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Simulation study on the control of ultrasound propagation in cortical bone
皮質骨中を伝搬する超音波の集束
–FDTD によるシミュレーション

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1. Introduction

Recently, the low intensity pulsed ultrasound technique is used for the healing of bone fractures. Clinical studies show that the ultrasound irradiation can reduce the healing time of bone fractures. In this technique, ultrasound is usually irradiated from skin near the fracture part. However, the ultrasound is not effectively irradiated because the actual sound field in the body is not well understood.

In this study, a time reversal wave technique was used to investigate the effective wave irradiation. This method is well known and used in the medical ultrasound and sonar studies [1, 2].

For this purpose, a simulation study was performed using a three-dimensional (3D) bone model. It contains anisotropic and heterogeneous elasticity and was constructed from experimental data of actual cortical bone [3]. Using this 3D model and the time reversal technique, wave convergence in the bone was challenged.

2. 3D model construction [3, 4]

To construct 3D heterogeneous bone model, we used the axial longitudinal wave velocity distribution of bovine cortical bone measured in the MHz range. For the simulation, the measured velocity distribution with a spatial resolution of 1 mm was interpolated to 40 μm using a bilinear interpolation and an arranged bilinear interpolation. Then a 3D model of longitudinal velocity was constructed from four two-dimensional velocity distribution using Piecewise Cubic Hermite Interpolating Polynomial. In this study, 3D model of the bone anterior part with axial velocity distribution was constructed [3,4].

To estimate elastic constants, we assumed that the bone has uniaxial anisotropy. Here, 1, 2, and 3 axes are radial, tangential, and axial directions. To estimate c_{33}, c_{44}, and c_{66}, we assumed that the bone density was 2000 kg/m^3, and Poisson's ratio was 0.33 [5]. To estimate c_{11}, and c_{13}, we referred to studies by Nakatsuji et al. and Yamato et al. for anisotropic information of bovine cortical bone [6,7].

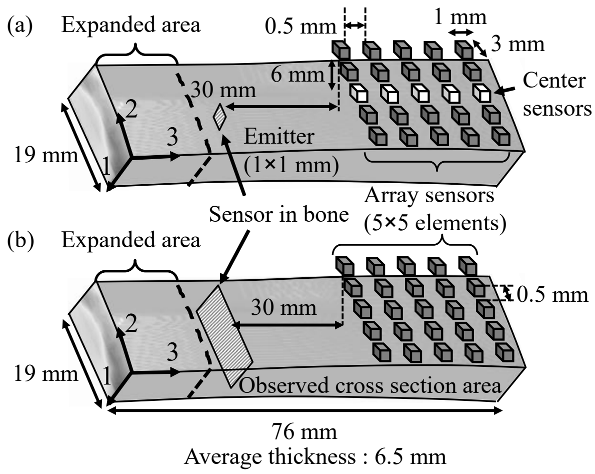

Fig. 1 Simulation conditions of (a) emission point and (b) observed cross section for time reversal wave.

3. Simulation conditions

3.1. Ultrasound emission from inside of the bone

In this study, a 3D elastic finite-difference time-domain (FDTD) method was used [8]. **Figure 1 (a)** shows the first simulation condition. The emitter side of the model was expanded by 16 mm to avoid wave reflection from the end. The Higdon's second order absorbing boundary condition was applied. For the Courant stability condition, the spatial and time resolution was 40 μm and 4.6 ns. The input signal was one cycle of sinusoidal wave at frequency of 1 MHz with Hanning window. The bone model was immersed in water. In the simulation, a virtual emitter was set in the bone model simulated bone fracture point, and receiver array (25 elements) was set in water. This emission point is the convergence target of the time reversal wave.

Figure 2 shows the simulated sound field at the cross section of the center part, at 13.8 μs after the emission. **Figure 3** shows the observed waveforms at center array sensors (5 elements). The first wave is the direct longitudinal wave. However, after the first wave, several longitudinal and transverse waves propagated through the bone model. Therefore, we used only this first

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longitudinal wave with Hanning window for the time reversal technique.

3. 2. Convergence by the time reversal waves

Figure 1 (b) shows the second simulation condition. The emitter array was set at the same position with the receiver array. Time reversal wave was transmitted from each emitter, and the wave intensity distribution was investigated at the cross section which includes the first emission point.

4. Results and discussion

Figure 4 shows a typical observed waveform at the cross section. **Figure 5** shows distribution of peak to peak value of observed waves. This value was normalized by the first emission signal. As a result, the intensity around the first emitter position was stronger than those of other points. The area of -3 dB is also shown in **Fig. 5**. The intensity in condition (a) was stronger than that of the condition (b). This is because condition (b) is closer to the side surface. The reflection wave from the side surface may overlap and the intensity becomes lower.

These results show that the wave convergence is possible using an array sensor and the time reversal technique. Therefore, this technique may be applicable to control ultrasound wave in bone.

5. Conclusion

In this study, we applied the time reversal technique to a heterogeneous and anisotropic bone model. Using an array sensor, the convergence of the wave was possible. The results indicate that the wave convergence at the arbitrary area can be possible in the future, which may be applicable to the sophisticated bone fracture healing. Of course further study is necessary for the effective and safe system.

Reference

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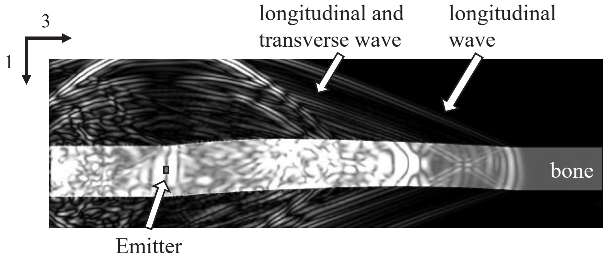

Fig. 2 Sound field at center cross section at 13.8 µs.

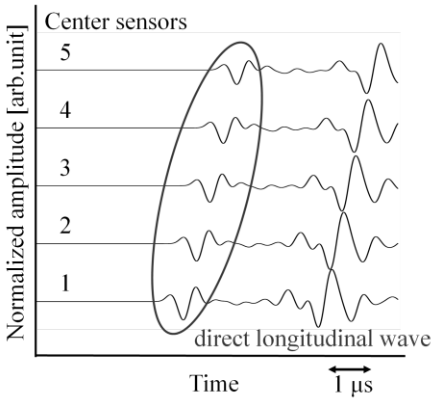

Fig. 3 Observed waveforms at each receiver in the center part.

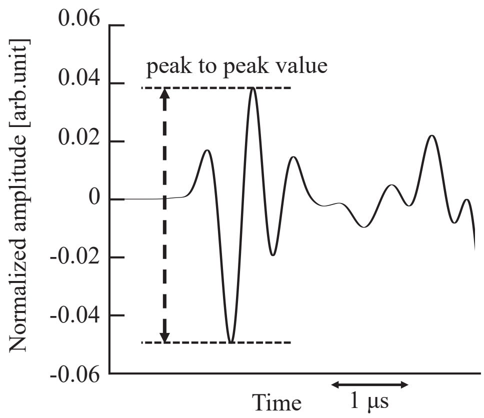

Fig. 4 A typical observed waveform.

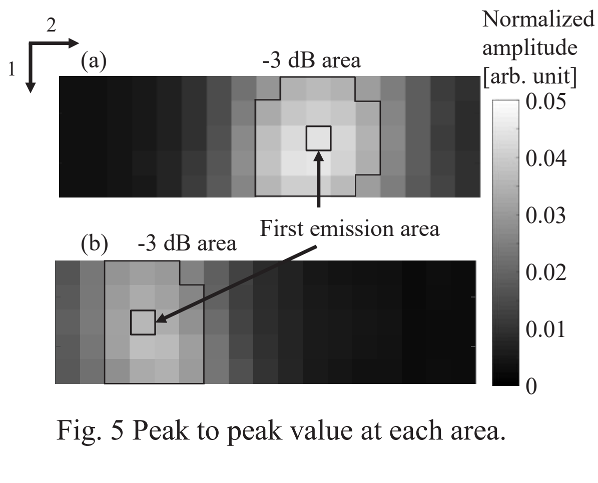

Fig. 5 Peak to peak value at each area.