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Effects of Soft-tissue Layer on Shear Wave Velocity Measurements in Cortical Bone Tubes

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1. Introduction

Bone loss and deterioration caused by bone diseases, such as Osteoporosis can be effectively assessed using Quantitative Ultrasound (QUS) methods[1)]. Although first arriving signals (FAS), longitudinal and guided waves have been used for these purposes, measurements of shear waves using an axial transmission (AT) arrangement have not been extensively reported. Shear waves are related to the shear modulus and torsional strength which are important factors in bone fracture. Shear wave detection has been demonstrated and analyzed in the time domain in bone plates[2)] by our group. In this study, the effects of soft tissue on the shear wave measured on a bone tube sample was analyzed in the frequency domain using the 2D-FFT method. Ultrasound radiated at different incident angles in the axial direction of the tube bone were characterized. Additionally, 3D-simulations of the wave propagation using the elastic FDTD method were implemented.

2. Samples and Method

One hollow cylinder fabricated from the cortical bone of bovine femora (*w* = 1.6 mm, length = 63 mm) and density of 1.81×10^3 kg/m^3, covered by a soft tissue - mimicking layer (10% Agar and water, thicknesses: 2.2 – 7.0 mm) was used for the wave characterization. Experiments using the AT technique were performed at incident angles of 15º, 30º, 45º and 60º and keeping the same geometries shown in Fig. 1. One cycle of sinusoidal electrical signal at 1 MHz was applied to a composite flat transducer (diameter: 13 mm, Japan Probe). Signals were received by a homemade PVDF flat transducer (diameter: 10 mm). The transmitter scanned a distance of 10 mm along the axial direction of the bone tube at step size of 0.1 mm. A sampling frequency of 500 MHz was selected to record the signals. A spongy block was placed between the transducers to avoid direct waves. Using a time-of-flight technique, wave velocities at different angles were determined as the gradient of the line described by the point being detected at different time. Dispersion curves, wave number versus frequency of the experimental data at 60º (angle of interest for an efficient shear wave detection according to Snell's law) with and without soft tissue layer, were obtained using the 2D-FFT method. Extracted waves were compared with the corresponding theoretical dispersion curves considering an isotropic free plate model.

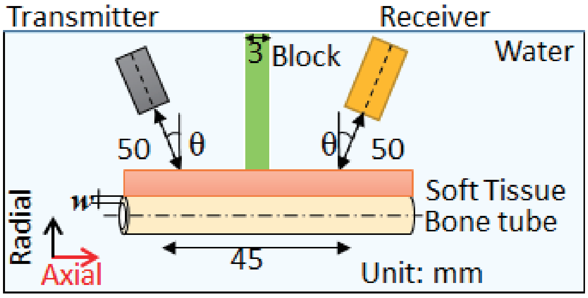

Fig. 1 Setup of the measurement system.

3. 3D-Simulations

Under similar experimental conditions, wave propagation was simulated using the elastic-FDTD method[3)]. An isotropic and homogeneous medium was considered for the 3D bone model surrounded by a soft tissue layer of 4.0 mm and density of 1043 kg/m^3, found in literature[4)].

Sound attenuation was not considered. The spatial resolution 74 µm and the time resolution 10.8 ns, both satisfied Courant's stability condition. In addition, Higdon's boundary condition was used. The transmitted signal with a Hann window was a single sinusoidal wave at 1 MHz. Longitudinal wave velocities of 4000 m/s for bone, 1561 m/s for soft tissue layer and 1500 m/s for water were assumed[5)], while shear wave velocity in bone was 1800 m/s. One emitter and 50 receivers separated 0.3 mm from each other were set at incident angles of 15º, 30º, 45º and 60º. The wave velocities and the dispersion curves were obtained following the described experimental method.

4. Results and Discussion

B-scan images of the measurement of the bone sample covered by 4.0 mm of soft tissue at angles of 15º, 30º, 45º and 60º are shown in Fig. 2. Similar trend was observed in the B-scan of the bone sample without the soft tissue layer. Critical angles calculated by means of Snell's law and obtained wave velocities suggested the detection of longitudinal wave at incident angles smaller than 30º and shear wave detection at incident angles larger than 30º. This angle dependence was observed in the

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cyjb3302@mail4.doshisha.ac.jp (Leslie Bustamante) wave velocities obtained from measurements of the bone sample with and without soft tissue layer shown in Fig 3. Wave velocities were determined considering the target waves, that is, the waves detected at the same initial incident angle and were selected after analyzing the simulations. Additionally, wave velocities obtained from the simulation of bone with and without 4.0 mm soft tissue shown in Fig. 3 demonstrated good agreement in the averaged wave velocities especially in the case of shear wave detection, 1700 m/s (exp. and simu.). Despite of the presence of soft tissue layer, the detection of shear wave showed good repeatability specially at $\theta = 60^\circ$, close to the critical angle ($\theta c = 56^\circ$). Since absorption was not considered, the simulations showed the interference of waves travelling on surface of the soft tissue layer, diffracting on the vacuum block edge and arriving first but at different incident angle. While in the experimental measurements, diffraction on the edge of the polymer sponge do not have a significant effect since part of this energy is absorbed by the block placed between the transducers.

Shear waves were characterized using the 2D-FFT method. Fig. 4 a) shows the wave characterization of bone without soft tissue layer at incident angle $\theta = 60^\circ$ (the angle for an efficient shear wave detection) and is compared with the simulation data. While Fig. 4 b) shows the wave characterization with a 4.0 mm soft tissue layer, at $\theta = 60^\circ$ and the simulation data. Dispersion curves extracted from the experiments with and without soft tissue layer showed good agreement with the theoretical dispersion curves that consider an isotropic free plate model. Signs of Lamb modes were difficult to identify in the tubular samples even though detected signals showed additional waves propagating at different frequencies. Lamb modes identification could be affected by problems with the spatial resolution found in the 2D-FFT method.

5. Summary

A frequency analysis of waves detected in a bone tube covered by a soft tissue layer was presented. The effects of soft tissue and bone curvature on the shear wave detection was analyzed. Wave velocities at incident angles of 60° showed good repeatability and good agreement with measurements performed in bone tubes without soft tissue layer. In the same way, experimental measurements were verified with simulations considering similar conditions. In the wave characterization, simulations using isotropic models and experiments demonstrated that shear wave axial transmission detection was not affected despite of the bone curvature and the addition of one layer over the sample. Additionally, results showed that isotropic plate models are still a reliable approximation to evaluate and characterize bone.

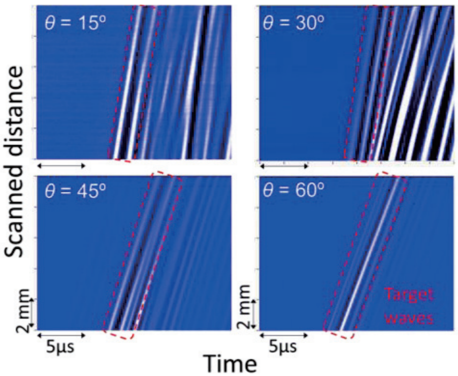

Fig. 2 B-scans of bone with 4 mm soft tissue layer.

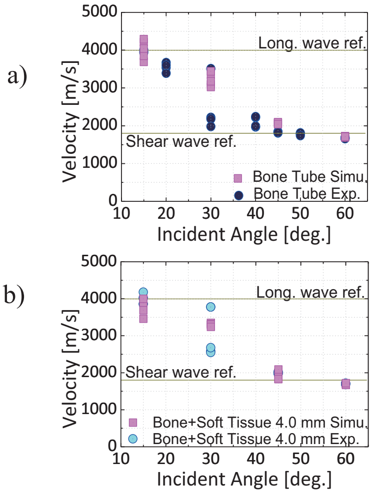

Fig. 3 a) Wave velocities of bone tube and b) bone covered by 4 mm soft tissue layer.

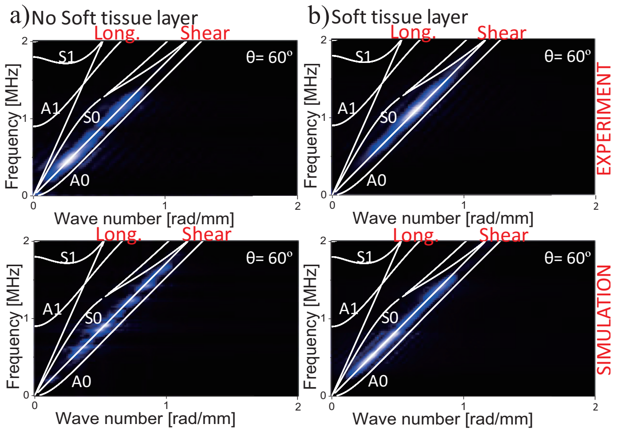

Fig. 4 Wave characterization with 4 mm soft tissue layer.

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