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Effect of Ultrasound Attenuation on Piezoelectric Signal Generation in Cancellous Bone

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1. Introduction

Bone fracture healing can be accelerated by ultrasound irradiation[1,2]. The bone formation can be accompanied by the piezoelectric effect in the bone[3]. To establish the healing method for a joint bone, which is mostly occupied by cancellous bone, the piezoelectric properties in cancellous bone are required to sufficiently understand. Because of large ultrasound attenuation in cancellous bone, the ultrasound wave may be weakly transmitted to deep part, and the piezoelectric signal may also be weakly generated.

In the author's study, the piezoelectric properties in bone, mainly in cancellous bone, at ultrasound frequencies has been investigated using piezoelectric finite-difference time-domain (PE-FDTD) simulations[4]. In this study, the change of the piezoelectric signal in cancellous bone due to the ultrasound attenuation was numerically investigated.

2. Methods

The governing equations of the PE-FDTD method are given as[4]

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

$$\begin{aligned}\frac{\partial \tau_{ii}}{\partial t}=&\left(\lambda+2\mu\right)\frac{\partial \dot{u}_i}{\partial x_i}+\lambda\frac{\partial \dot{u}_j}{\partial x_j}+\lambda\frac{\partial \dot{u}_k}{\partial x_k}-e_{ii}\frac{\partial E_i}{\partial t}\\&-e_{ji}\frac{\partial E_j}{\partial t}-e_{ki}\frac{\partial E_k}{\partial t}\end{aligned}, \qquad (2)$$

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

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

$$\frac{\partial D_i}{\partial t}=-\sigma_i E_i\,. \qquad (5)$$

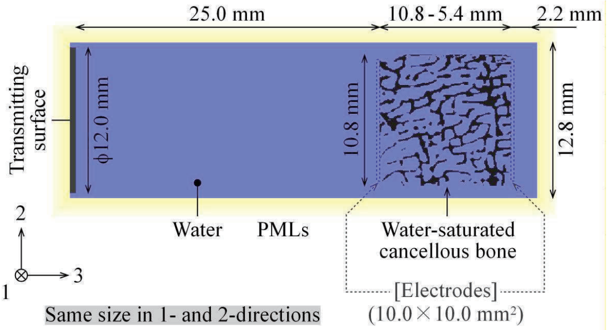

Fig. 1 Numerical model for simulating piezoelectric signal generated in cancellous bone by ultrasound irradiation.

Here, $\dot{u}_i$ is the particle velocity, τ_{ii} and τ_{ij} are the normal and shear stresses, respectively, E_i is the electric field, and D_i is the electric displacement. ρ is the density, λ and μ are the first and second Lamé coefficients, respectively, e_{ij} is the piezoelectric constant, ε_{ii} is the dielectric constant, and σ_i is the conductivity.

A cubic cancellous bone model with a size of 10.8 mm and a resolution of 45 µm was reconstructed from the X-ray microcomputed tomographic image of bovine bone. It was assumed that the pore spaces were saturated with water instead of bone marrow. The porosity was 0.73 (73%). Based on this cancellous bone model, two sets of the bone models with different thicknesses ranging from 10.8 to 5.4 mm were created, and are named the cancellous bone model (CBM) sets A and B. The thicknesses in the CBM sets were reduced in the directions parallel and perpendicular to the major trabecular orientation, respectively.

Using the PE-FDTD method, the piezoelectric signals generated in cancellous bone by ultrasound irradiation were simulated. **Figure 1** shows the numerical model for the PE-FDTD simulation. The irradiated ultrasound signal was applied to the normal stress components on the transmitting surface, and the experimental data of the pulse wave with a center frequency of 1 MHz was used. As the piezoelectric signals, the voltage waveforms were calculated from the electric fields in the trabecular elements between the front and back electrodes. Then, the electrodes were regarded as perfect conductors, and the elastic properties were ignored. The ultrasound wave was irradiated in the thickness directions of the cancellous bone models, namely, in

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the directions parallel and perpendicular to the major trabecular orientation in the CBM sets A and B, respectively. The ultrasound signal waveforms propagated through cancellous bone were also calculated from the normal stress components on the surface of the back electrode.

3. Results and Discussion

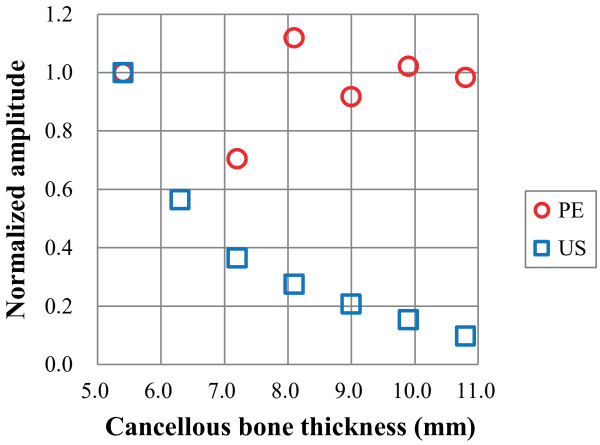
The peak-to-peak amplitudes of the piezoelectric (PE) and the ultrasound (US) signals were measured from the simulated waveforms. **Figure 2** shows the variations in the PE and US amplitudes with the cancellous bone thickness; (a) and (b) show the variations in the CBM sets A and B, respectively. In both CBM sets, the US signal amplitudes decreased with the cancellous bone thickness. In the CBM set A, the PE signal amplitude randomly varied. On the other hand, in the CBM set B, the PE signal amplitude scarcely varied at the cancellous bone thickness above 6.3 mm.

In the CBM sets A and B, the ultrasound wave was irradiated in the directions parallel and perpendicular to the major trabecular orientation, respectively. It is known that two separated waves of “fast and slow waves” are observed in the US signal transmitted in the parallel direction, but the overlapped single wave is observed in the perpendicular direction[5]. It was inferred from the simulated US signal waveforms that, in both CBM sets A and B, the peak-to-peak amplitudes corresponded to the slow wave amplitudes, which are much larger than the fast wave amplitudes. Therefore, it was considered that the variations of the US signal amplitudes in the two CBM sets with the cancellous bone thickness were similar.

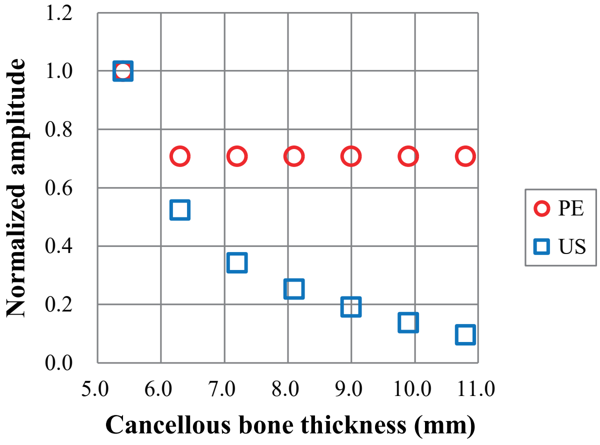
The variations in the PE signal amplitudes were different in the CBM sets A and B. It was considered that, in the CBM set A, the local PE signal generated at the deep part far from the front surface of cancellous bone could irregularly affect the whole PE signal, and that, in the CBM set B, the local PE signal at the shallow part was dominant. Anyway, comparing the variations in the US signal amplitudes, the variations in the PE signal amplitudes were not large. Accordingly, it is concluded that it is not easy to detect the strong PE signal at the deep part in cancellous bone.

4. Conclusions

Using the PE-FDTD simulations, the variations in the piezoelectric signal amplitudes with the cancellous bone thickness were investigated with the variations in the transmitted ultrasound signal amplitudes. In conclusion, the piezoelectric signal could be dominantly generated at the shallow part because of the high ultrasound attenuation.



(a) CBM set A



(b) CBM set B

Fig. 2 Variations in piezoelectric (PE) and ultrasound (US) signal amplitudes with the thickness in the cancellous bone model (CBM) sets (a) A and (b). The thickness in the CBM sets A and B were reduced in the direction parallel and perpendicular to the major trabecular orientation, respectively.

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