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Numerical Simulation of Piezoelectric Signal Generated in Cancellous Bone by Ultrasound Irradiation: Effect of Pore Fluid

超音波照射によって海綿骨で発生する圧電信号の数値シミュレーション：間隙流体の影響

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1. Introduction

From the fact that mechanical loads can drive bone formation,[1] low-intensity pulsed ultrasound (LIPUS) at a few megahertz has been applied to the medical healing of bone fracture.[2,3] Bone can behave as a piezoelectric material,[4] and the bone formation can be acconpanied by the piezoelectric effects.[5] However, the piezoelectric properties in bone, particularly in cancellous bone, at ultrasound frequencies are not sufficiently clarified.

In the previous study,[6] the piezoelectric signals in air- and water-saturated cancellous bones have been experimentally observed, and it was shown that the piezoelectric properties could be largely affected by the pore fluid. Moreover, piezoelectric simulations have been also performed using a piezoelectric finite-difference time-domain (PE-FDTD) method.[7] In this study, the effect of the pore fluid was investigated with the PE-FDTD simulations.

2. Method

In the PE-FDTD method, Eqs. (1)–(5) are used.

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

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

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

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

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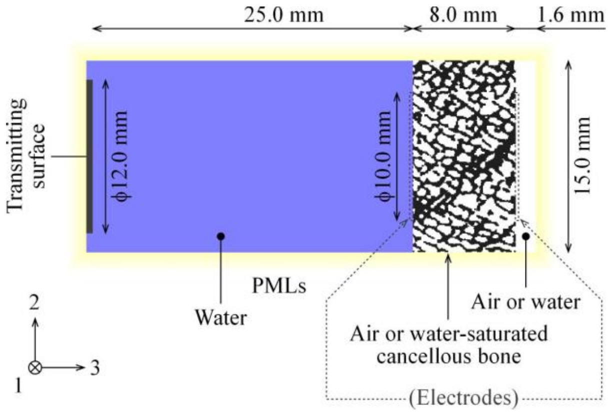

Fig. 1 Simulation model for piezoelectric signals in cancellous bone generated by ultrasound irradiation.

$$\frac{\partial D_i}{\partial t}=-\sigma_i E_i \tag{5}$$

Here, i, j, k = 1, 2, 3, and l, m, n = 4, 5, 6. In these equations, $\dot{u}_i$ (dot denotes the time derivative) is the particle velocity in the i-direction, τ_{ii} is the normal stress in the i-direction, t_{jk} ($j \neq k$) is the shear stress on the j–k plane, 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} (containing $i = j$) is the piezoelectric constant, ε_{ii} is the dielectric constant, and σ_i is the conductivity.

Figure 1 shows the three-dimensional (3D) simulation model. The cancellous bone model was reconstructed from the 3D X-ray microcomputed tomographic image of bovine bone. The porosity was 0.68 (68%), and the main trabecular elements were mainly oriented in two directions parallel and perpendicular to the thickness (or the ultrasound irradiation) direction. The pore spaces in the cancellous bone model were saturated with air or water, and the same-fluid layer was set at the back. The irradiated ultrasound signal was applied to the normal stress components τ_{ii} on the transmitting surface, and the experimental data of the burst wave at 1 MHz was used in this study. The piezoelectric signal was calculated from the electric fields E_i in the trabecular elements between the electrodes.

Then, the electrodes were regarded as perfect conductors, and the elastic properties were ignored. In the simulation models in the cases that the pore fluid was air and water, the same parameter values[7] were used except for the values of the pore fluid. The spatial and temporal intervals were 36.5 μm and 4 ns, respectively.

3. Results and Discussion

Figure 2 shows the simulated waveforms of the piezoelectric signals in cancellous bones generated by ultrasound irradiation at 1 MHz; (a) and (b) shows the waveforms simulated for the air- and water-saturated bones. In the simulated results, the amplitude of the piezoelectric signal in the water- saturated bone was approximately one-fourth of the amplitude in the air-saturated bone. In the PE-FDTD simulations, the piezoelectric signal could generate in the trabecular elements but not in the pore fluid. The difference between the simulation models in the cases that the pore fluid was air and water was only the difference in the parameter values of the pore fluid. Therefore, the difference between the simulated piezoelectric signals in the air and water-saturated bones could be caused only by the ultrasound propagation in the pore fluid.

In the previous experimental results,[6] the piezoelectric signal amplitude in the water-saturated bone was approximately four times of the amplitude in the air-saturated bone. Moreover, it was shown that the slow wave, which corresponded to the ultrasound wave propagating mainly in the pore fluid,[8] could transmit through the water-saturated bone but hardly through the air-saturated bone. Therefore, the larger piezoelectric signal amplitude in the water- saturated bone was considered to be associated with the slow wave.

Compared between the simulated and experimental results, the large/small relations of the piezoelectric signal amplitudes in the air- and water-saturated bones were reversed. On the other hand, it was simulated that the amplitude of the ultrasound signal transmitted through the water-saturated bone was much larger than the amplitude in the air-saturated bone. This simulated result could depend on the slow wave amplitude, which agreed with the experimental one. Therefore, it could be regarded that the simulations of the ultrasound phenomenon were adequate. In other words, it was considered that the simulations of the piezoelectric phenomenon were inadequate. In the PE-FDTD method, it was assumed that the piezoelectric signal could generate inside the trabecular elements, but it may be generate only on the surface (or the interface between the trabecular elements and the pore spaces).

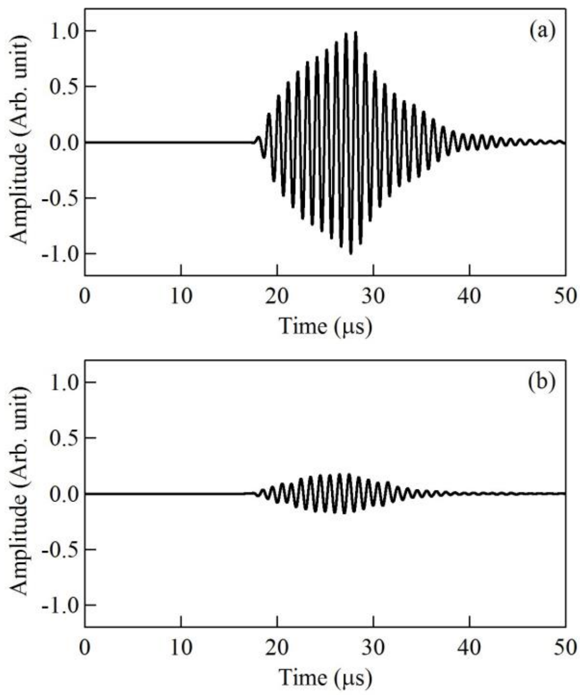

Fig. 2 Simulated waveforms of piezoelectric signals in (a) air- and (b) water-saturated cancellous bones generated by ultrasound irradiation at 1 MHz.

4. Conclusions

The piezoelectric signals in air- and water-saturated cancellous bones generated by ultrasound irradiation were simulated using the PE-FDTD method, and the effect of the pore fluid was investigated. As a result, it was considered that the simulation method should be modified so that the piezoelectric signal can generate only on the interface between the trabecular elements and the pore spaces.

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