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Effect of Cortical Bone Layer on Piezoelectric Signal Generated in Cancellous Bone

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1. Introduction

Low-intensity pulsed ultrasound (LIPUS) can accelerate bone fracture healing[1,2]. During the healing process, bone can be formed with the piezoelectric effects[3]. To develop a healing method for a joint bone, which is mostly occupied by cancellous bone, the piezoelectric properties in cancellous bone should be sufficiently understood. As *in situ* cancellous bone is surrounded by cortical bone, the ultrasound irradiation to cancellous bone has to be done through the cortical bone layer.

In the author's study, the piezoelectric signals generated in cancellous bone by ultrasound irradiation has been simulated by a piezoelectric finite-difference time-domain (PE-FDTD) method[4]. In this study, the effect of the cortical bone layer on the piezoelectric signal in cancellous bone was investigated by the PE-FDTD simulations.

2. Methods

The PE-FDTD method is an elastic FDTD method with piezoelectric constitutive equations, and the governing equations are as follows[5].

$$\rho \frac{\partial \dot{u}_i}{\partial t} = \frac{\partial \tau_{ii}}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \frac{\partial \tau_{ik}}{\partial x_k} \quad (1)$$

$$\frac{\partial \tau_{ii}}{\partial t} = (\lambda + 2\mu)\frac{\partial \dot{u}_i}{\partial x_i} + \lambda \frac{\partial \dot{u}_j}{\partial x_j} + \lambda \frac{\partial \dot{u}_k}{\partial x_k} - e_{ii}\frac{\partial E_i}{\partial t} - e_{ji}\frac{\partial E_j}{\partial t} - e_{ki}\frac{\partial E_k}{\partial t} \quad (2)$$

$$\frac{\partial \tau_{jk}}{\partial t} = \mu\left(\frac{\partial \dot{u}_j}{\partial x_k} + \frac{\partial \dot{u}_k}{\partial x_j}\right) - e_{il}\frac{\partial E_i}{\partial t} - e_{jl}\frac{\partial E_j}{\partial t} - e_{kl}\frac{\partial E_k}{\partial t} \quad (3)$$

$$\varepsilon_{ii}\frac{\partial E_i}{\partial t} = -e_{ii}\frac{\partial \dot{u}_i}{\partial x_i} - e_{ij}\frac{\partial \dot{u}_j}{\partial x_j} - e_{ik}\frac{\partial \dot{u}_k}{\partial x_k} - \frac{e_{il}}{2}\left(\frac{\partial \dot{u}_j}{\partial x_k} + \frac{\partial \dot{u}_k}{\partial x_j}\right) - \frac{e_{im}}{2}\left(\frac{\partial \dot{u}_k}{\partial x_i} + \frac{\partial \dot{u}_i}{\partial x_k}\right) - \frac{e_{in}}{2}\left(\frac{\partial \dot{u}_i}{\partial x_j} + \frac{\partial \dot{u}_j}{\partial x_i}\right) + \frac{\partial D_i}{\partial t} \quad (4)$$

$$\frac{\partial D_i}{\partial t} = -\sigma_i E_i \quad (5)$$

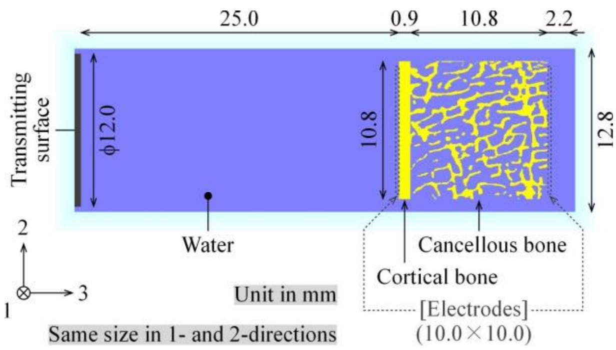

Fig. 1 Numerical model for simulating piezoelectric signal generated in cancellous bone with a cortical bone layer by ultrasound irradiation.

In Eqs. (1)–(5), the variables are $\dot{u}_i$ of the particle velocity, τ_{ii} and τ_{ij} of the normal and shear stresses, E_i of the electric field, and D_i of the electric displacement. The constants are ρ of the density, λ and μ of the first and second Lamé coefficients, e_{ij} of the piezoelectric constant, ε_{ii} of the dielectric constant, and σ_i of the conductivity.

A cubic cancellous bone model with a size of 10.8 mm and a porosity of 0.76 (24% solid bone) was reconstructed from the X-ray microcomputed tomographic image of bovine bone with a resolution of 45 μm. The pore spaces were saturated with water. Two cancellous bone models without and with a cortical bone layer were prepared. In the cancellous bone model with the cortical bone layer, a 100% solid bone layer with a thickness of 0.9 mm was attached on the front surface of cancellous bone.

Figure 1 shows the numerical model for the PE-FDTD simulations in cancellous bone with the cortical bone layer. The piezoelectric signals generated in the bone by ultrasound irradiation were simulated, together with the ultrasound signals propagated through the bone. The piezoelectric signals were calculated from the voltages induced between the front and back electrodes. Then, the electrodes were regarded as perfect conductors, and the elastic properties were ignored. The ultrasound signals were calculated from the normal stresses on the surface of the back electrode. The irradiated ultrasound wave was a pulsed wave with a center frequency of 1 MHz, and the direction was parallel to the major trabecular orientation of cancellous bone.

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3. Results and Discussion

Figures 2 and 3 show the simulated waveforms of the piezoelectric and ultrasound signals, respectively. In both figures, the black and red lines show the waveforms for the cancellous bone models without and with the cortical bone layer, respectively. In the piezoelectric signals in Fig. 2, the waveform amplitude in the case of the cancellous bone model with the cortical bone layer was much larger than the amplitude in the case without the layer. On the other hand, in the ultrasound signals in Fig. 3, the amplitude in the case without the cortical bone layer was much larger.

It is known that two waves of "fast and slow waves" can propagate through cancellous bone, and the fast and slow waves correspond to the waves propagating mainly in the trabecular elements and the pore spaces (or the solid and fluid parts), respectively[6]. In the ultrasound signals (Fig. 3), the waves before and after about 23 μs could be regarded as the fast and slow waves, respectively. The slow wave amplitude decreased by the cortical bone layer, although the fast wave amplitude little changed. This was considered to be because the slow wave propagation was hindered by closing the pore spaces on the front surface of cancellous bone with the cortical bone layer.

In the piezoelectric signal in the case of the cancellous bone model without the cortical bone layer (black waveform in Fig. 2), the wave amplitude increased at about 23 μs. This was considered to be due to the slow wave. In the piezoelectric signal in the case with the cortical bone layer (red waveform in Fig. 2), the wave amplitude increased immediately after the onset and thereafter decreased monotonically. Unlike the piezoelectric signal in the case without the cortical bone layer, the amplitude did not increase at about 23 μs. Therefore, the large piezoelectric signal amplitude in the case with the cortical bone layer was considered to be due to the piezoelectric signal generated in the cortical bone layer, rather than the ultrasound signal. Moreover, the piezoelectric signal amplitude in the case with the cortical bone layer was much larger than the amplitude in the case without the layer. Accordingly, it was concluded that the piezoelectric effect in the cortical bone layer was dominant.

4. Conclusions

Using the PE-FDTD method, the piezoelectric signals in cancellous bone without and with the cortical bone layer was simulated, together with the ultrasound signals. From the changes of the signal amplitudes, it was suggested that the piezoelectric signal could be dominantly generated in the cortical bone layer.

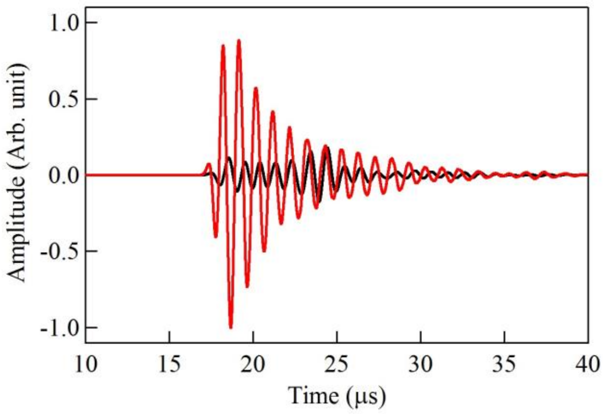

Fig. 2 Simulated waveforms of piezoelectric signals generated in cancellous bone by ultrasound irradiation. The black and red lines show the waveforms for the cancellous bone models without and with a cortical bone layer.

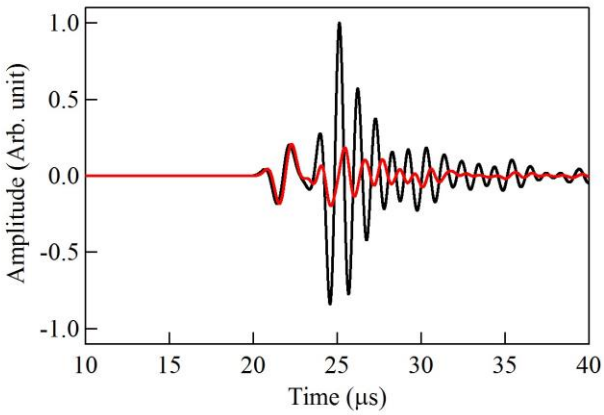

Fig. 3 Simulated waveforms of ultrasound signals propagated through cancellous bone. The black and red lines show the waveforms for the cancellous bone models without and with a cortical bone layer.

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