Progress in CMUTs for HIFU ablation of upper abdominal cancer

Serena H. Wong, Mario Kupnik, B.T. Khuri-Yakub
Department of Electrical Engineering
Stanford University
Stanford, CA USA

Ronald D. Watkins, Kim Butts Pauly
Department of Radiology
Stanford University
Stanford, CA USA

Abstract — High intensity focused ultrasound (HIFU) guided by magnetic resonance imaging (MRI) is a noninvasive treatment that can potentially reduce morbidity, lower costs, and widen accessibility for patients with upper abdominal cancers. Traditionally, piezoelectric transducers are used for HIFU, but recent developments in capacitive micromachined ultrasonic transducers (CMUTs) have made them competitive. Previously, we designed, fabricated, and tested HIFU CMUTs for use under MRI guidance and demonstrated successful unfocused heating of a HIFU phantom. In this paper, we use this CMUT design in the construction of an 8-element, equal area, concentric ring array for ablation of upper abdominal cancers. We report on the measurement of the beam profile of the transducer and compare it to models; in addition, we report on the effects of acoustic crosstalk on this array.

Keywords - CMUT, HIFU, MR-guidance

I. INTRODUCTION

Recently, high intensity focused ultrasound (HIFU) treatment guided by magnetic resonance imaging (MRI) has become popular because it reduces patient morbidity, lowers costs, and increases accessibility of treatments. For example, resection of metastatic colorectal cancer increases 5-year survival from 8% to 30%, but only 20% of patients are suitable for resection. For the remaining 80%, a noninvasive treatment, like MRI-guided HIFU, would greatly improve their outcome.

In previous work, we demonstrated that CMUTs have advantages including fabrication flexibility, improved bandwidth, and high power performance with minimal loss, compared to piezoelectric transducers. We also designed, fabricated and tested a CMUT cell design specifically developed for HIFU [1]. This CMUT cell design demonstrated a continuous wave (CW) output pressure of 1.7 MPa peak-to-peak for periods over an hour with minimal self-heating and degradation of response. This same cell design was also fabricated into a 2.5 mm by 2.5 mm, unfocused transducer, which was used to demonstrate unfocused heating. This test transducer heated a HIFU phantom by 18.6°C after 5 min, and was successfully monitored using MR temperature maps [2]. While we demonstrated that even an unfocused CMUT could provide the necessary reliability and output pressure to heat a region of tissue effectively, a focused transducer would heat tissue more rapidly in localized regions. In this paper, we report on the progress of a focused CMUT array designed for CW therapeutic treatment of upper abdominal cancers.

II. SYSTEM DEVELOPMENT

A. CMUT Design and Fabrication

An 8-element, equal-area concentric ring array with 3 cm diameter was designed to focus 35-55 mm into tissue and target 2-4 mm lesions in the focal plane for upper abdominal cancer ablation [3] (Fig. 1).

Each element in the array consists of close-packed circular CMUT cells, with 70 μm radius, 6 mm conductive membranes, and 0.4-mm large gaps, designed for operation at 2.5 MHz and 1.5 MPa peak-to-peak output pressure, as demonstrated in [1] (Fig. 2). The cells were fabricated using the wafer bonding process, which allows greater uniformity and flexibility in cell design.

After fabrication, the arrays were diced and then glued to a printed circuit board (PCB) with conductive epoxy. Wire bonds were used to connect the device pads to the PCB.
B. Electronics Design and Development

For HIFU operation, continuous wave focusing involves shifting the phase of the pressure wave from each element to cause the wave fronts to constructively interfere at the focal point (Fig. 3). The electronics we developed consisted of a direct digital synthesizer (DDS9m, Novatech Instruments, Inc., Seattle, WA), 4 channel phasing board, capable of sinusoidal signals up to 170 MHz with a resolution of 0.1 Hz. The DDS9m also has 14 bit programmable phase, translating to a resolution of 0.022 degrees. The AC signal was then amplified by 1 W (ZHL-3A-S) amplifiers (Minicircuits, Brooklyn, NY); a second bank of custom-designed 20 W amplifiers were also build and used when more power was needed. The AC signal from the amplifiers was then superimposed with a DC bias voltage using a bias T. The resulting signal was applied to the CMUT elements, each of which was tuned to 50 ohms using an air core inductor for efficient power transfer (Fig. 4).

III. Measurement Methods

The transducer array was immersed in a tank of soybean oil, which provided electrical insulation and also had acoustic properties similar to homogenized liver [4]. The tank was then placed on a motorized and electronically controlled x-y stage.

![Cross section of ring array with equation and figure](image)

Fig. 3: Calculation of the delays necessary to focus a ring array.

![Electronics system](image)

Figure 4: Electronics system used to drive the different array elements of the array.

For beam profile measurements, the electronics were connected to the four center elements and the phases were changed to focus the array to 35 mm. A continuous wave, 15 Vpp signal with bias voltage of 140 V was applied to each element. A hydrophone (HNV-0400, Onda Corporation, Sunnyvale, CA) was immersed in the oil and positioned 35 mm from the surface of the transducer. The array was scanned in the focal plane over a 15 mm squared area with 0.2 mm step size surrounding the focal point to form a beam profile in the focal plane (Fig. 5).

The measured beam profile was compared with a simulated beam profile of the four center elements. We used Huygen’s Principle for the calculation, which assumes the array is composed of a collection of spherical point sources.

![Figure 5: Beam profile comparison](image)
Acoustic crosstalk can cause deviations between the measured and calculated beam profile, depending on the design of the CMUT. The dispersive guided mode, which travels along the solid-liquid interface, is the primary cause of acoustic crosstalk between elements. These modes are determined by the periodic structure of the cells and propagate along the surface of the membranes, which causes cells in the same element to be out of phase. In addition, when the wave travels from one element to the other, it causes undesirable excitation of neighboring elements.

To measure the acoustic crosstalk effects, we applied 140 V bias voltage to the center element of the array and excited it with a 30 cycle, 2.5 MHz, 50 Vpp tone burst. The displacement of the transducer surface across a line passing through the center of the array elements was then measured using a laser interferometer (Polytec OFV511, Polytec Corporation, Tustin, CA). In this way, we generated a time-dependent, 2-D measurement across the diameter of the transducer spanning all the elements (Fig. 6). In addition, we measured the center displacements of cells in the middle of each element and compared the maximum amplitude of these displacements. In this way, we could determine the degree of crosstalk between neighboring elements.

IV. RESULTS

The measured beam profile matches well with the expected profile (Fig. 7). The lack of symmetry on the right of the profile...
in the beam profile is caused by the asymmetry in the actual array due to the need for front-side interconnects. These interconnects affect the cylindrical symmetry of the array. Looking at a slice of the beam profile through the diameter of the array, we see that the beam width is nearly the same; the measured beam width is slightly smaller than the calculated, but the side lobe energy is increased.

From crosstalk measurements, cells in neighboring elements showed a center displacement at least 10 dB down from the displacement of the excited element. We found surface waves traveling at 1182 m/s, which are related to dispersive guided modes (Fig. 8). This acoustic crosstalk causes the effective aperture to be increased, which decreases the beam width slightly, as observed in the beam profile. In addition, acoustic crosstalk waves also cause phase errors in neighboring elements, which increases the side lobe energy. Acoustic crosstalk causes the measured gain of the array (16.6) to be less than the calculated gain (27.4).

The agreement with the model is promising for developing an 8-element ring array for HIFU. However, the design of the array will need to be changed to improve the yield of large area rings. Because very small defects short very large areas, we can reduce the effects of these small defects by using a segmented 2-D array design, with switches connected to the backside electronics to remove the elements with defects. This reduces the amount of area that is affected by a defect, and allows us to retain enough area for ring array focusing.

V. CONCLUSION

CMUT membranes designed for non-invasive HIFU have been fabricated and tested. We have also demonstrated focusing of 4 elements in a concentric ring array. The measured and simulated beam profile matched very well; crosstalk effects were minimal and the amplitude of displacement of neighboring cells was depressed by 10 dB, which is sufficient for HIFU. However, we were unable to implement a full 8-element array because the yield of a large area device is quite difficult. In order to improve this yield, we can segment the device into smaller elements and simply eliminate the elements that have defects. By segmenting into smaller pieces, we reduce the amount of area that affected by a small area defect, such as oxidation defects and bonding defects. In addition, we could improve processing to reduce oxide breakdown by growing thicker post oxide and protecting the oxide using a layer of nitride. We can also improve the bonding quality by using hydrophilic surface treatments. In the future, we plan to build a full-scale ring array for liver ablation that is more robust to small fabrication defects.

ACKNOWLEDGMENT

This work is supported under NIH R01 CA77677, R01 CA 121163, F31 EB007170-02.

REFERENCES


Fig. 8: Graph showing crosstalk wave propagating at 1182 m/s.