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Ultrasonic wave propagation in the cortical bone with heterogeneous character.

皮質骨中の不均一性を考慮した超音波伝搬特性の検討

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1. Introduction

Osteoporosis is a skeletal disease which increases a risk of bone fracture. The DEXA (Dual Energy X-ray Absorptiometric Scan) has been used for the diagnosis criterion. However, QUS (Quantitative Ultrasound) is more suitable for mass screening than DEXA, because it is non-invasive, low cost, and easy to use.

One of the QUS techniques, AT (Axial Transmission technique), measures guided waves in the long cortical bone along the bone axis. The cortical bone supports body load, so the fracture directly decreases QOL (Quality of Life). The technique currently measures the FAS (First Arriving Signal) which is a leaky wave from the bone surface. Talmant has reported that the FAS velocity relates to age [1]. However, most of FAS studies assume that bone is uniform, which does not reflect the actual anisotropic distribution of elastic properties [2]. In this study, we have fabricated a bone model with anisotropy and heterogeneity estimated from experimental data, and studied its effect on the ultrasonic wave propagation using a simulation.

2. Samples

The samples were made from a 73-month-old female bovine. We sliced the long bone of bovine tibia into 4 samples with thickness of 10 mm. We created 2 holes before slicing the model as markers. The sample is shown in Fig. 1.

3. Experimental method

Figure 2 shows the experimental system used. A single sinusoidal wave at 1 MHz, with amplitude of 5 Vp-p from a function generator (Agilent Technologies, 33250A) was amplified 20 dB by a power amplifier (NF, HSA 4101), and applied to the transmitter. The transmitter was a PVDF flat transmitter (handmade, 3 mm in diameter). The waves that passed through the sample were converted into electrical signals at the receiver (hand-made, 3 mm in diameter) and recorded by a digital oscilloscope (Tektronix, TDS 524A) with 20 dB preamplifier (NF, BX-31). The transmitter was set 45 mm away from the receiver. The samples were held on using acrylic plates, and were set perpendicular to the bone axis and sound axis. The position of the samples was changed to measure the distribution during the measurement. The bone thickness at each measurement point was measured using a micrometer.

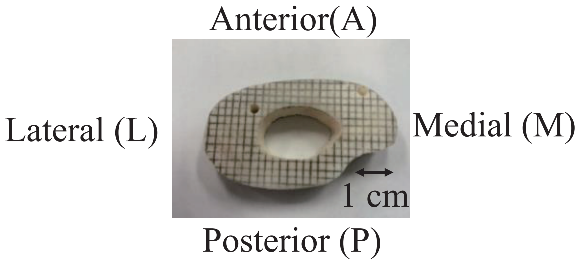

Fig. 1 Sample.

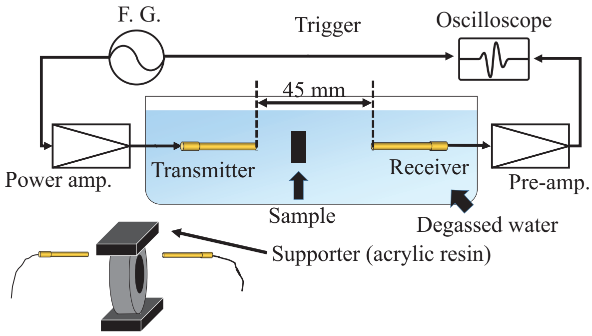

Fig. 2 Experimental system used.

4. Experimental results

We calculated the velocity in the bone form the time difference between the arrival times of waves through only water, or bone and water. Figure 3 shows one of the results, which indicates a distribution of velocity in the axial direction of bovine cortical bone. The outside velocities are lower than the inside velocities.

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5. Simulation method

The sound wave propagation was simulated using an FDTD (Finite Difference Time Domain) method (2 dimensions) [3]. The simulation area was the medial side of the bone. The bilinear interpolation and the PCHIP (Piecewise Cubic Hermite Interpolating Polynomial) were used for a model fabrication [4]. We assumed that the bone has uniaxial anisotropy to calculate each elastic constant. To estimate all constants, we assumed that the Poisson ratio was 0.33 [5] and referred to studies by Nakatsuji and Yamato for information on anisotropy of bovine cortical bone data [6-7]. The outside elastic constants were low according to the distribution of velocity. Figure 4 shows the simulation condition. The Higdon's second-order absorbing boundary condition was applied. The spatial resolution was 20 μm and the time resolution was 3.2 ns. The input signal was a single sinusoidal wave at 1 MHz with a Hann window.

6. Result and discussion

Figure 5 shows waveforms obtained by the simulation using a heterogeneous model. Figure 6 shows the paths of sound waves. FAS (①), a reflected longitudinal wave (②), a reflected shear wave (③), and a direct wave (④) were observed. The arrival time of FAS in uniform model was faster than that of the heterogeneity model. The FAS velocity in the uniform model was 4340 m/s, and the velocity in the heterogeneous one was 4200 m/s. Because the FAS mainly propagates on the surface of bone, it seems to be affected by the surface elastic constants.

7. Conclusion

In this study, we focused on the heterogeneous effect on an ultrasonic wave propagation. After measuring a distribution of velocity in bovine cortical bone, we investigated heterogeneous bone model for a simulation of the sound wave propagation. The FAS (first arriving signal) is normally measured to evaluate the bone strength in AT technique. The FAS comes from bone surface wave, so there are some possibilities of evaluating elastic constants of surface bone which do not reflect the total bone elasticity.

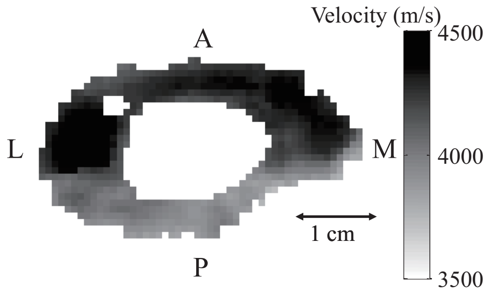

Fig. 3 Distribution of velocity.

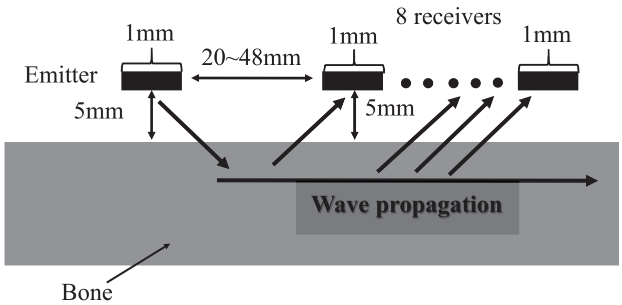

Fig. 4 Simulation condition.

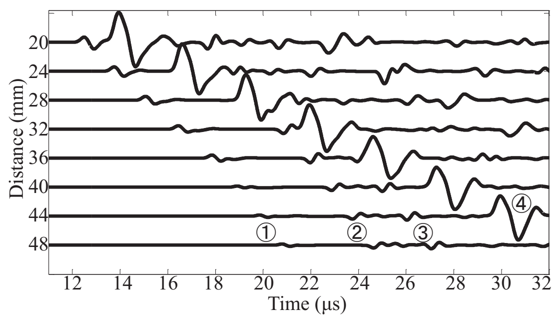

Fig. 5 Output signals (heterogeneity model).

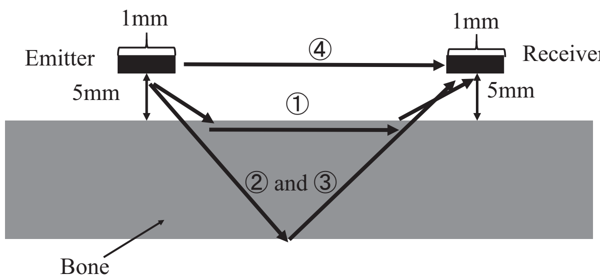

Fig. 6. The paths of sound waves.

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