Carotid Peak Blood Velocity Detection using a 5-Plane CMUT Array with Asymmetric Acoustic Lens: Initial Results

Der-Song Lin[1], Xuefeng Zhuang[1], Jessica Faruque[2], Ömer Oralkan[1], Sandy Napel[2], R. Brooke Jeffrey[2], and Butrus T. Khuri-Yakub[1]

[1]E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305
[2]Department of Radiology, Stanford University, Stanford, CA, 94305
Email: xzhuang@stanford.edu

***Abstract* – We report on the initial results on a 5-plane CMUT array built on a single silicon substrate for operator-independent carotid artery screening. The array is used for color flow Doppler detection of peak blood velocity (PBV), which is correlated with carotid stenosis. Asymmetric acoustic lenses provide fixed angle off-axis beam steering for color flow Doppler. In the proposed system, first, five parallel short-axis B-mode and color flow images of the carotid artery are obtained. Then, a custom software package automatically finds the center points of the blood flow, computes the vessel trajectory, Doppler angle and angle-corrected peak velocities. The fabricated CMUT arrays showed a center frequency of 8.1 MHz and a fractional bandwidth of 103% in immersion. In resonant frequency measurement in air, the uniformity across the array is excellent, with a standard deviation of 0.18% of the mean. Initial experiments on asymmetric acoustic lenses verified the off-axis steering capability. Using the in-house software package and a commercial 1D array, the calculated peak blood velocity has an error of less than 6%, when the Doppler angle is less than 45^o.**

***Key words* – CMUT; asymmetric acoustic lens; carotid stenosis; Doppler; peak blood velocity; automatic computation; operator independence**

I. INTRODUCTION

Stroke is the third leading cause of death in the United States [1]. In many cases, atherosclerotic stroke is caused by carotid stenosis (narrowing of the carotid artery due to fatty deposits on the artery side walls). Doppler ultrasound is a widely available screening tool for carotid stenosis. In the screening procedure, the peak blood velocity (PBV) in the carotid artery, which is correlated to carotid stenosis, is measured. However, in the current procedure, the technologist needs to align the ultrasound probe longitudinally with the carotid artery, and carefully position the probe in order to locate the peak blood velocity. Then, the technologist needs to manually position cursors on the ultrasound machine to determine the Doppler angle, which is essential for the accurate calculation of the PBV. Thus, the current procedure is highly dependent on the technologist. It not only requires a highly trained professional, but also makes the procedure lengthy (15-30 min). Moreover, the measurement results are prone to intra- and inter-operator variability.

We propose to use five parallel 1D CMUT arrays on a single substrate with asymmetric lenses to obtain five parallel B-mode and color flow images of the carotid artery. Custom-built board-level electronics interface the 5-plane array with a commercial ultrasound imaging system. In the elevation direction asymmetric acoustic lenses steer the acoustic beam at fixed angles for color flow Doppler measurements. A custom software package automatically computes the vessel trajectory, Doppler angle and angle-corrected peak velocities for the 5-plane transducer array.

II. METHODS AND RESULTS

A. System Overview

The goal of the proposed carotid screening system is to eliminate operator dependence, thus making it more reproducible and clinically accessible than the conventional method. This goal can be achieved by using five 1D transducer arrays located on a single substrate. CMUTs are well suited for this application because of the demonstrated performance advantages for carotid imaging [2], and the ease of array manufacturing, due to parallel micro-fabrication. Asymmetric acoustic lenses are formed on each array in the elevation direction. A custom-designed circuit board interfaces the CMUT array with a commercial ultrasound system (in our case a Siemens Antares system) via a standard probe cable. The board provides the needed DC biasing network, and the electronic circuits to switch between the five individual arrays. Minimal modifications to the existing ultrasound systems are needed to accommodate the CMUT arrays and the interface board. Thus, five cross-sectional B-mode and color flow images of the carotid artery can be obtained. A software package developed in-house then determines the center point of each cross-sectional slide of the vessel in the color flow image. The program uses this information to automatically compute the vessel trajectory, Doppler angle and angle-corrected peak velocities for the 5-plane transducer array. The system concept is illustrated in Figure 1.

This work is supported by the Stanford Bio-X Interdisciplinary Initiatives Program. Work was performed in part at the Stanford Nanofabrication Facility of NNIN supported by the National Science Foundation under Grant ECS-9731293.

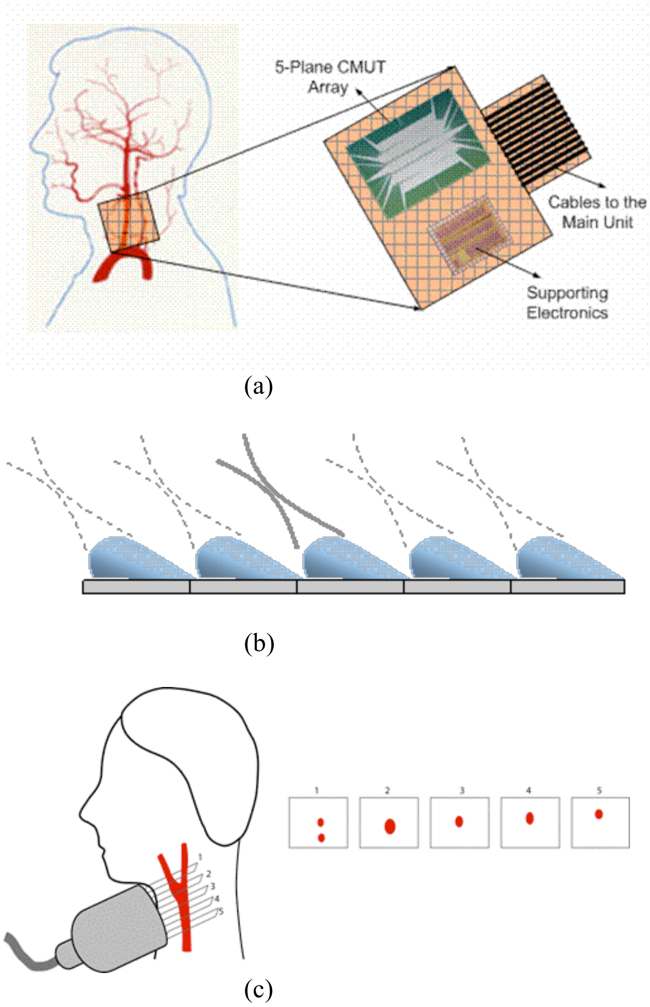


Figure 1. System concept for a new carotid screening tool based on a 5-plane CMUT array. (a) CMUT array and the interface board. (b) Asymmetric acoustic lens on each 1D array for fixed angle off-axis beam steering in the elevation direction. (c) Diagram of cross-sectional carotid images obtained using the proposed scheme.

B. *5-Plane CMUT Arrays*

CMUT arrays are designed to be interchangeable with a Siemens VF 13-5 SP ultrasound probe to minimize modification to the ultrasound system. Thus, the geometry of each 1D array (200 μm by 4 mm element size) as well as the center frequency (7.5 MHz) is determined by those of the VF 13-5 SP probe. To improve the device uniformity, two additional dummy CMUT elements are included on either side of the 128 active elements. The active array area is roughly 25 mm by 25 mm (Figure 2). The CMUT cavities are square shaped, with a side length of 40 μm. The membrane is made of 1.5-μm-thick single-crystal silicon. The vacuum cavity is 0.15 μm, over a 0.3 μm thick silicon oxide insulation layer. For such a design, the expected membrane resonant frequency is 12.11 MHz in air at 40 V DC bias, and the collapse voltage is 91 V. The key physical parameters of the CMUT array are summarized in Table I.

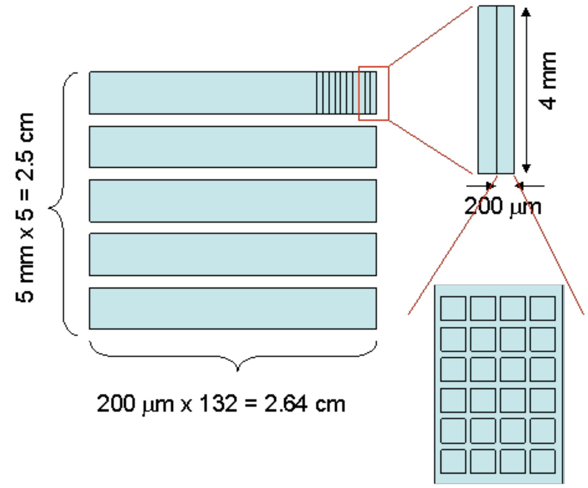
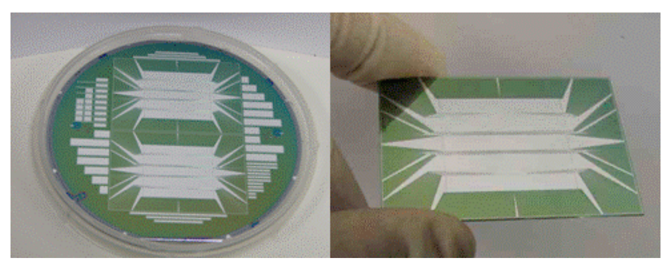


Figure 2. Active array area illustration.

Table I. Physical parameters of the 5-plane CMUT array.

Number of elements	132x5
Azimuth element pitch (μm)	200
Elevational element pitch (mm)	5
Elevational element size (mm)	4
Square membrane width (μm)	40
Vacuum cavity height (μm)	0.15
Insulation layer thickness (μm)	0.3
Membrane thickness (μm)	1.5
Aluminum layer thickness (μm)	0.3
Silicon substrate thickness (μm)	400
Chip length (mm)	53
Chip width (mm)	37



(a) (b)

Figure 3. (a) A 4-inch silicon wafer after the completion of fabrication. The center two devices are 5-plane CMUT arrays; the periphery contains test devices. (b) A 5-plane CMUT array diced off from the wafer.

The arrays are fabricated using SOI wafer-to-wafer fusion bonding [3]. CMUT cavities are first defined on a silicon wafer using oxidation and buffered oxide etching. An SOI wafer with a membrane silicon layer is fusion bonded to the device side of the first SOI wafer and annealed at 1000 ^{o}C. The handle wafer is then grinded back and removed in a heated tetramethylammonium hydroxide solution. The ground contact areas are patterned and etched. An aluminum layer is sputtered on the silicon membrane and the ground contact region. Following that, the aluminum top electrode, and the silicon membranes are patterned and etched to electrically separate the array elements. Device pictures after the completion of fabrication are shown in Figure 3. In the first demonstration, a simple fanout structure is used for electrical connections to the array elements from the front side of the substrate. The total chip size is enlarged to 53 mm x 37 mm due to the electrical connection traces. In future designs, through-wafer trench-isolated interconnects will be used to realize a reduced chip size. This will not only result in a more ergonomic ultrasound probe, but also result in more chips on a silicon wafer, thus reducing the cost.

We first tested the CMUTs in air using an impedance analyzer (Model 8751, Hewlett-Packard Company, Palo Alto, CA). The measured resonant frequency is 11.98 MHz at 40 V_{dc}, 0.13 MHz (1.1%) less than design target of 12.11 MHz. Across a 1D array, the resonant frequency showed a uniform distribution, with a standard deviation of 0.18% of the mean (Figure 4). Therefore, in air testing, the fabricated CMUTs showed excellent match to design targets.

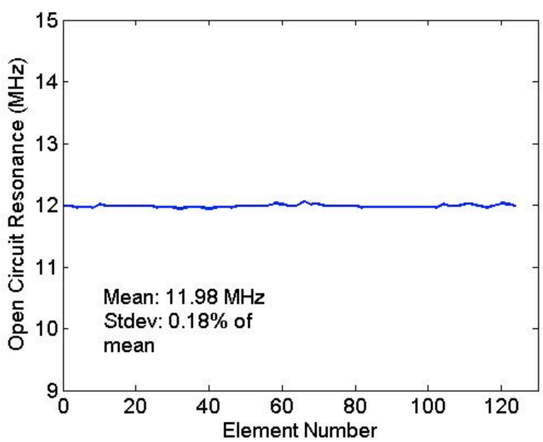


Figure 4. Resonant frequency distribution across a 1D array.

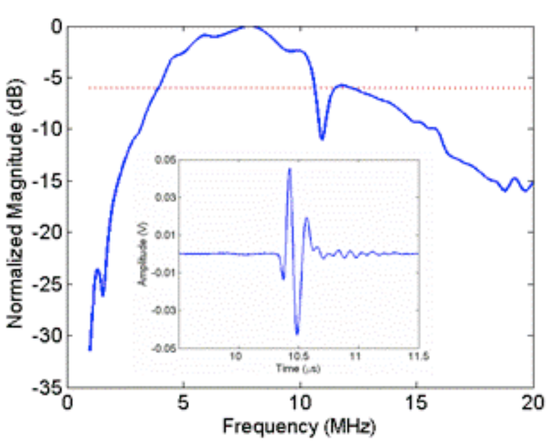


Figure 5. Pulse-echo signal, and corresponding spectrum.

Pulse-echo experiments were performed using a pulser-receiver (Model 5058PR, Olympus NDT, Waltham, MA 02254) in soybean oil. The oil-air interface was used as a plane reflector. The CMUT showed a center frequency of 8.1 MHz, and a 6-dB fractional bandwidth of 103% (Figure 5). The notch in the frequency spectrum at around 11 MHz is due to acoustic reverberation in the 400-μm silicon substrate. It can be pushed out of the operating spectrum by making the substrate thinner. The acoustic output pressure increased as the DC bias voltage and the AC excitation voltage increased (Figure 6). Using an 80-V DC bias and a 100-V, 50-ns AC excitation, the output pressure on the CMUT surface was measured to be 1.6 MPa p-p.

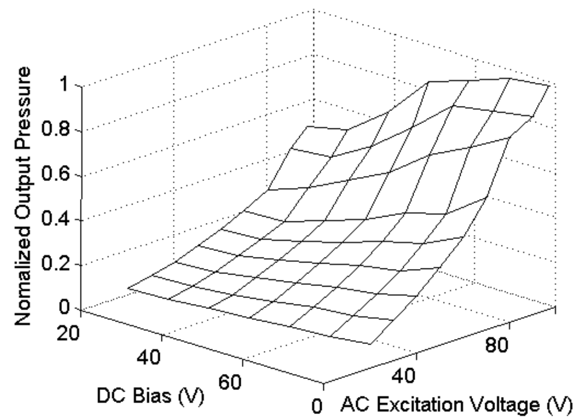


Figure 6. Normalized output pressure as a function of DC bias and AC excitation voltages.

C. Asymmetric Acoustic Lenses

For five parallel 1D arrays built on a single substrate, asymmetric acoustic lenses can provide an ergonomic means of achieving off-axis steering. Such off-axis beam steering is needed for Doppler measurements. We propose to use polydimethylsiloxane (PDMS, a kind of silicone rubber) as the lens material. As a first step, the effects of PDMS coating on CMUT were studied. A finite element model which accounts for the viscoelastic nature of the PDMS was developed [4]. In essence, viscoelasticity means that the Young's modulus of the coating material should be considered differently for static (low frequency) and dynamic (high frequency) conditions. This model is able to accurately predict the static behavior, e.g. DC collapse voltage, and the dynamic behavior, e.g. AC membrane displacement, simultaneously.

As a second step, we investigated off-centered cylindrical acoustic lenses. The basic principle of off-axis steering is illustrated in Figure 7(a). A simple calculation yields that, to achieve as large of a steering angle as possible (small Doppler angle), the ratio between the acoustic velocity in the lens material and that in water, should be as large as possible [Figure 7(b)]. Common types of PDMS possess acoustic velocities that would yield maximum steering angles of 20^o-25^o. In a first experiment, an off-centered cylindrical lens was formed on a 1D CMUT element. A four-degree steering angle was measured. A better lens material with a slower acoustic velocity is desired to achieve a larger steering angle.

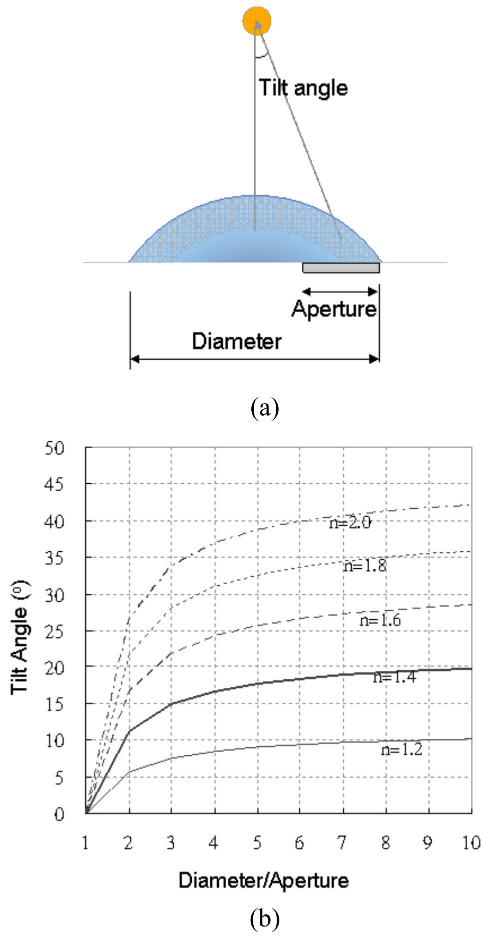


Figure 7. (a) Illustration of off-axis beam steering using an off-centered cylindrical lens. (b) Tilt angle as a function of the ratio of acoustic velocities in the lens material and in water ($n = v_{water}/v_{lens}$).

D. *PBV Calculation*

PBV is automatically computed once color flow images are obtained from the five parallel 1D arrays. The computation is carried out using a software package developed in-house. In our preliminary experiments, the five color flow Doppler images, overlaid on B-mode images, are obtained using a commercial 1D array. A mechanical fixture is built so that the 1D array is tilted at a fixed angle, and can slide along a rail. We imaged a straight tube vessel phantom, pumping blood-mimicking fluid through the tube to simulate blood flow in an artery (Figure 8). The software first removes the background B-mode images from the color flow Doppler images extracted form the ultrasound imaging system. Then, the software determines the center points of the vessel cross sections in the color flow images. Using this information, the vessel trajectory and thereby the angle between the transducer and the vessel is calculated. The PBV can then be found out by correcting for the Doppler angle. When the Doppler angle is less than 45°, the PBV calculated using the proposed scheme has an error of less than 6% when compared to that determined by the conventional method.

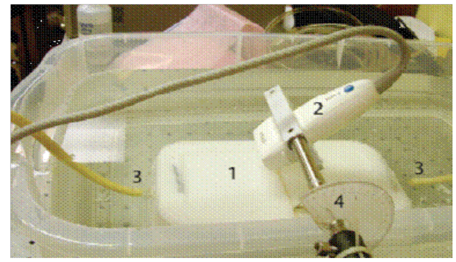


Figure 8. Setup of using a 1D array to obtain five cross-sectional color flow Doppler images of a phantom.

III. SUMMARY AND FUTURE WORK

A new screening method for carotid stenosis is proposed. The key components of the system include a 5-plane CMUT array, asymmetric acoustic lenses, an electronic interface board, and a software package for automatic PBV calculation. We have completed the design, fabrication and testing of the first generation 5-plane CMUT arrays. The arrays showed uniform element-to-element performance, and are suitable for the proposed application. Preliminary experimental results validate the viability of the asymmetric acoustic lenses. An in-house software package has been developed for PBV calculation once the five color flow Doppler images are obtained.

For future work, we will develop 5-plane CMUT arrays with through-wafer interconnects for compact packaging. We will test different materials to find the best lens material for improved steering angle. We are currently designing the supporting electronics to connect the 5-plane array to the ultrasound system, provide the needed DC biasing network, and switch between the arrays.

ACKNOWLEDGEMENT

The authors would like to thank Siemens Medical Solutions for loaning the Siemens Antares ultrasound system, and for providing valuable advice on system interfacing. We would also like to thank the Taylor Lab at Stanford for providing us with the ultrasound phantom.

REFERENCES

[1] American Stroke Foundation (http://www.americanstroke.org/content/view/36/56/).
[2] D. M. Mills, "Medical imaging with capacitive micromachined ultrasound transducer (cMUT) arrays," in *Proc. IEEE Ultrason. Symp.*, 2004, pp. 384-390.
[3] Y. Huang, A. S. Ergun, E. Haeggstrom, M. H. Badi, and B. T. Khuri-Yakub, "Fabricating capacitive micromachined ultrasonic transducers with wafer-bonding technology," *IEEE/ASME J. Microelectromech. Syst.,* vol. 12, pp. 128-137, 2003.
[4] D. S. Lin, X. Zhuang, S. H. Wong, M. Kupnik, and B. T. Khuri-Yakub, "A viscoelastic finite element model for polymer coatings on CMUTs," in *Proc. IEEE Ultrason. Symp.*, 2008.