

# TIME-COURSE CHARACTERIZATION OF HIGH-INTENSITY FOCUSED ULTRASOUND EXPOSURE USING B-MODE ULTRASOUND IMAGING

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## 1 Introduction

High-Intensity Focused Ultrasound (HIFU) is an emerging non-invasive surgical technique. HIFU systems are generally designed to deliver a fixed amount of energy to tissue, but because the tissue thermal response is variable across patients and tissue type, this approach can often lead to underdosing or overdosing. In order to improve the dosing precision in HIFU we are investigating real time monitoring of the energy deposition process through high-frequency diagnostic ultrasound imaging. Ultimately the development of monitoring techniques will allow real-time adjustment of energy to obtain optimal treatment. We present results from an exploratory study into the transient response of HIFU exposure in phantoms and animal tissue. The transient response observed in the B-mode ultrasound images is due to a combination of the thermal-acoustic lens effect, thermal expansion of the medium and cavitation. These preliminary experiments will inform the development of new image analysis techniques for determining dosage received in tissue during HIFU exposure.

## 2 Method

### 2.1 HIFU System

HIFU deposition was performed in phantoms and chicken breast using a commercial HIFU system across a range of energy levels at a frequency of 4MHz. HIFU deposition points had an exposure duration of 40ms and a focal spot diameter of 100 $\mu$ m. Energy levels of 0.75J and 1.2J were used, corresponding to an intensity level of approximately 60kW/cm<sup>2</sup> and 95kW/cm<sup>2</sup> respectively.

### 2.2 Imaging system

Imaging was performed with a Visual Sonics Vevo 2100 50 MHz ultrasound imaging system with 40 $\mu$ m resolution and a maximum B-mode frame rate of 1000Hz. The imaging plane was taken at an angle 105 degrees from the axis of HIFU deposition.

### 2.3 Overview of Experiments

Temperature recordings were obtained in the region surrounding the HIFU focal spot during deposition in a polybutadiene rubber phantom material. Recordings were obtained at a sampling interval of 35ms using a 200 $\mu$ m diameter, type T thermocouples (Omega HYP-0).

To investigate the effect of a HIFU focal spot on the resulting ultrasound image, a 21-gauge needle was inserted into the polybutadiene rubber phantom material such that its edge was approximately 2mm distal to the HIFU focal spot in the imaging plane. The effect of HIFU deposition on the

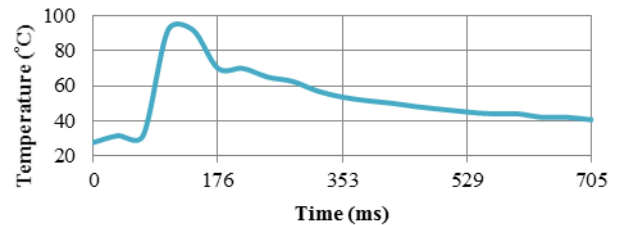
appearance of the straight and stiff metal needle as observed in the acquired ultrasound image was analyzed.

Lastly, HIFU deposition was performed in chicken breast. The acquired time-course images of the HIFU focal spot were analyzed using ImageJ software to obtain intensity decay plots of characteristic features.

## 3 Results

### 3.1 Thermocouple Measurement

An average of two thermocouple measurements obtained in the polybutadiene rubber phantom material before, during, and after HIFU exposure at 1.2J is shown in Figure 1. A peak temperature greater than 90°C was reached at the end of the 40ms HIFU exposure period. After HIFU was turned off, measured temperatures decreased as a result of diffusion.



**Figure 1:** Temperature profile of HIFU deposition in phantom material with values prior to, during and after exposure as obtained by thermocouple measurements at the HIFU focal spot.

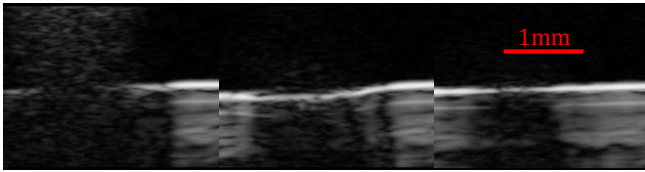
### 3.2 HIFU Deposition in Phantom Material

The time course of the ultrasound images indicated that shadowing distal to the focal spot temporarily prevented the needle from being observed. The extent of this shadowing was dependent upon the energy level. In Table 1, the maximum deflection of the needle was measured when its edge reappeared in the image.

Energy Level (J)	0.75	1.20
Shadow Width immediately post HIFU (mm)	1.0	1.45
Time of Max Deflection post HIFU (ms)	676	907
Max Deflection Width (mm)	2.2	2.32
Max Deflection Height (mm)	0.12	0.18
Deflection Height 4 seconds post HIFU (mm)	0.03	0.05

**Table 1:** Resulting deflection of the embedded needle as observed in the ultrasound image following HIFU deposition

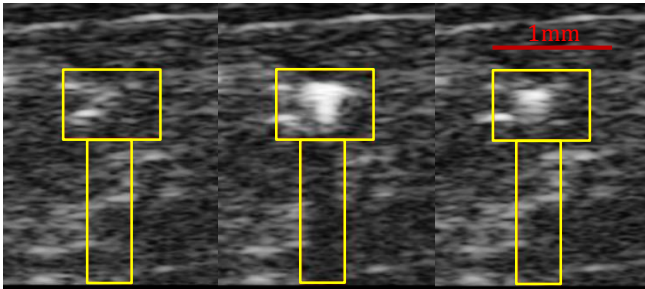
The results indicate that changing the energy level of deposition will alter the observed curvature of the needle. The observed deflection of the needle is not permanent and 4 seconds post HIFU the needle has almost returned to its original straight line form. An abbreviated time course of the ultrasound images is shown in Figure 2.



**Figure 2:** Effect of HIFU deposition in the phantom material on a straight metal needle: (left) immediately post HIFU, (middle) time of max deflection, (right) 4 seconds post HIFU

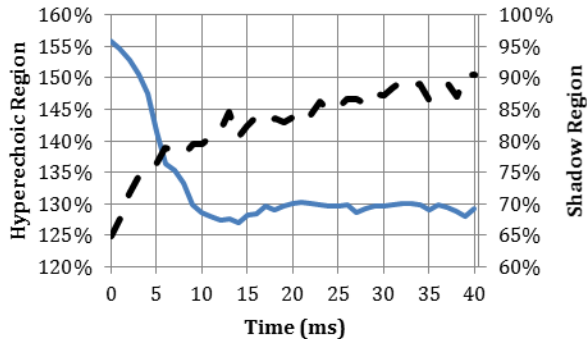
### 3.3 HIFU Deposition in Chicken

The deposition of HIFU in chicken breast at an energy level of 1.2J resulted in the formation of a hyperechoic region and signs of shadowing at distal locations in the captured B-mode ultrasound images. As shown in figure 3, these characteristic features were transient over time.



**Figure 3:** HIFU deposition in chicken breast as observed with B-mode ultrasound images: (left) prior to HIFU, (middle) immediately post HIFU, (right) 0.5 seconds post HIFU. Top box shows hyperechoic region and bottom box shows shadowing.

Referring to figure 4, immediately after HIFU exposure the mean greyscale value of the hyperechoic region in the ultrasound image was 55% greater than pre-exposure levels. A higher greyscale value corresponds to a whiter area in the ultrasound image. Within 10ms after HIFU exposure, the mean reduced to a steady state that was 30% above pre-exposure values. The tissue in the hyperechoic region appeared to shrink and contract as the tissue cooled, which could be the effect of thermal expansion in the tissue. The mean greyscale value of the shadow region rose logarithmically towards pre-exposure levels. In the first 40ms post exposure, the mean of the shadow region increased from 65% to 90% of pre-exposure greyscale values.



**Figure 4:** Mean greyscale value of regions in ultrasound images following HIFU exposure in chicken breast relative to pre-exposure values. Solid line (left axis) represents hyperechoic region and dashed line (right axis) represents shadow region.

## 4 Discussion

The high temporospatial resolution of the Vevo 2100 allows for a unique time-course characterization of the material response to HIFU exposure. Gudar et al [1], has also performed high frequency ultrasound imaging of HIFU exposure, however they only were able to achieve a M-Mode frame rate of 100Hz. The achieved B-Mode frame rate of 1000Hz in our study revealed transient behaviour within a 40ms observation window post HIFU exposure.

Other studies commonly use lower intensities maintained for longer exposure periods [2]. A threshold intensity of 1kW/cm<sup>2</sup> produced a hyperechoic spot in less than 1 second. Increasing the intensity to 8 kW/cm<sup>2</sup> for 5 seconds formed visible lesions within tissue. The effect of using higher intensities (>60 kW/cm<sup>2</sup>) for shorter durations (40ms), as in our experiments, still remains to be fully investigated. It is believed that the hyperechoic region is from cavitation producing vapour bubbles in the material [2]. These bubbles may also cause the temporary shadowing observed throughout our experiments.

It is important to note the difference in time scale between the temperature and RF intensity decay plots. At present the quick transient behaviour of the hyperecho observed in the chicken breast experiment cannot be due solely to a reduction in temperature. Our measured peak temperatures exceeded 90°C near the HIFU focus and may indicate thermal cavitation. It is possible that following HIFU exposure, the quick collapse of microbubbles formed from cavitation could cause the observed changes in the first 40ms of ultrasound images.

In the phantom material, the HIFU focal spot appears to act like a converging lens due to the distortion of the embedded needle. The local increase in temperature modifies the speed of sound and the local refractive index of the medium. If the heated region is spherical, one could adapt optical lens equations to compute a focal length of the resulting thermal-acoustic lens. By analyzing the observed needle deflections, the radius of curvature may align with the focal length of the thermal lens. This lensing effect could provide a method of monitoring HIFU dosage.

## 5 Conclusion

This exploratory study has identified phenomena that could be useful in real-time monitoring of high-intensity focused ultrasound with high-speed B-mode imaging. The characteristic features observed were the thermal-acoustic lens effect, hyperechoic decay and shadow decay rates. With the development of appropriate image analysis techniques these may be useful in measuring HIFU dose.

## References

- [1] Gudar et al. High-frequency rapid B-mode ultrasound imaging for real-time monitoring of lesion formation and gas body activity during high-intensity focused ultrasound ablation. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 59:1687-1699, 2012.
- [2] Vaezy et al. Real-time visualization of high-intensity focused ultrasound treatment using ultrasound imaging. *Ultrasound in Medicine & Biology*, 27:33-42, 2001