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Evaluation of temperature rise in a tissue mimicking material during HIFU exposure

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Abstract. In pre-clinical testing it is essential to characterize clinical high intensity focused ultrasound (HIFU) devices using tissue-mimicking materials (TMMs) with well known characteristics, including temperature rise and cavitation properties. The purpose of this study was to monitor cavitation behavior and correlate its effect with temperature rise in a HIFU TMM containing an embedded thermocouple. A 75-μm fine wire thermocouple was embedded in a hydrogel-based TMM previously developed for HIFU. HIFU at 1.1 and 3.3 MHz was focused at the thermocouple junction. Focal pressures from 1-11 MPa were applied and the temperature profiles were recorded. Three hydrophones were used to monitor cavitation activity during sonication. A hydrophone confocal with the HIFU transducer and a cylindrical hydrophone lateral to the HIFU beam were used as passive cavitation detectors for spectral analysis of signals, and a needle hydrophone placed beyond the HIFU focus was used to record changes in the pressure amplitude due to blockage by bubbles at or near the focus. B-mode imaging scans were employed to visualize bubble presence during sonication. In a separate measurement, schlieren imaging was used to monitor the change in field distribution behind the TMM. All hydrophone methods correlated well with cavitation in the TMM.

1. Introduction
A reusable hydrogel-based tissue mimicking material (TMM), which has both thermal and acoustic properties close to that of soft tissue, has been developed in order to characterize the output of HIFU devices [1]. During HIFU exposure, the occurrence of cavitation can either enhance or diminish the treatment. In order to further characterize the cavitation phenomena in the TMM, and correlate cavitation detection techniques with temperature rise, experiments were done to expose the TMM to HIFU pressures, record the temperature rise at the focus using embedded thermocouples (TCs) and monitor the occurrence of cavitation with hydrophones placed at several locations. B-mode imaging was employed to visually monitor the effects of cavitation on HIFU temperature measurements. The reusability of the TMM was determined by performing the same set of exposures on one TMM over several weeks.

2. Materials and Methods

2.1. System Setup
The setup of the experiment is shown in Fig. 1. The driving electronics consisted of a function generator and power amplifier. A 50 dB dual-directional coupler, two power sensors and a power...
2.2. Experimental Protocol

The TC was positioned at the HIFU focus using low ultrasound power. The needle hydrophone was positioned for maximum output also using low ultrasound power. Each TMM was sonicated using 20 s exposures, starting at the lowest pressure level (level 1) and the temperature rise and the three hydrophone responses were recorded before, during and after sonication. B-mode images were taken during and after sonication. Each TMM underwent the complete range of sonications three times, first while the TC was positioned at the HIFU focus, next after the TC was moved 1 cm radially from the focus, and last, after the TC was moved back to the focus. To determine reusability of the TMM, one TMM was used three times, one week apart for each sonication, for a total of seven data sets. For the
1.1 MHz sonications, the focal pressure range was approximately 1 to 5 MPa. For the 3.3 MHz sonications, the focal pressures range was approximately 1 to 11 MPa.

2.3. Calculation of Threshold Pressures and Temperature Analysis
In order to obtain a more accurate assessment of the actual acoustic pressure at the focus within the TMM, simulations from a two-layer nonlinear propagation model based on the KZK equation were performed using the measured acoustic power, transducer focusing geometry, and attenuation coefficient of the TMM [2]. The simulation yielded the axial pressure and intensity waveforms, the axial harmonic distribution and the pressure waveform on the axis at the location of peak positive pressure. Directly from the simulation, we obtained the peak negative pressure and the time averaged intensity. For establishing the cavitation threshold, we used the pressure derived from the computed spatial-peak, temporal-average intensity. Both peak negative pressure values (P -) and pressure values derived from intensity (P calc = \sqrt{2I/\rho c}) are listed in Table I.

The temperature measured by the TC at the end of sonication (EOS) may be different than the actual temperature were the TC not present due to viscous heating of the TC [3] or TC-mediated cavitation at the TC junction. To correct for these rapidly decaying measurement artifacts, the thermal decay curve, beginning 2 s after the EOS, was extrapolated back to the ultrasound "off" time [4]. An example of a normal heating curve with an overlay of the cubic fit is shown in Fig. 2a Other TC artifacts (thermal conduction due to the metal of the TC or distortion of the ultrasound beam due to the wire) are unlikely to be significant due to the small thermocouple wires.

Table I. Pressure Values obtained from Simulation for 1.1 and 3.3 MHz sonications.

| Sonication level | 1.1 MHz | 3.3 MHz |
|------------------|---------|---------|
| P (MPa) | P calc (MPa) | P (MPa) | P calc (MPa) |
| 1 | 0.7 | 1.1 | 1 | 1.4 |
| 2 | 1.4 | 2.1 | 2.6 | 4.4 |
| 3 | 2.0 | 3.1 | 3.9 | 7.4 |
| 4 | 2.6 | 4.2 | 4.5 | 9.1 |
| 5 | 3.2 | 5.2 | 5.1 | 10.9 |
| 6 | 3.7 | 6.3 | 5.6 | 12.7 |
| 7 |  | 6 | 14.7 |  |
| 8 | 6.4 | 16.6 |  |

3. Results
3.1. Thermally Significant Cavitation Threshold Results at 1.1 and 3.3 MHz
Our standard for indication of cavitation, against which we compared the different cavitation monitoring techniques, was the observation of anomalies in the temperature trace. At 1.1 MHz, 13 sets of exposures were done in five TMMs. The average cavitation threshold value was first calculated for each TMM. Then the average cavitation threshold value from the five TMMs was calculated as 4.3 ± 1.2 MPa if P calc was used and 2.7 ± 0.5 MPa if P was used. Cavitation in the five TMMs occurred between pressure levels 3 and 6. For all cases in which the sonication level was below the cavitation threshold, the temperature traces were well behaved (Fig. 2a), the needle hydrophone signal was either constant or slowly changing, the two PCD signals were both flat and the B-mode imaging showed at the most slight streaking [5]. An example of the signals seen at a post-cavitation level is shown in Fig. 2b. In this case, anomalies in the temperature trace occurred at 9 s and continued until the end of sonication. A hyperechoic region in the B-mode images is seen at the start of the sonication
and at 5 s, but then seems to elongate at 9 s. At the end of sonication, the elongated bubble pattern persists. Both PCDs showed low frequency broadband noise indicative of inertial cavitation, with strong spikes at and after 9s. The needle hydrophone output decreased significantly after 9 s.

At 3.3 MHz, eight sets of exposures were done in three TMMs. The final average cavitation threshold value calculated as 12.5 ± 3.0 MPa if $P_{calc}$ was used and 5.4 ± 0.8 MPa if $P_{c}$ was used.

Figure 2. (a) Example of pre-cavitation detection in TMM; (b) Example of cavitation in TMM. The HIFU transducer is located to the right of the B-mode images.

3.2. Reusibility of the TMM
One TMM was used to assess reusability. A full set of exposures was done on this TMM at three different times. The average temperature rise and standard deviation of the EOS temperature results were calculated at each level when cavitation did not occur and are given in Table II

4. Discussion and Conclusions
For all cases where the sonication level was below the cavitation threshold, the temperature traces were normal, the hydrophone signals contained no sudden transitions and the B-mode images contained very little, if any, acoustic interference. When anomalies in the temperature trace indicative of cavitation were observed, there was correlation between the output of the three hydrophones and strong acoustic interference in the B-mode images, often followed by a persistence of bubble clouds in the region surrounding the focus. The B-mode images showed multiple interference patterns centered at the focus, often times culminating in a bubble cloud elongated in the direction of the HIFU beam axis.

| Level | T rise (°C) | STDev |
|-------|-------------|-------|
| Level 1 | 1.7 | 0.2 |
| Level 2 | 6.6 | 0.2 |
| Level 3 | 14.3 | 0.3 |
| Level 4 | 25.3 | 1.2 |
| Level 5 | 38.3 | 1.2 |

Table II. Average temperature rise and standard deviation of the EOS temperature results in one TMM.

Anomalies also were seen in the needle hydrophone signal such as noisy jumps and overall decrease of signal. However, at 1.1 MHz, 10% of cases produced uncertain results in that the temperature traces were well behaved but a decrease in the needle hydrophone signal was seen (Fig. 3a), indicating a change of transmitted energy that was not due to blocking by thermally significant cavitation. This phenomenon was seen in nearly half the cases at 3.3 MHz and was much more
pronounced (Fig. 3b). In order to understand the reason for the decrease in signal, exposures were performed in a schlieren system (Optison, Onda Corp., Sunnyvale, CA), so that the transmitted ultrasound field could be imaged (Fig. 4). It was found that while the total transmitted energy distal to the TMM may not have decreased with time, the spatial distribution changed, which affected the needle hydrophone output. Since the levels used were below cavitation thresholds, we hypothesized that temperature changes could be causing acoustic property changes and hence altering distal intensity profiles via refraction. Therefore, another test was performed in which a small volume of the TMM around the focus was heated by passing a DC current through the thermocouple (Peltier heating). The TMM was then sonicated with very low pressure ultrasound (< 1 MPa, <<1° C temperature rise at focus). As shown in Fig. 5, the needle hydrophone signal was affected. We therefore believe that changes in temperature-dependent quantities such as acoustic impedance are occurring in the TMM that affect the distal beam. Therefore, one should be aware that slowly varying changes in the needle hydrophone output may not indicate cavitation phenomena. This affect was much more pronounced at the higher frequency and happened over a larger range of mid-level pressures.

Fig. 3. Needle hydrophone anomaly during normal temperature rise at (a) 1.1 MHz and (b) 3.3 MHz.

Fig. 4. Example of schlieren image of HIFU beam passing through TMM. As the TMM was heated at sub-cavitation threshold levels, the distal (lower) beam pattern was seen to distort, possibly due to refraction caused by temperature-induced impedance changes in the TMM in the perifocal region.
In summary, when anomalies in the temperature trace were observed, the various cavitation monitoring techniques produced corresponding results. Of the several methods studied for detecting cavitation, the needle hydrophone was a convenient adjunct to spectral analysis for evaluating cavitation activity in the TMM at 1.1 MHz but not at 3.3 MHz. The TMM proved to be reusable for cavitation experiments since non-cavitation temperature results varied very little each time the TMM was used.

Reference

[1] R. L. King, B. A. Herman, S. Maruvada, K. A. Wear, G. R. Harris, “Development of a HIFU Phantom,” Proceedings for 6th International Society on Therapeutic Ultrasound, Oxford, UK, 2006, pp 351-356.

[2] J. Soneson, “A User-Friendly Software Package for HIFU Simulation,” Proceedings for 8th International Society on Therapeutic Ultrasound, Minneapolis, MN, 2008, pp. 165-169.

[3] H. Morris, I. Rivers, A. Shaw, and G. ter Haar, “Investigation of the viscous heating artifact arising from the use of thermocouples in a focused ultrasound field”, Phys. Med. Biol, (53), 2008, pp. 4759-4776.

[4] S. Maruvada, Y. Liu, B.A. Herman and G.R. Harris, “Temperature Measurements in Tissue-Mimicking Material during HIFU Exposure,” Proceedings for 8th International Society on Therapeutic Ultrasound, Minneapolis, MN, 2008, pp. 286-290.

[5] C-C Wu, C-N Chen, M-C Ho, W-S Chen, and P-H Lee, “Using the acoustic interference pattern to locate the focus of a high-intensity focused ultrasound (HIFU) transducer,” Ultrasound Med. Biol., 34 (1), 2008, pp. 137 – 146