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Detection of Thermally-Induced Lesion Using Shear Wave Imaging in Cavitation-Enhanced High-Intensity Focused Ultrasound Therapy

超音波せん断イメージングを用いた気泡援用強力集束超音波治療における熱変性領域検出

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1. Introduction

High-Intensity Focused Ultrasound (HIFU) therapy is a less invasive method of cancer treatment, in which ultrasound is generated outside the body and focused at the tumor tissue to be thermally coagulated. In order to improve the safety and reliability of HIFU therapy, a noninvasive method to monitor thermally-induced lesion formation and to accurately measure the size of coagulated regions is necessary.

Ultrasound Elastography is a diagnostic method that measures stiffness of tissue or lesion noninvasively. Since thermally-induced lesions by HIFU are commonly stiffer than surrounding tissues, the elastography has the potential to detect coagulated regions from the difference between the propagation velocity of shear wave in the coagulated tissue and that in the surrounding normal tissue.

To overcome the problem of a long treatment time of HIFU therapy, arising from a small therapeutic volume by a single insonification, we proposed the method using acoustic cavitation bubbles to accelerate the treatment by enhancing the heating effect of ultrasound. The presence of cavitation bubbles may interrupt the propagation of the shear wave itself and the detection of the accompanying displacements. In this study, shear wave imaging is tested to detect tissue coagulation in the existence of microbubbles due to cavitation or boiling.

2. Materials and Methods

2.1 Shear wave propagation

The spatial-temporal variation of axial shear displacement is described by the wave equation as follows:

$$\frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial y^2} = \frac{1}{{c_s}^2}\frac{\partial^2 u_z}{\partial t^2} = \frac{\rho}{G}\frac{\partial^2 u_z}{\partial t^2} \qquad (1)$$

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where c_s, G and ρ are the shear wave velocity, the shear modulus, and the density of the medium respectively. The tissue elasticity map can be recovered by tracking the axial displacements and calculating the shear wave velocity orthogonal to them using ultrasonic imaging.

2.2 Ultrasonic imaging

Shear waves were induced and observed using a linear array probe (EUP-L54MA, Hitachi Aloka Medical) with a center frequency of 9.75 MHz, connected to an ultrasonic imaging system (Verasonics). Plane wave transmission followed by parallel beamforming[1)] was employed to achieve a frame rate of 5000 fps, which was high enough to acquire the shear wave motion at a velocity typically 1 to 10 m/s. The axial displacements were calculated by the phase shift of the 1-D cross-correlation between adjacent frames.

To induce adequate displacements of quasi-planar shear waves by radiation force, shear sources were created at five different depths[2)], 10, 15, 20, 25, 30 mm and +3 mm in width at a driving frequency of 5.00 MHz.

2.3 Experimental setup and sequence

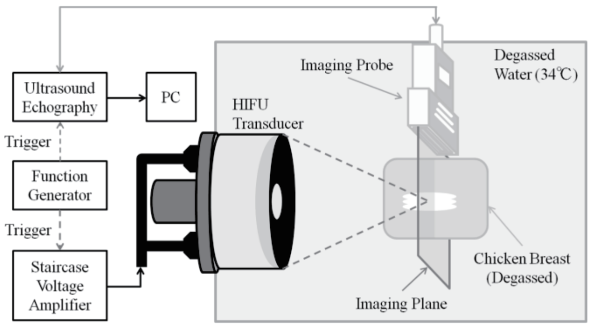

Fig. 1　Schematic of experimental setup

A fresh chicken breast was perfused with degassed saline to eliminate remaining gas, and a sample was set in a water tank containing degassed water as shown in **Fig. 1**.

HIFU was insonified from a 256-channel array transducer (Imasonic) at 1.0 MHz with an outer diameter and a geometrical focal length of 120 mm. In order to efficiently generate tissue coagulation, 'multiple-triggered HIFU' sequence[3] was used, in which the focus was scanned at each corner of a regular hexagon 3 mm each side. 'Trigger Pulses' at an intensity of 64 kW/cm^2 with a duration of 25 µs for 4 cycles were followed by 'Heating Waves' at an intensity of 2.2 kW/cm^2 with a duration of 25 µs for 834 cycles. This sequence was repeated 160 times, resulting in a total HIFU exposure time of about 22 s.

The overall sequence of HIFU exposure, shear wave generation, and RF data acquisition is shown in **Fig. 2**. The imaging of shear wave propagation had been performed six times, before HIFU exposure, 0 s, 30 s, 90 s, 3 min and 5 min after HIFU exposure.

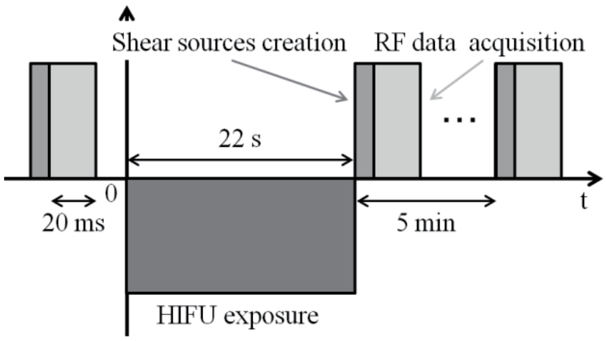

Fig. 2 Sequence of HIFU exposure and RF data acquisition

3. Result and Discussion

The diameter of the coagulated region induced by the multiple-triggered HIFU in the actual cross section was about 9 mm on average. **Fig. 3** shows the average shear wave velocities at a depth of 22 mm, corresponding to the coagulated regions and the non-coagulated tissue.

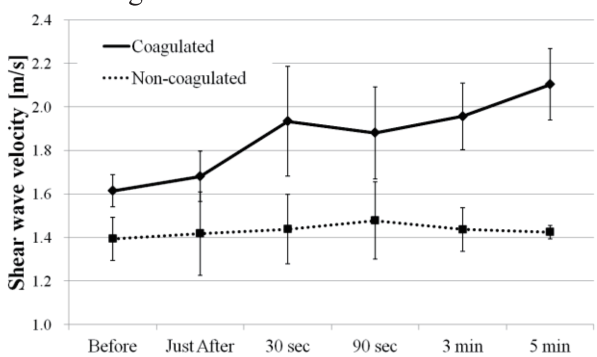

Fig. 3 Shear wave velocity of chicken breast with each timings

These velocities were calculated from the direction-time maps of the axial displacements of the observed shear waves, shown in **Fig. 4**. The slope of the bright regions, which looks constant in the normal tissue, was steeper in the portion corresponding to the coagulation area, located about -12.5 mm to 3.5 mm in the lateral direction.

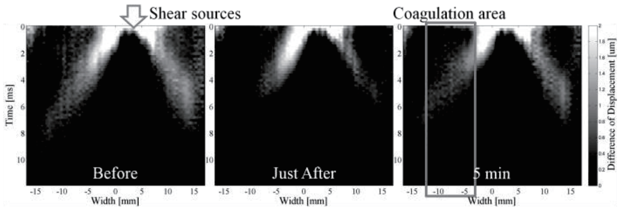

Fig. 4 Spatial-temporal displacements map before, just after, and 5 min after HIFU exposure.

The shear wave velocity started increasing at the end of insonification, then increased gradually as time elapsed, and reached a plateau after around 90 s. The presence of microbubbles and the temperature rise[4] can account for the late change in shear modulus observed in this experiment. Fig. 4 also shows an increase in attenuation, for which the microbubbles can also account.

4. Conclusion

In this study, the shear wave propagation was captured by high-speed ultrasonic imaging, and its velocity was calculated. The results suggest that RF data acquisition to analyze shear wave propagation is possible even in the presence of microbubbles generated by either cavitation or boiling, but it was necessary to wait for a few minutes until the microbubbles disappear and the temperature rise becomes small.

Acknowledgment

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