoscopic transducer.

Transducer fabrication, 7 MHz

The 7 MHz transducer was built on a 10 layer flex circuit with 504 transducer element pads set in a 36 x 36 array pattern. The interelement spacing is 0.18 mm. Figure 7 shows the flex circuit. The transducer was fabricated in the same way as the 5 MHz, except the array elements needed to be subdiced. Since we want this transducer to operate at 7 MHz, the PZT thickness is 0.19 mm thick. To ensure that the elements will vibrate in the correct mode, they were subdiced at 0.090 mm spacing yielding a width to thickness ratio of 0.37. The four subdiced elements are all electrically connected in parallel.

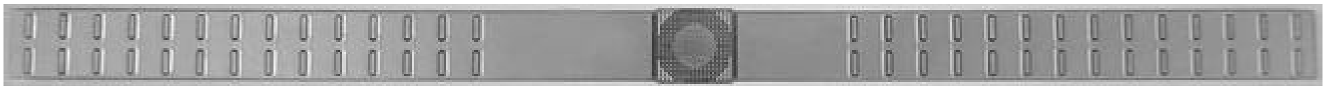


Figure 7. The ten layer flexible circuit used to build the 7 MHz laparoscopic transducer.

Animal preparation

This study procedure was approved by the Institutional Animal Care and Use Committee at Duke University and conforms to the Research Animal Use Guidelines of the American Heart Association. The canine was sedated with ketamine hydrochloride 15-22 mg/kg IM, and an IV established in a peripheral vein. Anesthesia induction was achieved with inhalation of isoflurane gas 1-5% delivered through a nose cone. The animal was placed on its back on a water heated thermal pad and endotracheally intubated. The animal was then placed on its left side and started on a respirator (North American Drager; Telford, PA). A femoral arterial line was placed via a percutaneous puncture or cut down. Electrolyte and respirator adjustments were made based on serial electrolyte and arterial blood gas measurements. An IV maintenance fluid with 0.9% sodium chloride was started and maintained at 5 ml/kg/min. Blood pressure, lead II electrocardiogram, and temperature were continuously monitored throughout the procedure.

For the 5 MHz transducer, a substernal incision was made to allow the transducer to be introduced. The transducer was advanced until it touched the pericardial surface of the heart near the apex of the left ventricle. For the 7 MHz transducer, a right parasternal incision was made so that the transducer could be advanced until it came in contact with the pericardium near the right atrium. The pulmonary valves were imaged using part of the right atrium as a stand off.

Results

5 MHz transducer

Figure 8 shows the completed 5 MHz transducer. Figure 8A shows the diced elements and figure 8B shows the completed transducer inserted into a 12.5 mm O.D. trocar. The 2 mm lumen of the tool port is visible next to the transducer.

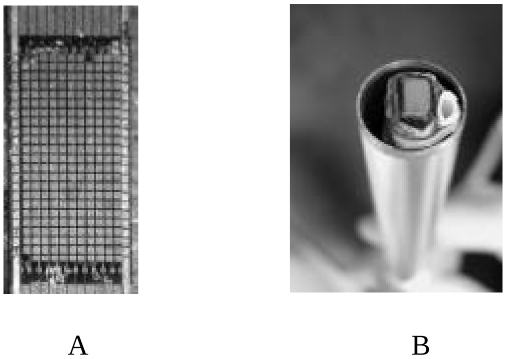


Figure 8. The 5 MHz transducer after dicing (fig. 8A). After completion, the transducer fits into a 12.5 mm (O.D.) trocar. Notice the 2mm tool port (fig. 8B).

Figure 9 shows a typical pulse and spectrum from the 5 MHz transducer. The average measured center frequency is 4.5 MHz, and the -6 dB bandwidth ranges from 15% to 30%. The 50 Ohm insertion loss, including the MicroFlat cabling, is -81.2 dB. The spectrum shows a low frequency peak below 0.5 MHz caused by ringing in the flexible circuit substrate.

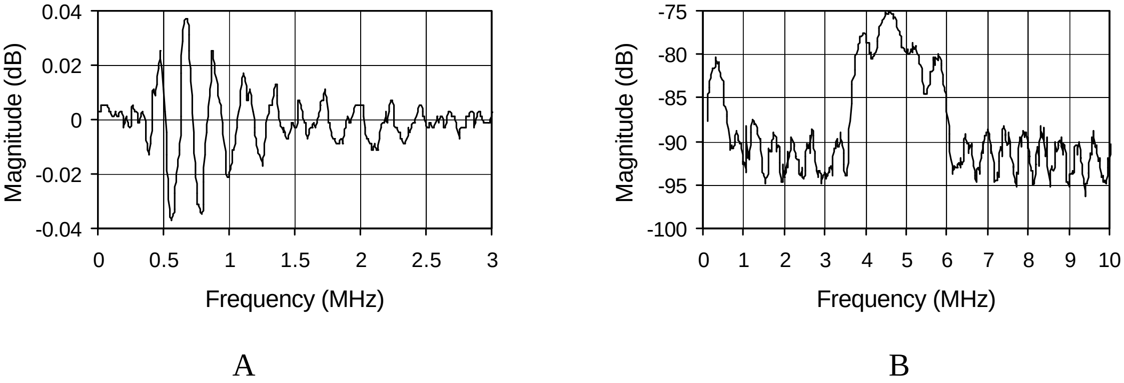
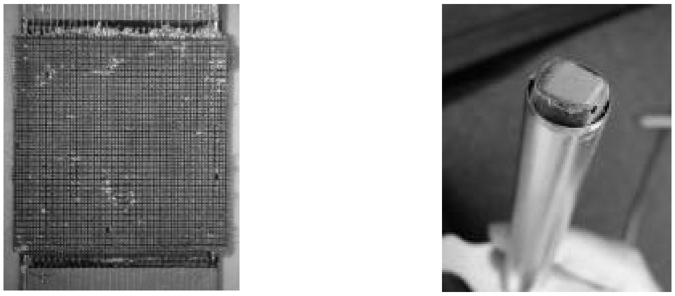


Figure 9. Pulse (fig. 9A) and spectrum (fig. 9B) from the 5 MHz laparoscopic transducer. The measured center frequency is 4.5 MHz and the – 6dB bandwidth is 30%.

7 MHz transducer

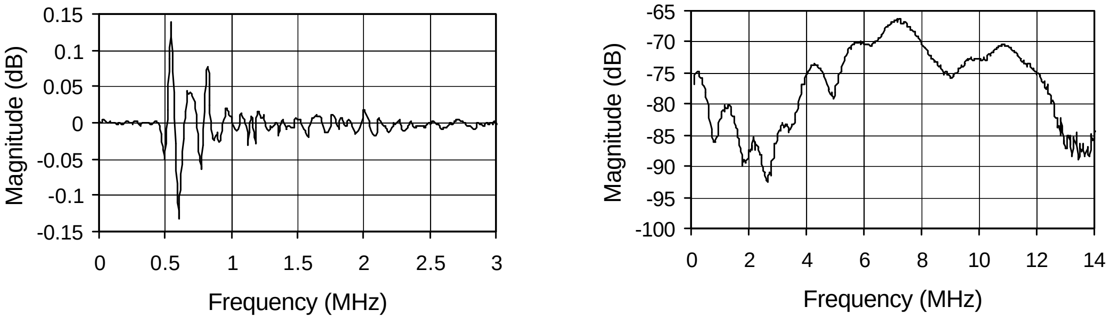
Figure 10A shows the completed diced array for the 7 MHz transducer. The elements have been subdiced. Figure 10B shows the completed transducer inside a 14 mm (O.D.) trocar. Since the transducer aperture is symmetric, this transducer comes closer to filling the area of the trocar than the 5 MHz transducer.

Figure 11 shows a typical pulse and spectrum from the 7 MHz transducer. The average measured center frequency is 7.2 MHz, and the -6 dB bandwidth ranges from 18% to 33%. The 50 Ohm insertion loss is -79.5 dB, including the MicroFlat cable. This spectrum also shows a low frequency peak below 0.5 MHz caused by ringing in the multi layer flexible circuit substrate.



A B

Figure 10. The completed diced 7 MHz transducer. The elements have been subdiced (fig. 10A). After completion, the transducer fits into a 14 mm O.D. trocar (fig. 10B).

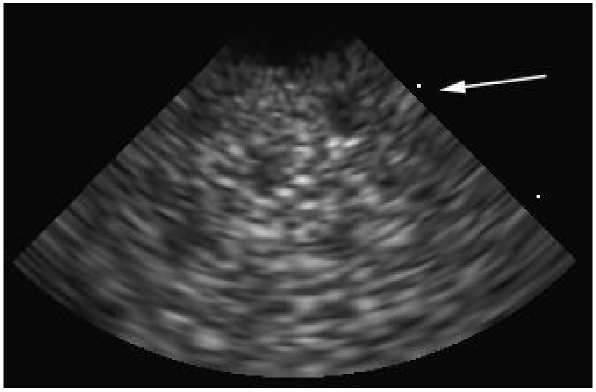


A B

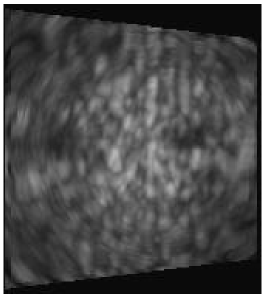
Figure 11. Pulse (fig. 11A) and spectrum (fig. 11B) from the 7 MHz laparoscopic transducer. The measured center frequency is 7.2 MHz and the – 6dB bandwidth is 33%.

Images

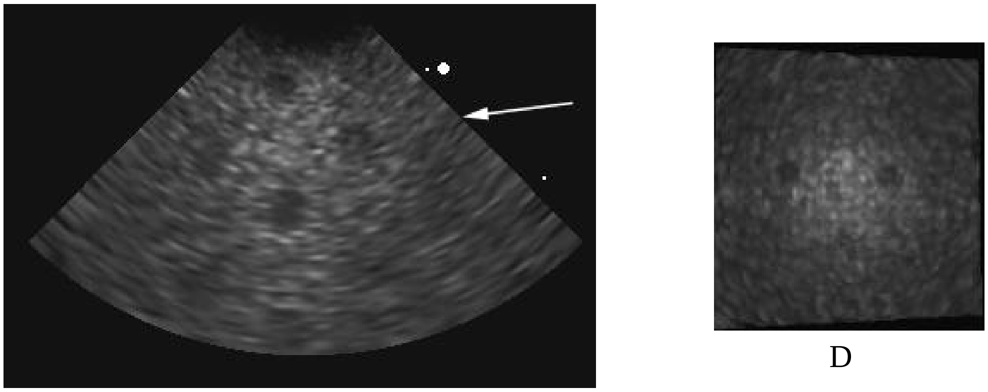
All images have a display dynamic range of 48 dB. Figure 12 shows images from an RMI Model 408 spherical lesion phantom (Middleton, WI). The lesions are 4 mm in diameter. Figure 12A shows a 3cm deep 90º B-Scan made with the 5 MHz laparoscope and fig. 12B shows a corresponding C-scan made at the level of the arrow shown in fig. 12A. Figures 12C and D show images made in the same phantom with the 7 MHz transducer. As expected from the increase in frequency and aperture size versus the 5 MHz transducer, the lesions are better defined with the 7 MHz transducer. We also see a finer speckle pattern.



A



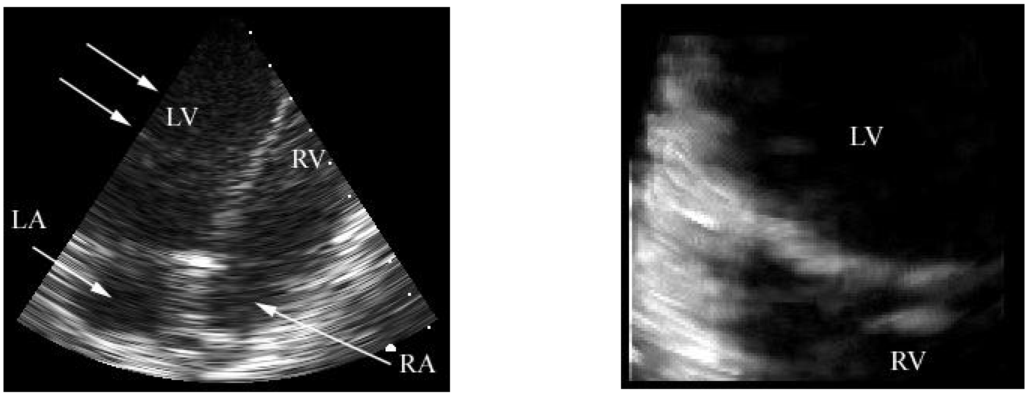
B



C D

Figure 12. Images from the RMI spherical lesion phantom. Figure 12A is a 3 cm deep 90º B-scan, and fig. 12B is the corresponding real time C-scan made at the plane indicated by the arrow. Both images were made with the 5 MHz laparoscopic transducer. Figures 12C and 12D show the same phantom using the 7 MHz laparoscopic transducer. The higher frequency and larger aperture of the 7 MHz transducer result in an improved image with better boarder detection of the lesions and a finer speckle pattern.

Figure 13 shows a 4 chamber view of a canine heart made with the 5MHz laparoscopic transducer. The image was made by inserting the transducer through a substernal incision in the chest. Figure 13A shows a 10 cm deep 65º B-scan including all 4 chambers of the heart. Figure 13B is the real time rendered view across the ventricular septum as indicated by the arrows in the left of 13A.



A B

Figure 13. A 4 chamber view (fig.13A) of a canine heart made with the 5 MHz laparoscopic transducer showing the left ventricle (LV), right ventricle (RV), left atrium (LA) and right atrium (RA). The arrows in the left of the image indicate the rendering planes. The real time rendered view (fig. 13B) nicely shows the ventricular septum. The images were obtained from a substernal incision in the chest wall.

Figure 14 shows a view of the right pulmonary veins (PV) in a canine model made with the 7 MHz transducer. We inserted the transducer via a right parasternal incision in the chest. Figure 14A shows a 6 cm deep 90º B-scan with the two pulmonary veins labeled. The rendering planes are indicated by the arrows on the right side of the image. Figure 14B shows the real time rendered view of the same pulmonary veins. In both views the opening of the pulmonary veins is easy to see, making it easy to guide a cardiac ablation catheter.

A B

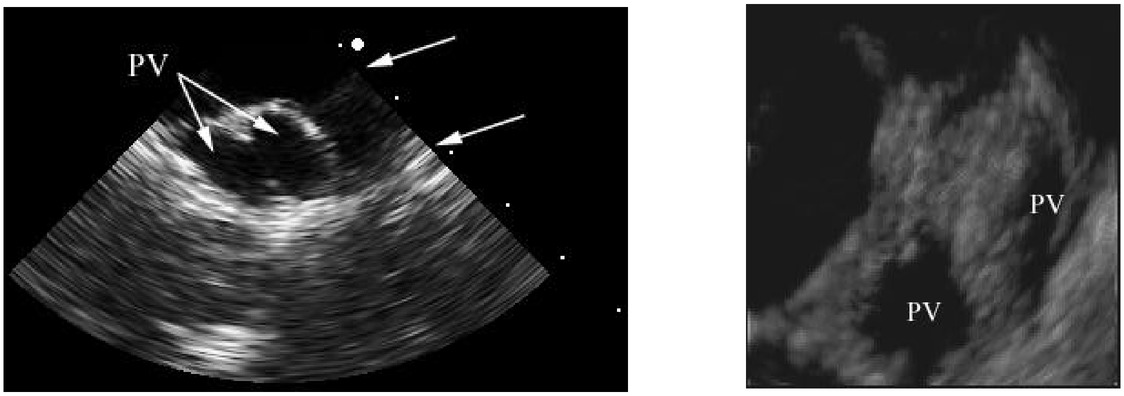


Figure 14. Images of the right pulmonary veins (PV) in a canine. The images were made from a right parasternal incision in the chest wall. Figure 14A is a 6cm deep 90º B-scan and shows the two PV's in cross section. Figure 14B is a real time rendered image if the ostium of the PV's. The arrows on the right side of figure 14A indicate the rendering planes.

Discussion

We were able to successfully adapt our flex circuits that were designed for side looking transducers to forward viewing devices. Bending the flex circuit to allow the 90º change could have damaged the traces and reduced element yield. However, this did not happen. By sub dicing our elements, we were able to increase the frequency versus previous transducers built on these flex circuits.

Figures 12-14 show our image quality and utility of our transducers for real time 3D laparoscopic ultrasound imaging. While we used the transducer to show cardiac structures, we believe they will perform equally well in abdominal laparoscopic procedures. We were initially concerned about the depth of penetration for these transducers. The 5 MHz transducer only has 198 channels in a relatively small aperture. Even though the 7 MHz transducer has 504 channels, our imaging system is not designed for imaging at this frequency.[19] While the images of the phantom in figure 12 are good, they are only 3 cm deep. However, the 5 MHz transducer still penetrates 10 cm into the heart when placed upon the heart wall (figure 13A). The excellent images of the pulmonary veins in figure 14 show that by getting the transducer close enough, the 7 MHz device has enough penetration to image important structures of the heart. These preliminary results are encouraging for the use of these transducers for guiding minimally invasive procedures as well as monitoring cardiac function both during these procedures and post operatively.

Image quality can still be improved. While we are close to reaching the frequency response limit of our imaging system, we have shown we can build 2D array transducers operating up to 14.5 MHz. An imaging system with a wider frequency response would allow us to make clinically useful images at higher frequencies. Also, acoustic matching layers would improve our bandwidth and gives us a 6 dB improvement in sensitivity. This would give us better axial resolution and deeper penetration.

Acknowledgements

We would like to thank Olaf von Ramm, John Castellucci, Greg Bredthauer and Johnny Kuo for their aid in making the images with the 15 MHz transducer on their new prototype real time 3D imaging system. We also thank Ellen Dixon-Tulloch for her work during the *in vivo* study. This research was supported by NIH grants HL 72840 and HL 64962 and NSF grant DMR-0313764.

References

1. Smith, S. W., Trahey, G. E., and von Ramm, O. T., Two-dimensional arrays for medical ultrasound, *Ultrasonic Imaging 14*, pp. 213-233 (1992).
2. Smith, S.W., Pavy, H.E., and von Ramm, O.T., High speed ultrasound volumetric imaging system part I: transducer design and beam steering, *IEEE Trans. Ultras., Ferro. and Freq. Control 38*, pp. 100-108 (1991).
3. Light ED, S., SW, Two-dimensional arrays for real-time 3D interluminal ultrasound imaging (abstract only). *Ultrasonic Imaging*, 2004. **26**: p. 266-267.
4. Kolecki, R. and Schirmer, B., Intraoperative and laparoscopic ultrasound, *Sug clin north Am* 1998; vol. 78, pp. 251-271.
5. Matin S.F. and Inderbir S.G., Laparoscopic ultrasonography, *Journal of Endourology*, 2001, Vol. 15, pp. 87-92.
6. Minimally invasive cardiac surgery, Cohen, Mack, Fonger,Landreneau , eds.,Quality Medical Pub., St Louis, MO, 1999.
7. Minimally invasive cardiac surgery, Oz MC and Goldstein DJ, eds., Humana Press, Totowa, NJ, 1999.
8. T Aybek, S Dogan, G Neidhart, P Kessler, G Matheis, G Wimmer-Greinecker, A Moritz, Coronary Artery Bypass Grafting Through Complete Sternotomy in Conscious Patients, Heart Surgery Forum 4,32987, 2001.
9. Reynolds, H.R., Nayar, A.C., McAleer, E.P. et al, Substernal epicardial echocardiography: review of a new technique, *Journal of the American Society of Echocardiaography*, vol. 16, no. 11, pp, 1204-1210, 2003.
10. Lister JW, Klotz DH, Jomain SL, Stuckey JH, Hoffman BF, Effect of Pacemaker Site on Cardiac Output and Ventricular Activation in Dogs with Complete Heart Block. *Am J Cardiol*. Vol 14:494-503, 1964.
11. Quan KJ, Biblo LA, Gill IS, Izutani H, Biventricular pacing for congestive heart failure: early experience in epicardial lead placement vs. coronary sinus placement, *Inter. Soc. Min. Inv. Surg*., June 21, 2002.
12. Lee, W., Idriss, S.F., Wolf, P.D. and Smith, S.W., Dual lumen transducer probes for real-time 3-D interventional cardiac ultrasound, *Ultrasound in Med & Biol 29*, No. 9, pp. 1297-1304 (2003).
13. von Ramm, O.T., Smith, S.W**.**, and Pavy, H.E., High speed ultrasound volumetric imaging system part II: parallel processing and display, *IEEE Trans. Ultras., Ferro. and Freq. Control 38*, pp. 109-115 (1991).
14. Light, E.D., Idriss, S.F., Wolf, P.D. and Smith, S.W., Real time three dimensional intracardiac echocardiography, *Ultrasound in Med & Biol 27*, No. 9, pp. 1177-1183 (2001).
15. Smith, S.W., Light, E.D., Idriss, S.F. and Wolf, P.D., Feasibility study of real time three dimensional intracardiac echocardiography for guidance of interventional electrophysiology. *Pacing and Clinical Electrophysiology 25*, No. 3, pp. 351-357 (2002).
16. Lee, W., Idriss, S.F., Wolf, P.D. and Smith, S.W., A miniaturized catheter 2-D array for real-time 3D intracardiac echocardiography *IEEE Trans. Ultras. Ferro. And Freq. Control,* 51, 1334-1346, 2004.
17. Jensen, J. A. and Svendsen, N. B., Calculation of pressure fields from arbitrarily shaped, apodized, and excited ultrasound transducers, *IEEE Trans. Ultrason. Ferro. and Freq. Control 39*, pp. 262-267 (1992).
18. Pua, E.C., Idriss, SF, and Wolf, PD and S.W. Smith, Real-time 3D transesophageal echocardiography, *Ultrasonic Imaging,* 26, 217-232, 2004.
19. Ligh**t**, E.D. and Smith, S.W., Two dimensional arrays for real time 3D Intravascular Ultrasound, Ultrasonic Imaging, No. 26, pp 115-128, 2004.