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Analysis of temperature increase in excised porcine liver tissue induced by cavitation-enhanced HIFU
強力集束超音波照射時にキャビテーションが豚肝臓に及ぼす温度上昇の解析

Eiko Iwasaki[1‡], Ayumu Asai[1], Tatsuya Moriyama[1], Takashi Shishitani[1], Shin Yoshizawa[1] and Shin-ichiro Umemura[1] ([1] Tohoku Univ.,)
岩崎永子 [1‡]，浅井歩 [1]，森山達也 [1]，獅子谷卓 [1]，吉澤晋 [1]，梅村晋一郎 [1] （[1] 東北大）

1. Introduction

In high-intensity focused ultrasound (HIFU) therapy, ultrasound is focused on target tissue for its coagulation. This method is attracting attention as noninvasive therapeutic modality, but has a problem of a long treatment time. Ultrasonically induced cavitation is known to enhance tissue heating.[1)] To improve the efficiency of the treatment, we have been developing a method to coagulate a large region in a short time by utilizing multiple clouds of acoustic cavitation and named it "triggered HIFU", in which extremely intense focused ultrasound pulses to initiate cavitation (trigger pulse), immediately followed by moderate-intensity long-burst focused ultrasound for heating (heating waves), are used.[2)]
Although it is well known that a cavitation cloud converts ultrasound to heat efficiently, its absorption coefficient remains unknown. To solve this problem, measurement of the temperature in excised pig liver tissue during exposure to HIFU was performed, and the result was compared with numerical simulation.

2. Materials and methods

Multifunction generators (WF1974, NF) were used to generate sinusoidal waves and connected to RF amplifiers (100A2, E&I) to drive the array transducer (Imasonic) having 128 equal-area elements, a central frequency of 1.0 MHz, outer and inner diameters of 100 and 36 mm, respectively, and a radius of curvature of 100 mm. 100 among the 128 elements of the transducer were driven by ten amplifiers at the same phase.
An excised pig liver was submerged in degassed water (DO 30-40%, 36-37°C) and exposed to ultrasound. First, a trigger pulse at an intensity of 19 kW/cm^2 was irradiated for 0.1 ms to the geometrical focal point. Immediately after this pulse, heating waves at an intensity of 0.6 kW/cm^2 were irradiated for 3 s. The temperature rise in the tissue at the focal point was measured with a thermocouple for 20 s including the series of irradiation. The temperature rise without the trigger pulses was also measured, and fit by the double exponential in the form as

$$T = T_0 + T_1\left(1-\exp\left(\frac{-t}{\tau_1}\right)\right) + T_v\left(1-\exp\left(\frac{-t}{\tau_v}\right)\right) \quad , \qquad (1)$$

to separate viscous heating (the third term) and absorption heating (the second term) where τ_v is smaller than τ_1 by orders of magnitude. Then, the absorption coefficient was obtained as

$$\alpha = \frac{\rho c}{2I}\left(\left[\frac{\partial T}{\partial t}\right]_{t=0} - \frac{T_v}{\tau_v}\right) \qquad (2)$$

for both cases with and without the trigger pulses, where ρc and I are the volumetric heat capacity and the intensity of ultrasound, respectively. The temperature rise by the trigger pulses alone was ignored because they were short enough to ignore their energy.
Simulation and experiment of coagulating a large region by triggered HIFU[3)] were performed at the same condition. In the experiment with an excised pig liver, a trigger pulse at an intensity of 19 kW/cm^2 was irradiated for 100 µs to each one of the three electronically steered focal points at x = 0 and ±4 mm, respectively. This cycle was repeated for 10 times, resulting in the total irradiation time at each focal point of 1 ms.
In the simulation, the regions with the higher absorption coefficient due to cavitaion formed by trigger pulses were located as shown in Fig. 1. The *x* and *z* axes are perpendicular and parallel to the ultrasound propagation, respectively. The size of the regions was determined according to the results of high-speed photography of the cavitation clouds in a gel generated by the trigger pulses[3)].
Right after cavitation cloud formation, heating waves at an intensity of 0.6 kW/cm^2 at the geometrical focal point were irradiated for 10 s with heating waves with a widened focus covering all the three trigger focal points. In the simulation, a bio-heat transfer equation (BHTE) without a blood

iwasaki@ecei.tohoku.ac.jp

flow term was used to obtain temperature distribution.

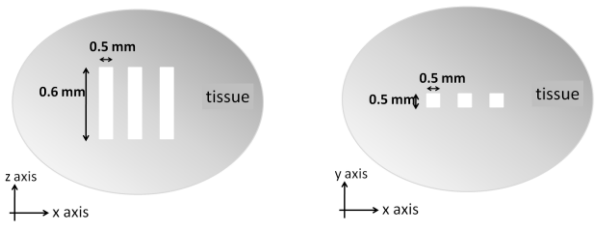

Fig.1 Location and size of cavitation clouds with higher absorption coefficient. The sizes are 2 mm (axes x and y), 10 mm (axis z) .

3. Results

Fig. 2 shows the measured temperature with and without trigger pulses. Temperature measurement with and without trigger pulses was performed three times, respectively and the average value was used. The obtained absorption coefficient with and without trigger pulses was 9.8 and 2.2 Np/m, respectively. The other parameters used in the simulation are shown in **Table 1**. The simulated acoustic field of the widened-focus heating waves is shown in **Fig. 3**. **Figs. 4** **(**a) and (b) show the simulated temperature field right after 10-second radiation of HIFU with and without cavitation clouds, respectively. The maximum temperature with and without cavitation were 98.4°C and 73.8°C, respectively. The results of the coagulation experiments of excised pig liver tissues with and without trigger pulses are shown in **Figs. 4** (c) and (d), respectively. The coagulated region with cavitation was larger than that without cavitation.

4. Discussion

The following two points are important. First, laterally aligned cavitation clouds make it possible to coagulate the tissue between the cavitation clouds due to the thermal diffusion. Next, the result of simulation using experimentally determined absorption coefficients agreed with the coagulated region in the experiment assuming that the tissue coagulates above 55°C. Coagulation did not expand much in the direction of ultrasound propagation probably because of the reflection by the cavitation clouds.

5. Conclusion

The absorption coefficient of a tissue with cavitation clouds was determined from the temperature rise in excised pig liver. This made possible to perform simulation of tissue temperature rise by triggered HIFU by taking the effect of cavitation clouds into account.

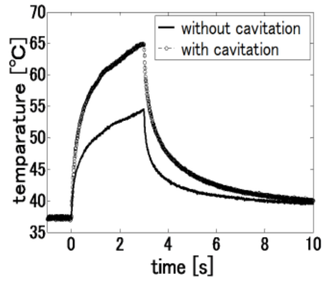

Fig.2 Measured temperature in tissue.

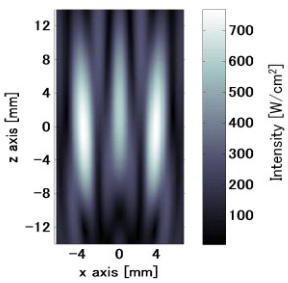

Fig.3 Simulated acoustic intensity distribution for heating

Table 1 Parameters used in simulation.

ρc (kJ/K/m^3) [4]	3685
I (W/cm^2)	600
Heat conductivity (W/m/K) [4]	0.528

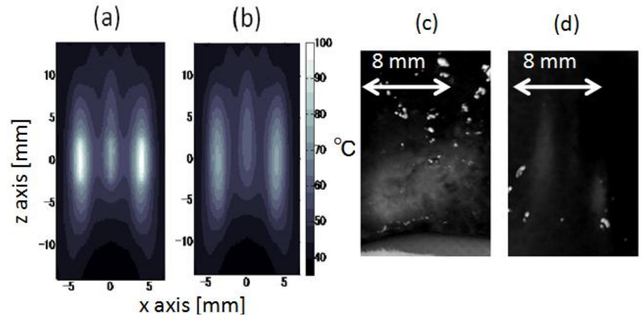

Fig. 4 Temperature field right after 10s radiation by HIFU in simulation (a and b) and coagulated excised pig liver tissue (c and d) with (a and c) and without (b and d) trigger pulses.

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