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Temperature Distributions Measurement of High Intensity Focused Ultrasound using a Thin-film Thermocouple Array and Estimation of Thermal Error caused by Viscous Heating

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Abstract—**To improve the throughput of high intensity focused ultrasound (HIFU) treatment, we have considered a focus switching method at two points. For this method, it is necessary to evaluate the thermal distribution under exposure to ultrasound. The thermal distribution was measured using a prototype thin-film thermocouple array, which has the advantage of minimizing the influence of the thermocouple on the acoustic and temperature fields. Focus switching was employed to enlarge the area of temperature increase and evaluate the proposed evaluation parameters with respect to safety and uniformity. The results indicate that focus switching can effectively expand the thermal lesion while maintaining a steep thermal boundary. In addition, the influence caused by the thin-film thermocouple array was estimated experimentally. This thermocouple was demonstrated to be an effective tool for the measurement of temperature distributions induced by HIFU.**

I. INTRODUCTION

High-intensity focused ultrasound (HIFU) has potential for the minimally invasive treatment of tumors. HIFU treatment requires the repetition of ultrasound emission and movement of the focal point, due to the small lesion area per sonication, to obtain a large focal gain. However, the cooling time required between ultrasound emission leads to long treatment time (of more than a few hours) [1]. Thus, a general anesthesia is required for such long treatment times in some cases. This is one reason why the application of current HIFU therapy is limited to cases of small tumors. The purpose of this work is to shorten the treatment time by enlarging the lesion area per sonication. This is achieved by specifically enlarging the area of temperature increase by moving the focal point during exposure.

In many clinical situations, the transducer position is highly restricted. For example, during a prostate treatment, the HIFU transducer is fixed in the rectum, which is adjacent to the prostate. For liver treatment, the HIFU beam should be irradiated between gaps in the ribs surrounding the liver. In addition, for magnetic resonance imaging (MRI)-guided HIFU, the HIFU transducer is mounted in the MRI bed. In these examples, motion of the HIFU transducer is strongly restricted in the narrow space. In these cases, the wave propagation paths are overlapped partially during each exposure, even if the focus moves. As a result, heat accumulates in the area close to the transducer or the body surface during multiple exposures. Therefore, movement of the focus during exposure does not always effectively enlarge the thermal lesion. In contrast, HIFU can be irradiated from various directions for the treatment of breast tumors [2]. We are developing a HIFU treatment system for the treatment of breast cancer with focal motion during exposure is a promising method to shorten the treatment time. There are various ways of directing the focus, as follows:

(1) Focus scanning

If the scanning speed and exposure dose are constant, the temperature distribution can not be controlled uniformly, due to heat accumulation. Therefore, uniform enlargement of the temperature increase area requires control of the scanning speed and exposure dose.

(2) Split focus [3]

This method splits the focal area by controlling the phase distribution of the transducer. Interference of the acoustic waves causes several separated temperature peaks on the focal zone, and a large thermal lesion is formed caused by heat conduction between the peaks.

(3) Focus switching

Since the development of multi-element high-power RF amplifiers, focal control for HIFU has become available, such as the beam control for imaging. Therefore, uniform enlargement of the temperature increase area can be easily achieved by adjusting the distance between the focal points and the switching frequency [4]. Compared to the split focus method, focus switching has the advantage of more flexible setting of the distance between foci.

Therefore, our present aim is to enlarge the temperature increase area using the focus switching method with two points. To achieve this, a wide range of lesion area and uniformity of temperature increase are required.

II. MATERIALS AND METHODS

A. *Focus Switching Method*

The experimental setup shown in Fig. 1 was constructed for simultaneous control of the focus and measurement of the temperature distribution during HIFU exposure.

The HIFU focal point during irradiation was directed using phased arrays [5]. A 2 MHz transducer consisting of 56 elements on a spherical shell was used to control the focal position.

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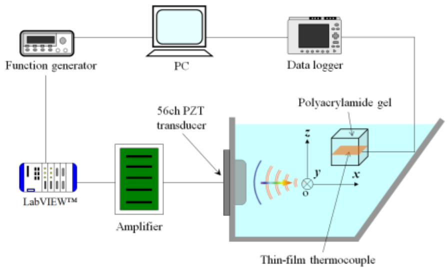


Fig. 1. Experimental setup.

A system was required for temperature measurement during HIFU irradiation to evaluate the proposed method. However, when metal thermocouples are used in an ultrasound field, artificial heating occurs, which is referred to as viscous heating [6]. It occurs because of a steep velocity gradient of a traverse wave on the surface of a thermocouple. Recently, a thin-film thermocouple array has been developed that has flexible thermocouple patterning on a thin film, which would enable multipoint measurement of the temperature. A prototype thin-film thermocouple array with 49 measurement points was developed, as shown in Fig. 2. Thermocouple printed wires (200 nm diameter, 50 μm long) were fabricated on a 25-μm-thick polyimide film. The printed wire and film were sufficiently thin so as to not disturb ultrasonic propagation. In addition, the wire diameter was approximately one-thousandth that of conventional fine thermocouples, so that viscous heating was minimized.

The HIFU focus was switched at two points to enlarge the lesion area. A target area was set up to evaluate the efficiency of the proposed HIFU treatment (Fig. 3), where margins were required to simulate the remaining non-treated areas. Distances between foci of 2.2, 2.6 and 3.0 mm were examined. This focus distance parameter was selected in consideration of the trade-off between uniformity and expansion efficiency. The switching frequency and acoustic intensity at the focal point was 1.67 Hz and 380 W/cm^2, respectively.

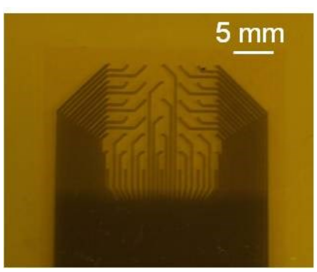


Fig. 2. Photograph of the thin-film thermocouple array.

Fig. 3. Schematic diagram of the target area.

B. *Estimation of Thermal Error caused by Viscous Heating*

It is necessary to clarify influence on thermal measurement error caused by the thin-film thermocouple array. It was difficult to estimate independently both heating sources, ultrasound absorption in propagation media and viscous heating at the surface of the thermocouple. Both distributions of heat source can be estimated as follows; the former was estimated by measuring acoustic filed, and the latter was estimated as uniformly distributed on a thin-film thermocouple array. Therefore, the width of temperature increase distribution by ultrasound absorption is much wider than that by viscous heating. These effects are separable by measuring the integration value of temperature distribution because the effect of ultrasound absorption is dominant in this value. In the study, the peak temperature and the width of heating area estimated by a shift of propagation time passing through temperature rise area were measured. A remaining unknown parameter, ratio of these two quantities, was estimated from the comparison between propagation time shifts in the experiment and calculation, which was calculated by solving thermal diffusion equation in several different ratios of these two quantities.

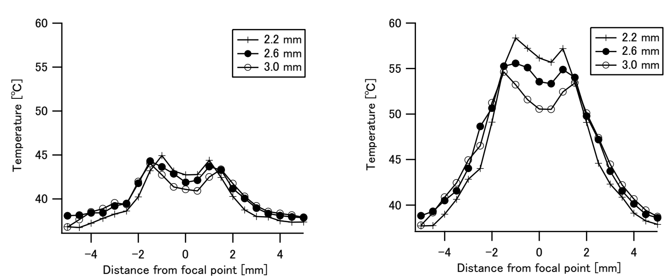
We used a single plate 2.2 MHz HIFU-transducer with f-number of 1. While measuring temperature rise at focus by the thin-film thermocouple, the ultrasound was received by the second transducer placed at the opposite side of the thin-film thermocouple from the HIFU transducer.

Burst wave which repeats irradiation time 90 ms and non-irradiation time 10 ms is exposed. Acoustic intensities are 190, 330 W/cm^2. Exposure time is 10 seconds. Temperature at focus and the reception of ultrasonic were measured in every 100 ms at beginning of the burst wave.

III. Results

A. *Focus Switching Method*

Fig. 4 shows the temperature increase at 3 and 10 s from the start of HIFU irradiation for various foci distances. The results indicate that the temperature gradient can be adjusted by changing the distance between the foci. In addition, the temperature increase with switching was compared to that without switching for various distances between foci; Fig. 5 shows the normalized temperature increase at 10 s from HIFU irradiation. The width of the lesion area was increased by focus switching from that without focus switching.



(a) t = 3 s (b) t = 10 s

Fig. 4. Temperature increase at 3 and 10 s from the start of HIFU irradiation.

B. Estimation of Thermal Error caused by Viscous Heating

The temperature change of the focus measured by the thin-film thermocouple array is shown in Fig. 6. The relation between exposure time and change of propagation time of ultrasound is shown in Fig. 7. The ratio of the quantity of heat by ultrasound absorption in the propagation media to that of heat by viscous heating at the surface of the thermo-couple was calculated by comparing an experimental result with a calculation result about the propagation time of ultrasound. At this time, the result of Fig. 6 was used as the maximum of a temperature rise area. As a result, the ratio of the quantity of heat by ultrasound absorption in the propagation media to that of heat by viscous heating at the surface of the thermo-couple is 0.029 at 190 W/cm^2 and 0.012 at 320 W/cm^2. It succeeded in evaluating the influence by the thin film thermocouple quantitatively.

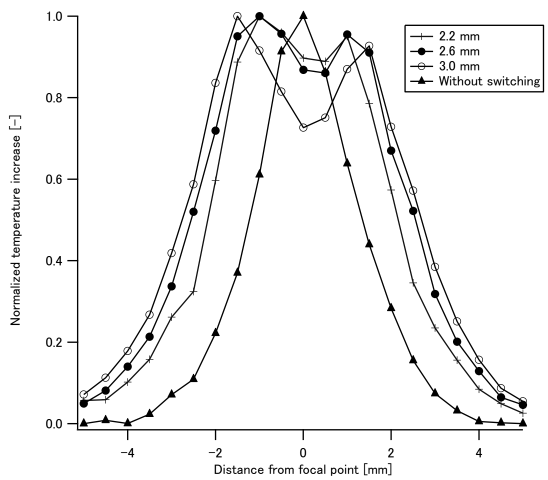


Fig. 5. Normalized temperature increase at 10 s from the start of exposure.

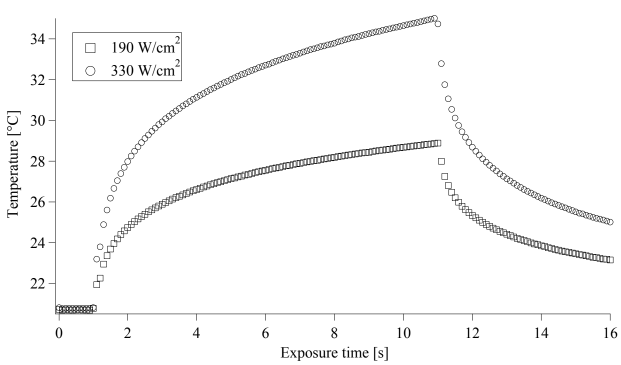


Fig. 6. Temperature rise at focus.

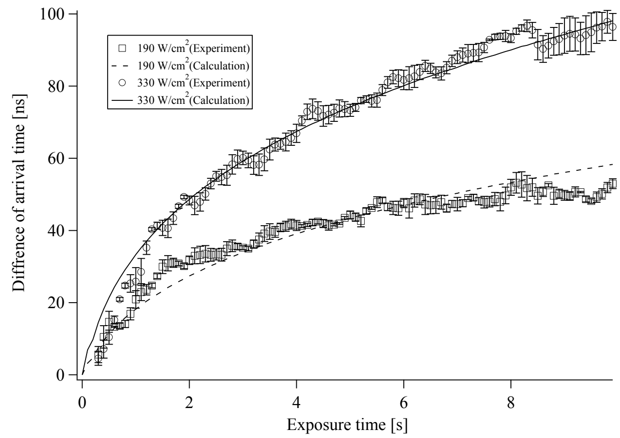


Fig. 7. Difference of arrival time.

IV. Discussion

A. Focus Switching Method

The HIFU treatment was evaluated using temperature uniformity in the focal area and temperature ratio of the inside and outside of the target area for localizing therapeutic effects, as schematically shown in Fig. 8. The parameter of uniformity is the normalized temperature difference at the target and the parameter of safety is the normalized temperature increase at the normal non-target tissue areas (margins). Fig. 9 shows that the uniformity parameter over time is improved by focus switching and the safety parameter over time is slightly worsened by focus switching. However, the safety parameter was approximately 0.2 when the distance between foci was 2.2 or 2.6 mm for a HIFU irradiation time of less than 10 s. Thus, the maximum temperature increase at the non-target area is 4 °C when the treatment temperature is 60 °C. Under this condition, the thermal coagulation lesion is localized within the treated area. Therefore, focus switching has sufficient safety, depending on the treatment conditions employed. The temperature uniformity and safety are dependent on the distance between foci and this parameter will therefore require further investigation for optimization.

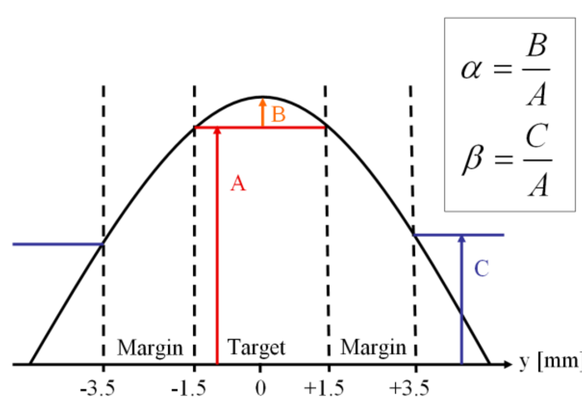
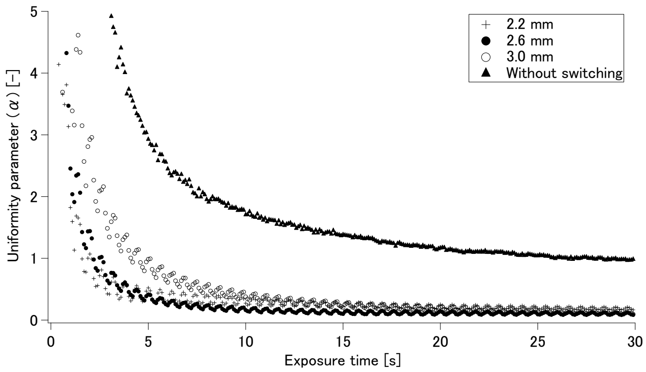
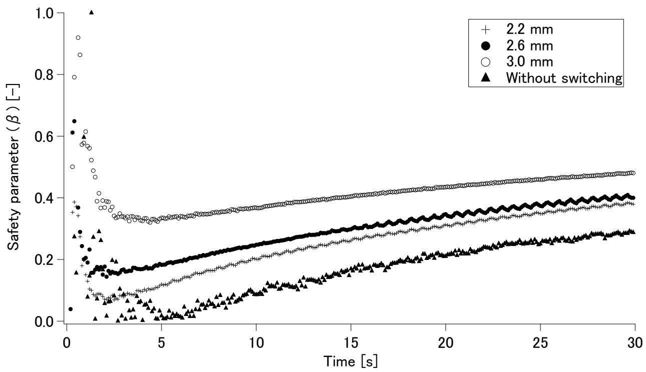


Fig. 8. Parameters used for the evaluation of HIFU treatment.



(a) Uniformity parameter.



(b) Safety parameter.

Fig.9. Parameter of uniformity and safety over time.

B. *Estimation of Thermal Error caused by Viscous Heating*

Fig.10 shows relative error by thin-film thermocouple when the ratio of the quantity of heat by ultrasound absorption in the propagation media to that of heat by viscous heating at the surface of the thermocouple is 0.029. The influence of thin-film thermocouple is not negligible. However, this influence was minimized compared to conventional wire thermocouple [7]. In addition, this influence is considered to be smaller in body tissue because body tissue has much attenuation than the gel used in this study. From this result, the reliability of measurement of temperature distribution and the performance of a thin-film thermocouple were evaluated.

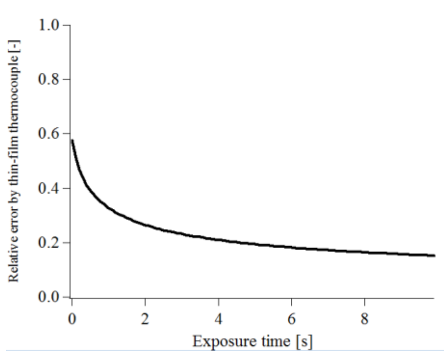


Fig. 10. Relative error.

V. Conclusion

The width of the thermal coagulation lesion area was enlarged uniformly by focus switching with a steep temperature gradient at the border of the heating area and the non-target margin area. Therefore, focus switching has potential as a method to reduce the HIFU treatment time. In addition, we proposed the way to evaluate the effect of viscous heating by measuring the propagation time through heating area and it succeeded in evaluating the influence by the thin film thermocouple quantitatively. For the future, we examine a thinner thin-film thermocouple to minimize the influence of viscous heating.

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