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Advantage of Annular Focal Region Generated by Sector-Vortex Array in Cavitation-Enhanced High-Intensity Focused Ultrasound Treatment

気泡援用強力集束超音波治療における円環状焦域を用いた場合の有意性

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1. Introduction

HIFU (High-Intensity Focused Ultrasound) treatment is a non-invasive method which can selectively coagulate target tissue such as cancer by irradiating it with focused ultrasound generated outside the body. To make this treatment more efficient, cavitation bubbles are utilized to the enhance heating effect through oscillating the bubbles. Since a HIFU focus is axially long, lateral enlargment of the focal region can increase the heating effect through minimizing the surface volume ratio. In this paper, we compared single-spot scanning and direct synthesis of an annlar focal region as the method for the lateral enlargment. They were used for tissue heating through oscillating the cavitation bubbles generated by lateral single-spot scanning.

2. Material and Method

2.1 Multi-Triggered HIFU

"Triggered HIFU" is the method to enhance the heating effect by oscillating the cavitation bubbles[1)]. In this method, a high-intensity short pulse, named as "Trigger Pulse", generates cavitation bubbles and a following low-intensity long burst, named as "Heating Waves", oscillates the bubbles. "Multi-Triggered HIFU" is its version to enlarge the focal region laterally by scanning the focal spot. Here, it was scanned at each corner of a regular hexagon 3 mm each side for utilizing the heat conduction from the adjacent focal spots[2)].

2.2 Sector-Vortex Array[3)]

Direct synthesis of an annular focal region was performed using a Sector-Vortex array method. A 128-channel array transducer was divided into N sectors of equal size. The i-th sector was driven by the complex signal A (θ_i) given by

$$A\,(\theta_i) = A_0 \exp j(m\theta_i)$$

for $i = 1, 2, \cdots, N$, where $\theta_i = i2\pi/N$, m is the vortex mode number, and A_0 is a constant. We applied this method to Heating Waves in Multi-Triggered HIFU sequence. Immediately after spot scanning of Trigger Pulse at each corner of a regular hexagon the direct synthesis of annular focal region 3 mm in radius with N=12 was performed. The mode numbers m=4 and -4 were used to switch the spiral direction periodically between clockwise (m>0) and counter-clockwise (m<0)[4)].

2.3 HIFU sequence

Fig. 1 shows the Triggered HIFU sequence. The intensity for spot scanning of Trigger Pulse and Heating Waves was 48 kW/cm^2 and 1.5 kW/cm^2, respectively. The same total acoustic power as the spot scanning of Heating Waves was used for the direct synthesis of annular focus. The subtotal duration of Trigger Pulse and Heating Waves was 672 µs and 145.1 ms, respectively. This sequence was repeated for 80 cycles. It is well known that cavitation clouds generated by focused ultrasound tend to grow backward from the focal point[5)]. Therefore, we intentionally offset the focal points of Trigger Pulse by 7 mm forward from the geometrical focus to match the axial position of the generated clouds to that of the heating focus.[2)]

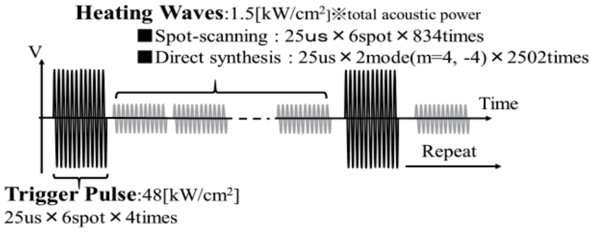

Fig. 1 Triggered HIFU sequence

2.4 Experimental setup

Fig.2 shows the experimental setup. Excised chicken breast tissue was submerged in degassed water (DO: 20-30%) in a tank. The 128-ch array transducer, with both geometrical focal length and outer diameter of 120 mm, was driven by staircase-wave amplifiers (Microsonic). An ultrasound imaging system (Verasonics) and an imaging probe (UST51205, Hitachi Aloka) inserted in the central hole of the transducer were used to monitor the cavitation bubbles in the tissue.

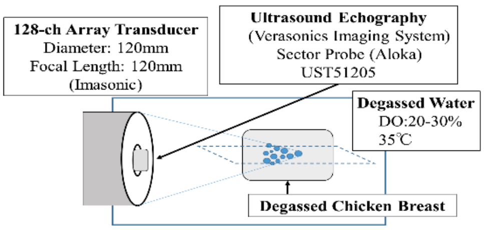

Fig. 2 Schematic of Experimental Setup

3. Result and Discussion

Fig.3 shows the coagulation areas by direct synthesis and spot-scanning of heating foci without and with Trigger Pulse, respectively. Without cavitation bubbles generated by Trigger Pulses, coagulation did not take place, with the direct synthesis, while it took place significantly backward from the geometrical focus with spot-scanning. This is because spot-scanning resulted in a high spatial-peak temporal-peak (SPTP), causing nonlinear propagation and absorption. The harmonic components thereby generated caused the large shift in the location of acoustic power absorption. Fig.4 shows B-mode images using Pulse Inversion, in which direct synthesis (a) and spot-scanning (b) correspond to (c) and (d) in Fig.3. Between the dotted lines in both images, cavitation bubbles started being generated at a depth of 25 mm and grew backward up to a depth of 15mm from the tissue surface. The coagulation took place at a depth of 27-37 mm and 24-41 mm in (c) and (d) of Fig.3, respectively. The coagulation volume by direct synthesis matched well with the observed cavitation cloud area. It was probably because the low SPTA intensity caused less nonlinear phenomena.

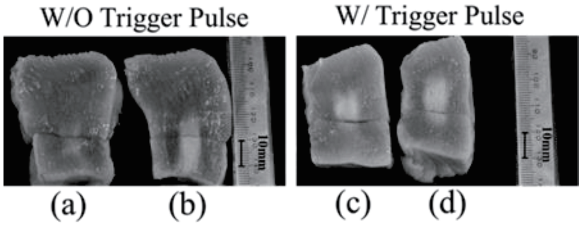

Fig.3 Gross pathology of coagulation area. (a) and (c): direct synthesis, (b) and (d): spot-scanning..

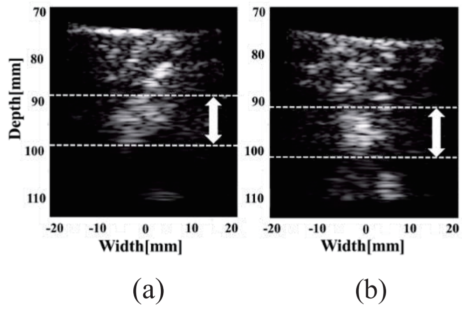

Fig.4 B-mode images of cavitation bubbles.
(a) direct synthesis, (b) spot-scanning.. Each corresponds to (c) and (d) in Fig.3.

4. Conclusion

In this study, the conventional Triggered HIFU method using spot scanning for Heating Waves, and a new method using direct synthesis are compared. The direct synthesis produced coagulation only at the area where both cavitation bubbles and Heating Waves were present. The proposed approach will make Triggered HIFU treatment more predictable.

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