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Effect of Difference in Shear Modulus of Biological Tissue on Heat Source Distribution of High-intensity Focused Ultrasound Estimated by Acoustic Radiation Force Imaging

生体組織の剛性率の違いが音響放射力イメージングによる HIFU 加熱分布推定へ及ぼす影響

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1. Introduction

High-intensity focused ultrasound (HIFU) has been investigated as a tool for the noninvasive treatment of cancer, and is expected as a potential alternative to conventional therapies. In this method, the prediction of a HIFU heat source in prior to the exposure for treatment is important to prevent unwanted thermal damage to normal tissues and enhance the efficacy of the treatment. The previous study[1)] showed that acoustic radiation force impulse (ARFI) imaging using a short HIFU burst has a potential to make the prediction of a HIFU heat source possible. In the HIFU radiation force method, the HIFU heat source distribution was estimated from the distribution of the tissue displacement, with the assumption of a uniform shear modulus.

The displacement mainly depends on the acoustic attenuation and shear modulus in the target tissue. Therefore, in this study, the effect of difference in shear modulus on the estimation of heat source was experimentally investigated by applying HIFU radiation force imaging to different biological tissues.

2. Materials and Methods

2.1 HIFU radiation force imaging

The procedure has two steps: estimation and coagulation modes. In the estimation mode, the acoustic radiation force is applied in a target tissue by a HIFU burst exposure. The HIFU radiation force F can be described by,

$$F = 2\alpha I/c \qquad (1)$$

where α, c and I are the acoustic attenuation coefficient, the speed of sound in the tissue (1520 m/s), and the acoustic intensity, respectively. In the coagulation mode, HIFU is continuously exposed, which causes the significant temperature rise in the tissue. The HIFU heat Q can be expressed as,

$$Q = 2\alpha_a I \qquad (2)$$

where α_a is the acoustic absorption coefficient. Assuming that the attenuation is proportional to the absorption, the right sides of **Eqs. (1)** and **(2)** are considered to be proportional. Since the acoustic radiation force is proportional to the displacement u and shear modulus μ, the following relational expression is satisfied:

$$Q \propto cF \propto c\mu u \qquad (3)$$

Therefore, the heat source distribution can be estimated from the displacement distribution on the assumption that the uniform shear modulus in the region of interest (ROI).

2.2 Experimental setup and Sequence

Figure 1 shows a schematic of the experimental setup. HIFU was generated by a 256-channel array transducer (Imasonic) at 1 MHz with both outer diameter and geometrical focal length of 120 mm. An imaging probe (Hitachi Aloka Medical) with 80-channel and a center frequency of 3.5 MHz was set in the central hole of the transducer. The imaging plane wave was transmitted to acquire RF data from an ultrasound imaging system (Verasonics, Vantage 256). Excised fresh chicken breast and liver were used as sample tissues and submerged in a degassed and deionized water.

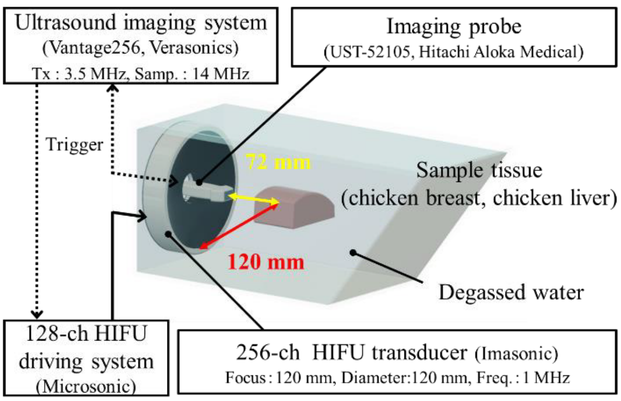

Fig. 1 Schematic of experimental setup.

The ultrasonic exposure sequences of the estimation and coagulation modes are shown in **Fig. 2**. In the estimation mode as shown in **Fig. 2(a)**, a HIFU burst at a total acoustic power (TAP) of 20 –

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60 W with a duration of 500 μs was focused to the tissue, and before and after the HIFU exposure, a single plane wave was transmitted from the imaging probe. The axial displacement is calculated by applying the 2D combined autocorrelation method[2] between the frames before and after the HIFU burst exposure. On the other hand, in the coagulation mode as shown in **Fig. 2(b)**, HIFU at the same frequency and TAP in the estimation mode, was continuously irradiated for 20 s.

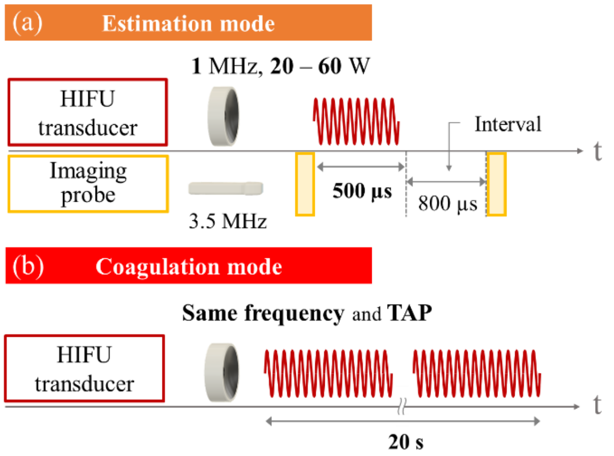

Fig. 2 Ultrasound exposure sequence of (a) estimation mode and (b) coagulation mode.

3. Results and Discussion

Figures 3(a) and **3(b)** show the results of the estimation by the short burst and the gross pathology after coagulation in chicken breast, respectively. The estimation map, shown in **Fig. 3(a)**, is that the displacement distribution from the maximum to the half is superimposed on the B-mode image. The TAP of HIFU exposure in estimation and coagulation modes was 20 W in both cases. **Figure 4** shows the results of the estimation and the gross pathology in the chicken liver by HIFU exposure at a TAP of 20W and 60 W. When the liver was exposed by HIFU at a TAP of 20 W, as shown in **Fig. 4(b)**, the coagulation cannot be observed; unlike the case in the breast at 20 W. As can be seen in **Fig. 4(d)**, however, the case of HIFU expose at 60 W, the coagulation region can be clearly seen. The coagulation area mostly corresponded to the estimated area in **Fig. 4(c)** in the size and the position. Notice the maximum displacement in the estimation mode; that in the liver in **Fig. 4(c)** was about 8 times that in the breast in **Fig. 3(a)**. The difference is mainly because of the difference in shear modulus of the chicken tissues.

The shear modulus in the chicken breast and the liver tissues, which were acquired using shear wave elastography (SWE) method[3], were 7.1 ± 1.6 kPa and 1.0 ± 0.25 kPa, respectively; so that the mean shear modulus in the breast was about 7 times higher than that in the liver. Considering **Eq. (3)**, the liver case requires larger displacement, according to the difference in shear modulus, than the breast case to acoustically generate the same amount of heat. Therefore, the difference of the displacement between **Fig. 3(a)** and **Fig. 4(c)** can be considered in the reasonable range. The results demonstrate that the TAP of HIFU required for the treatment can be quantitatively determined based on the measurements of the displacement and the shear modulus in the target tissue.

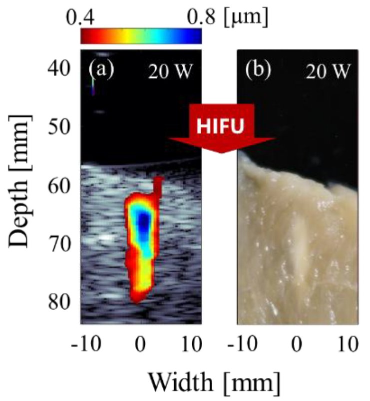

Fig. 3 (a) Estimation map and (b) gross pathology in chicken breast by HIFU at 20 W.

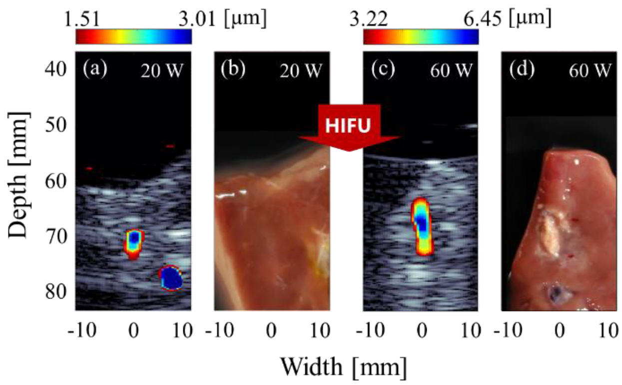

Fig. 4 Estimation maps and gross pathologies in chicken liver by HIFU at (a), (b) 20 W and (c), (d) 60 W.

4. Conclusion

In this study, we demonstrated that the estimation method could have a potential to determine the appropriate HIFU power from the displacement with considering the shear modulus even in different tissues.

References

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