2P5-2

Focusing Efficiency Improvement of Focused Ultrasound by Refraction Compensation

生体内における屈折の補償による超音波の集束効率の向上に関する検討

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1. Introduction

Refraction at boundaries between different tissues causes focus region shift and deformation of focused ultrasound and they reduces quality of ultrasound B-mode images. Especially, refraction between subcutaneous fat and muscle is a mejor factor because fat tissue has slower sound of speed than muscle tissue. It is suggested that compensating such refraction improves quality of B-mode images. In previous studies, time reversal method[1], which corrects delay time of array transducers by using back-propagation from focus point, is proposed. However, thime reversal method, virtual sound source is required at focus point in tissue and it supposed to be difficult to apply to real medical scene. The objective of this study is to propose a refraction compensation method using ray theory which does not need virtual sound source. Additionally, correction effect of the method was evaluated numerically.

2. Material and method

2.1 Principle of refraction compensation method

Principle of refraction compensation using ray theory[2] is explained by a simple model as shown in Fig. 1. Focused ultrasound is transmitted from an array transducer which has *N* elements ($S_1 \sim S_N$). Sound of speed of media 1 and media 2 are c_1 and c_2, respectively. Position of ideal focus is *F*. In this method, firstly, tissue boundary is detected by B-mode images. Second, the boundary positions are discretized to *M* points ($P_1 \sim P_M$) and angles of each points α_j are also calculated. Third, a path $S_i \rightarrow P_j \rightarrow F$ is calculated using Snell's law. Then, time of flight (TOF) of the path is calculated using path length and sound of speed of each medias. Finally, delay times of transmitted ultrasound from each elements are calculated.

Fig. 2 shows a flow chart of this method. Detailed procedure is explained as below.

First, φ is calculated by Eq.1;

$$\varphi = \arcsin\left(\frac{\overline{FH}}{\overline{P_jF}}\right) - \alpha_j \qquad \cdots\text{(Eq.1)}$$

θ and *IS'* is calculated by Eq. 2 and Eq.3;

$$\tan(\theta + \alpha_j) = \tan\left\{\arcsin\left(\frac{c_1}{c_2}\sin\varphi\right) + \alpha_j\right\} \qquad \cdots\text{(Eq.2)}$$

$$IS' = P_jI\tan(\alpha_j + \theta) \qquad \cdots\text{(Eq.3)}$$

Element number *i* is calculated to select S_i by Eq.4;

$$i = \frac{\overline{S_1I} + \overline{IS'}}{pitch} + 1 \qquad \cdots\text{(Eq.4)}$$

Where 'pitch' is width of each elements. TOF of $S_i \rightarrow P_j \rightarrow F$ (t_{TOFi}) is calculated by Eq.5;

$$t_{TOFi} = \frac{\overline{S_iP_j}}{c_1} + \frac{\overline{P_jF}}{c_2} \qquad \cdots\text{(Eq.5)}$$

After calculating all of TOF from $S_1 \sim S_N$ to *F*, compensated delay times (t_{Di}) of each elements are calculated by Eq 6.

$$t_{Di} = \max(T_{TOF}) - t_{TOFi} \qquad \cdots\text{(Eq.6)}$$

$$T_{TOF} = \{t_{TOF1}, t_{TOF2}, t_{TOF3}, \cdots t_{TOFN}\}$$

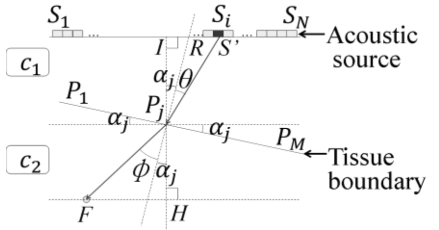
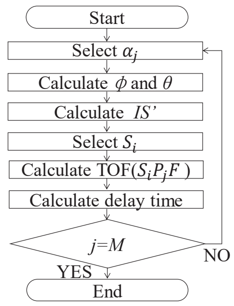


Fig. 1 Schematic of refraction correction



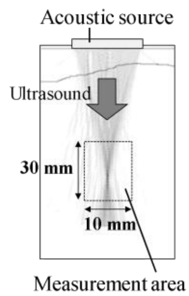


Fig. 2 Flow chart of refraction compensation

Fig.3 Numerical model

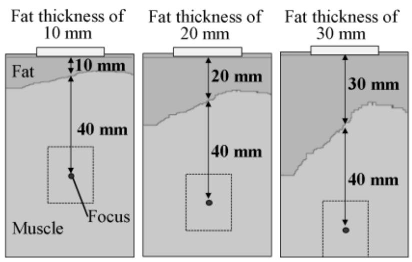


Fig. 4 Evaluated cases

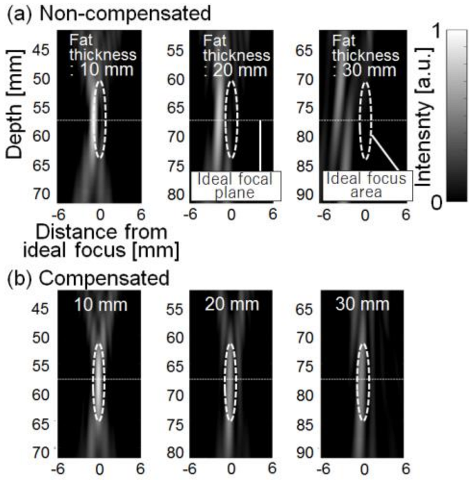


Fig. 5 Acoustic intensity distribution

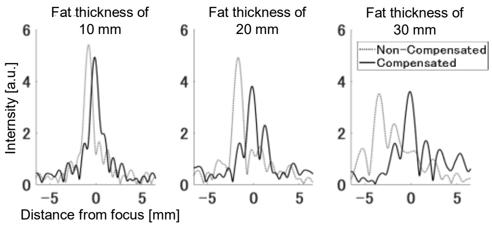


Fig. 6 Relationship between fat thickness and focus shift

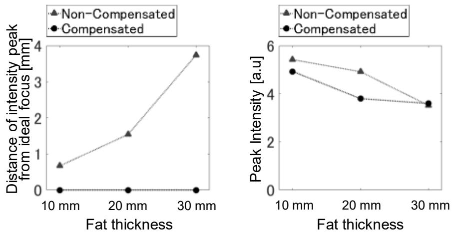


Fig.7 Quantified peak position and intensity

2.2 Procedure of numerical evaluation

To evaluate correction effect of this method, numerical models are created as shown in Fig 3 using PZFlex(PZFlex LLC, USA). Focused ultrasound with non-compensated and compensated delay time is transmitted at a frequency of 3.5 MHz from linear array transducer whose aparture was 13 mm and distribution of acousitc intensity around ideal focus was calculated. Three models whose center thickness of 10 mm to 30 mm were evaluated as shown in Fig.4. A shape of tissue boundary was created by a optical camera(D600, Nikon, Japan) picture of pork. In all cases, distance between center of fat surface and ideal focus were fixed at 40 mm. Sound of speed of fat and muscle were set at 1465 m/s and 1560 m/s, respectively. Acoustic intensity distribution was calculated in each cases. Correction effect was evaluated by quantifying distance from ideal focus and a position of peak intensity uisng profiles of focal plane intensity.

3. Results

Fig.5 shows acoustic intensity distribution around ideal focus. In non-compensated case, intensity peak was shifted from ideal focus area. Additionally, in case of fat thickness of 30 mm, focus area was splitted. On the other hand, in compensated cases, both focus shifts and splits were corrected and intensity peaks locate in ideal focus areas in all subctaneous fat thicknesses.

Profiles of acoustic intensity on focal planes are shown in Fig.6 and quantified intensity peak position and intensity itself are shown in Fig.7. In all non-compensated cases, position of intensity peak were shifted and it become larger as the fat thickness become larger. The shifts were corrected in compensated cases within 0.01 mm in all cases. On the other hand, the peak intensity of 10 mm and 20 mm of fat thickness become smaller than those of non-compensated cases.

4. Discussion

Resolution of B-mode images are critically affected by profiles of acoustic intensity. By refraction compensation method, positions of peak intensity were well corrected toward ideal focus position in all subcutaneous fat thickness. Therefore, there is a possibility to improve resolution of B-mode by the refraction compensation. The peak intensity in 10 mm and 20 mm of fat thickness become smaller by compensation. The reason for this is that the refraction compensation method compensates delay time only considering acoustic path. However, distance attenuation which become longer as the acoustic path length become larger is not considered. There are cases paths length become longer by the refraction compensation, therefore, there is a possibility to intensity peak bocome smaller by the refraction compensation method. Peak intensity affects penetration of B-mode images, further study is needed to improve refraction compensation method considering peak intensity.

5. Conclusion

In this study, to correct focus shift and deformation, a refraction compensation method was proposed. As a result, both focus shift and deformation was corrected. This method is supposed to be useful for improving ultrasound B-mode images.

References

1. M. Fink: IEEE Trans. Ultrason. Ferro. And Freq. Control. **39** (1992) 555.
2. J. Koskela *et al.*: J. Acoust. Soc. Am. **136** (2014) 1430.