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Numerical Simulation of Piezoelectric Signal Generated in Cancellous Bone by Ultrasound Irradiation: Effect of Trabecular Orientation

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：骨梁配向の影響

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1. Introduction

Low-intensity pulsed ultrasound (LIPUS) at a few megahertz (MHz) has been applied to the medical healing of bone fracture,[1,2] which is based on the fact that mechanical loads can drive bone formation.[3] The piezoelectric effects in bone can acconpany the bone formation,[4] but the piezoelectric properties at ultrasound frequencies are not sufficiently understood. In particular, it is considered that the piezoelectric properties in cancellous bone are too complex to easily clarify. In such a case, numerical simulations, which enable visualization in a "black box", can be helpful.

In this study, piezoelectric finite-difference time-domain (PE-FDTD) simulations[5] were performed to investigate the effect of the trabcular orientation on the piezoelectric signal in water-saturated cancellous bone.

2. Method

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

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

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

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

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

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

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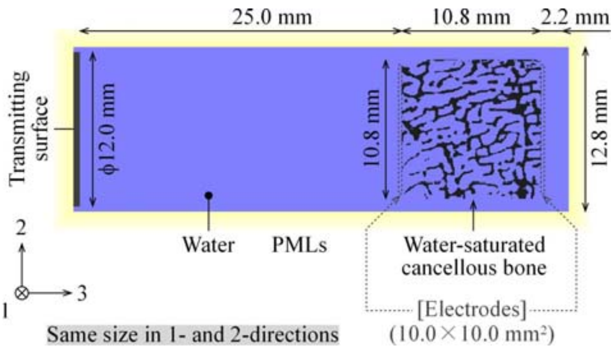

Fig. 1 Simulation model for piezoelectric signals in cancellous bone generated by ultrasound irradiation.

Here, i, j, k = 1, 2, 3, and l, m, n = 4, 5, 6. In these equations, $\dot{u}_i$ 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 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. 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. The spatial and temporal intervals were 60 µm and 4 ns, respectively.

A cubic cancellous bone model with a side of 10.8 mm was reconstructed from the 3D X-ray microcomputed tomographic image of bovine bone. The porosity was 0.73 (73%), and the pore spaces were saturated with water. The three orthogonal directions were named as x1-, x2-, and x3-directions. Table I lists the mean intercept lengths (MILs)[6] of the trabecular element and the pore space. The trabecular orientations were stronger in order of the x1-, x2-, and x3-directions. In order to observe the piezoelectric signal when the ultrasound wave was

Table I MILs of trabecular element and pore space of cancellous bone.

	Trabecular element	Pore space
*x*1-direction	0.38 mm	0.98 mm
*x*2-direction	0.34 mm	0.87 mm
*x*3-direction	0.32 mm	0.82 mm

irradiated in each direction, the cancellous bone model was rotated.

In the simulations, it was assumed that the piezoelectric signal generation could occur from the whole of the trabecular elements.

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), (b), and (c) show the waveforms when the ultrasound wave was irradiated in the *x*1-, *x*2-, and *x*3-directions, respectively. The piezoelectric signal amplitude increased in order of the ultrasound irradiation in the *x*1-, *x*2-, and *x*3-directions. In other word, the amplitude was larger as the trabecular orientation in the ultrasound direction was stronger. Thus, it was shown that the trabecular orientation can affect the piezoelectric signal in cancellous bone.

Similar to the previous study,[7] the simulations on the assumption that the piezoelectric signal generation could not occur from the surface of the trabecular elements were also performed. The simulated results showed that the piezoelectric signal waveforms were different from the waveforms on the assumption of the piezoelectric signal generation from the whole trabecular elements. Accordingly, it is considered that the piezoelectricity at the interface between the trabecular elements and the pore spaces can be significant to simulate the piezoelectric signal in cancellous bone. These simulated results should be compared with the experimental results to confirm which assumption is valid.

4. Conclusions

The piezoelectric signals in water-saturated cancellous bone generated by ultrasound irradiations in different directions were simulated using the PE-FDTD method, and the effect of the trabecular orientation was investigated. The simulated results showed that the piezoelectric signal amplitude could vary with the strength of the trabecular orientation. In a future study, the comparison between the simulated and experimental results will be performed.

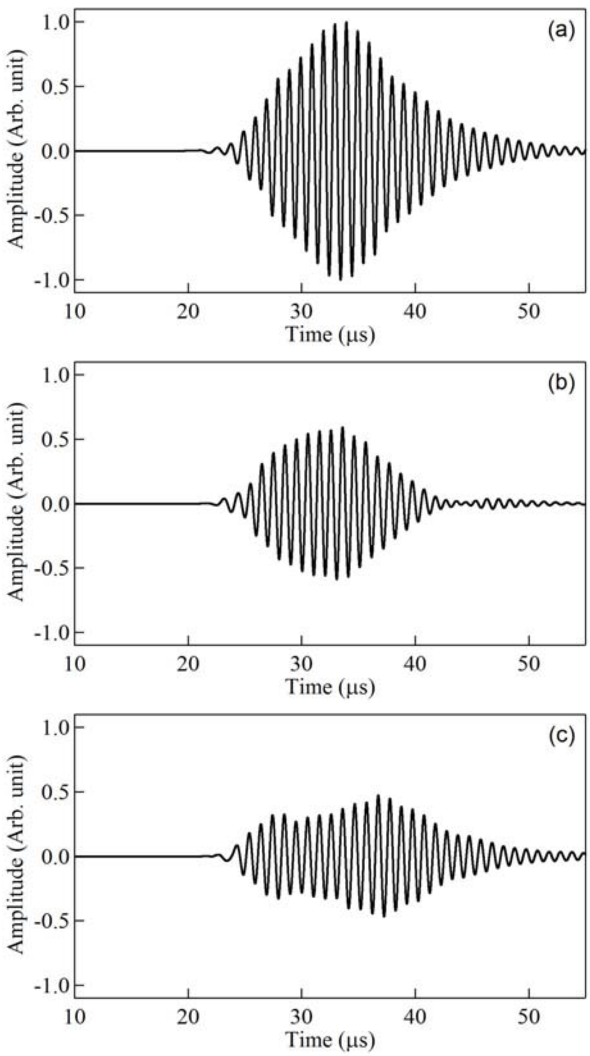

Fig. 2 Simulated waveforms of piezoelectric signals in water-saturated cancellous bones generated by ultrasound irradiation at 1 MHz in the (a) *x*1-, (b) *x*2-, and (c) *x*3-directions, respectively.

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