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Proceedings of Symposium on Ultrasonic Electronics, Vol. 31 (2010) pp. 559-560
6-8 December, 2010

Computational Investigation of Generation Mechanism of Fast Wave in Cancellous Bone
海綿骨中の高速波生成メカニズムのシミュレーションによる検討

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1. Backgrounds and Objectives

In cancellous bone, longitudinal waves often separate into fast and slow waves depending on the alignment of bone trabeculae in the propagation path [1]. This interesting phenomenon becomes an effective tool for the diagnosis of osteoporosis because wave propagation behavior depends on the bone structure [2]. Nagatani *et al*. pointed that fast wave requires certain propagation distance for steady propagation [3]. However, the precise mechanism of fast wave propagation is not clarified yet. In this study, therefore, we investigated the detailed behaviour of fast wave generation by using three-dimensional simulation technique.

2. Simulation Technique: Elastic FDTD Method

In this study, the elastic three-dimensional finite-difference time-domain (FDTD) method was used. In order to reflect the absorption effect, the values of the normal and shear stresses are attenuated in each calculation step of propagation. The frequency dispersion of attenuation was not considered. In this simulation, the elastic anisotropy of the solid portion was not considered. It was confirmed by our group that the simulated waveform of fast wave and slow wave was in good agreement with the experimental results [3,4].

3. Simulation Model

For FDTD simulation, 3-D CT images of three parallelepipedic bovine cancellous bone samples (A, B, and C) obtained from the femoral head of 36 months old bovine were used. The size of three samples used was 15×15×9-12 mm. Spatial resolution of the CT images was 46 μm. The value at each point in the CT images was binarized in order to separate the ambiguous border between solid parts (trabeculae) and liquid parts (marrow) with a specific threshold. The total simulation field was 17×17×13 mm with cube lattice of 46 μm. In this model, the bone sample was fully immersed in water instead of bone marrow.

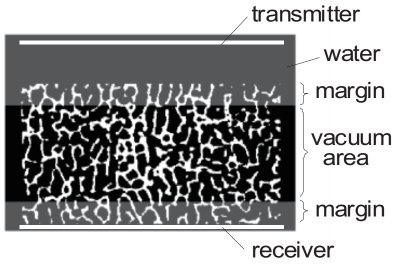

Fig. 1: Simulation model. The specimen was immersed in water. The middle part of specimen was assumed to be vacuum.

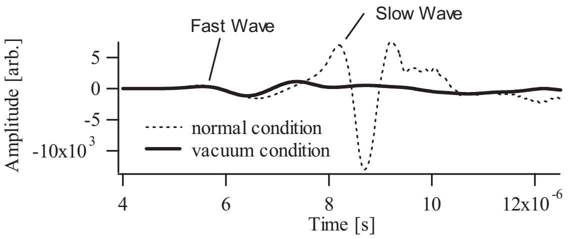

Fig. 2: Examples of the received waveforms in normal condition (no vacuum area) and vacuum condition.

In order to investigate the behavior of fast wave generation, the liquid area in the central portion inside the specimen was virtually assumed to be vacuum (**Fig. 1**), so that soundwave can propagate only in solid portion. This process lets us understand the genesis of each wave respectively. As an initial particle velocity, single sinusoidal wave at 1 MHz with Hanning window was impressed to the plane transmitter shown in Fig. 1.

4. Results and Discussions

Figure 2 shows examples of the received waveforms in normal condition (no vacuum area) and vacuum condition (bilateral margin size outside of vacuum area was 1.5mm). The porous portion in the margin area was immersed with water.

Beside the similar fast wave components, the slow wave can not be seen in vacuum condition. This phenomenon proves that slow wave mainly propagates in liquid portion, which was often projected by previous studies.

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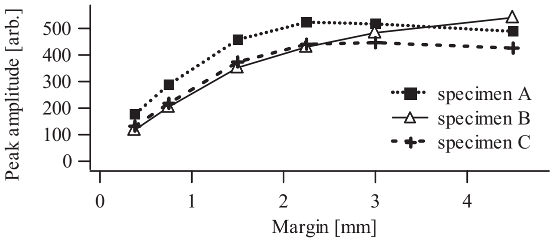

Fig. 3: Relationship between the thickness of the margin and peak amplitude of the fast waves.

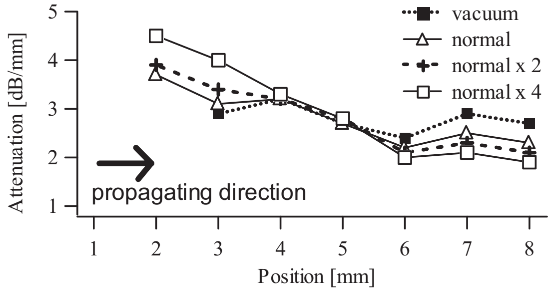

Fig. 4: Distribution of fast wave attenuation.

In order to investigate the role of margin, the thickness of margin was varied from 0.38 mm (a quarter of wavelength in water) to 4.5 mm (3 times of wavelength). **Figure 3** shows the relationship between the thickness of the margin and peak amplitude of the fast waves. The results of three specimens show similar tendency: The peak amplitude of fast wave gradually increases, then plateaus at 1.5 to 3.0 mm (1 to 2 times of wavelength). This interesting tendency tells us that fast wave is mainly originated from the soundwave that goes into trabecular within only 1 to 2 times of wavelength after entering the cancellous bone.

Moreover, the effect of the propagating length inside trabeculae was confirmed by grounding the specimen gradually from the bottom surfaces [3]. The samples were shorten gradually from 9 to 3 mm thickness with an interval of 1 mm. Then, using the sample with smaller thickness, the simulation was performed again. By comparing the amplitudes of the first peak of calculated waveforms obtained at each thickness, the spatial distribution of the attenuation in the sample (dB/mm) was obtained. (e.g.: the ratio of the peak amplitude where the thickness of the specimen was 9 mm and 8 mm indicates the attenuation within the shortened 1-millimeter-area.) The acoustic impedance (elastic modulus) of the liquid portion in the middle of specimen was changed to those of (a) vacuum, (b) water, (c) 2 times of water, and (d) 4 times of water. The wave speeds of the medium (c) and (d) were equalized to that of water.

Figure 4 shows the distribution of fast wave attenuation of specimen A. As Nagatani *et al.* already pointed [3], the amount of the attenuation is higher in the early state of propagation and gradually decreases as the propagation proceeds. However, the degradation rate of the attenuation depends on the acoustic impedance of the liquid portion. The higher impedance results in the greater degradation. This interesting phenomenon can be interpreted as coming from the leakage of soundwave from solid portion into liquid portion.

When the acoustic impedance of the liquid part is higher, the soundwave inside solid part can easily goes out into liquid part. The leaked wave may be emitted in shatters in the early state of propagation because the wavefront inside trabeculae is not clearly formed yet. This mechanism causes the higher attenuation in the early state of propagation. On the contrary, in the final state of propagation, the wave front inside trabeculae is formed tidily. Therefore, the greater emission of soundwave into liquid portion from solid portion results in smaller attenuation.

5. Conclusions

In this study, the detailed behaviour of fast wave generation was investigated using three-dimensional simulation technique. Fast wave is mainly originated from the soundwave that goes into trabecular within 1 to 2 times of wavelenth after entering the cancellous bone. When the acoustic impedance of the liquid part is higher, the degradation of fast wave attenuation was higher caused by the leakage of soundwave from solid portion into liquid portion. These interesting phenomena help us understand the precise behaviour of soundwave inside cancellous bone.

Acknowledgment

This study was supported by the Grant-in-Aid for Young Scientists (B) (20791218) of the Ministry of Education, Culture, Sports, Science and Technology. This study was partly supported by bilateral joint project between JSPS and CNRS, in addition to Prof. Mami Matsukawa and Katsunori Mizuno of Doshisha University and the Academic Research Frontier project of Doshisha University and Ministry of Education, Culture, Sports, Science and technology in Japan.

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