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Shear Wave generation in Living Body by Mode Conversion of Longitudinal Wave at Elasticity Boundary

弾性境界での縦波からのモード変換による生体内での横波弾性波の生成

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1. Background, Motivation and Objective

Shear Wave elastography has been attracted attention as a quantitative method for measuring tissue elasticity [1]. In the inside of it, acoustic radiation force impulse (ARFI) imaging has been proposed [2], and various improvements have been advanced [3]. On the other hand, effects on the living body of ARFI are strongly concerned. Moreover, since attenuation of shear waves is large in a living body, mechanical vibration added to the surface of a body cannot generate shear wave in the depths in a body. Hence, in this study, within the framework that shear waves are generated acoustically inside the body, we propose a novel scheme for elasticity imaging with low risk for the living body.

2. Method

ARFI imaging needs high acoustic radiation force impulse. With considering the safety for the living body, we study the scheme in which we transmit longitudinal waves having amplitude on the same level with those for B-mode imaging, and use the shear waves arising via the mode conversion from the longitudinal waves at the elasticity boundary for measuring elasticity.

Generally, it is hard to propagate shear wave of high frequency in viscoelastic medium like a living body. Hence, in this research, longitudinal waves are propagated to a tumor. Using shear waves occurring at the tumor as a mode conversion of a longitudinal wave, the depths of a living body is expected to be imaged as avoiding long-range propagation of shear waves.

Since such the elastic boundaries cannot be known in advance, we detect the existence of the mode conversion by scanning the beam for generating the shear waves and observing the echoes using the tracking beam, and we measure the sound speed of the shear waves in there. By measuring the weak shear waves during a long period of time with continuous beam transmission.

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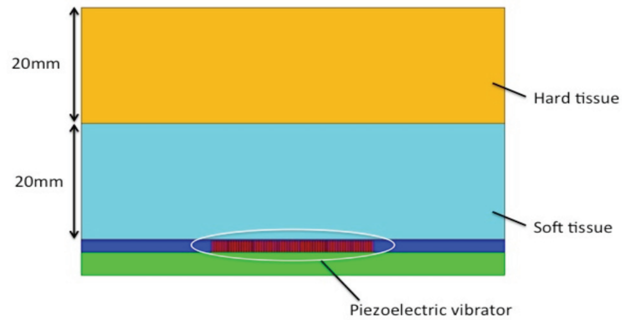

Fig. 1 simulation model

In this study, to confirm the effectiveness of the proposed imaging scheme, we evaluate the intensity of the shear wave occurring due to the mode conversion at the elastic boundary through simulations. It should be noted that to examine only the characteristics of the shear wave generation, not the characteristics of the propagation, in this study the viscous damping for shear waves is omitted.

3. Simulation

Equation (1) expresses a definition of a stress deviation tensor, which is introduced by deducting an isotropic component from the stress tensor and expresses a shear component of a pressure. The square root of the secondary invariant of a stress deviation tensor can be used as a value equivalent to shear wave strength.

$$\begin{bmatrix} \sigma'_{11} & \sigma'_{12} & \sigma'_{13} \\ \sigma'_{21} & \sigma'_{22} & \sigma'_{23} \\ \sigma'_{31} & \sigma'_{32} & \sigma'_{33} \end{bmatrix} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} - \frac{1}{3}(\sigma_{11}+\sigma_{22}+\sigma_{33}) \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

As shown in **Fig. 1**, we model a layered elasticity boundary using soft tissue with an elastic modulus of 1.0kPa, which is placed on the input side of longitudinal waves with the width of 20mm, and hard tissue with various values of elastic modulus. The density of all the tissues is fixed as 1000g/cm^3. In a viscoelastic medium like a living body, it is generally hard to propagate shear waves in a high frequency domain. On the other hand,

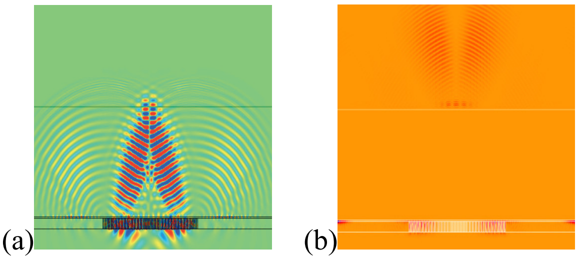

Fig. 2: simulation process of shear wave generation; (a) radiation to the boundary of longitudinal wave, (b) Shear wave which arose by mode conversion

waves with low frequency have low directivity, and hence sharp focusing is difficult. Therefore, in order to examine the suitable frequency for this study, simulation is performed with 1.0 MHz, 2.0 MHz, 3.0 MHz, and 4.0 MHz of transmitted longitudinal beams.

4. Result

The parameter values of the soft tissue are shown in **Table. 1**, and those of the hard tissue applicable to a tumor portion are shown in **Table. 2**.

Table. 1 The parameter values of soft tissue

Longitudinal wave velocity [m/s]	1500
Shear wave velocity [m/s]	1
Density [g/cm^3]	1000
Attenuation of longitudinal wave [dB/cm/MHz]	0.5
Attenuation of shear wave [dB/cm/MHz]	0.0

Table. 2 The parameter values of hard tissue

Longitudinal wave velocity [m/s]	1500
Shear wave velocity [m/s]	2, 5, 10
Density [g/cm^3]	1000
Attenuation of longitudinal wave [dB/cm/MHz]	0.7
Attenuation of shear wave [dB/cm/MHz]	0.0

The following equation indicates the elastic property.

$$\mu = \rho c^2 \tag{2}$$

μ : elastic modulus, ρ : density, c: wave velocity

From Tables. 1 and 2, the elastic moduli for shear waves are calculated as 1.0kPa, 4.0kPa, 25.0kPa, 100kPa. The elastic boundary is prepared and the value of shear wave intensity for every frequency is shown in Table 3. Also for the case that no elastic boundaries exist, shear wave intensity was evaluated and the result is shown in **Table 4**.

Table. 3 Shear wave intensity with elastic boundary

Soft / Hard	1.0 / 4.0 kPa	1.0 / 25.0 kPa	1.0 / 100 kPa
1.0 MHz	0.035	0.216	0.854
2.0 MHz	0.123	0.757	3.05
3.0 MHz	2.67	14.4	58.7
4.0 MHz	0.45	2.7	10.9

Table. 4 Shear wave intensity without elastic boundary

	4.0 kPa	25.0 kPa	100 kPa
1.0 MHz	0.033	0.201	0.79
2.0 MHz	0.11	0.70	2.82
3.0 MHz	2.51	13.4	53.0
4.0 MHz	0.42	2.51	10.0

From Table. 3, it can be known that large difference of elasticity is desirable for the mode conversion from longitudinal waves to shear waves. For the frequency of the transmitted longitudinal wave, low frequency is not suitable to generate high intensity shear waves. However, 4.0 MHz is too high, i.e. it is expected that there is an adequate frequency for the mode conversion. By comparing Table. 3 and Table.4, elasticity boundary seems to be favorable for the mode conversion.

5. Discussion and Future Work

We confirmed that the mode conversion certainly occurs and suitable shear waves can be generated. However, the frequency examined in this study may be too high to measure the velocity of the shear wave because of its high attenuation characteristics disregarded in this study. In future, we will construct a mode conversion method by which sufficiently low frequency shear waves are generated from high frequency longitudinal waves using various frequency conversion techniques

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