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Characterization of Ultrasonic Waves in Cortical Bone using Axial Transmission Technique

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1. Introduction

Quantitative ultrasound (QUS) methods using an axial transmission arrangement has become an effective technique for the evaluation of long bones[1)]. Longitudinal and guided waves are commonly used to characterize thin layers such as human cortical bone. However, shear waves for bone evaluation have not been extensively investigated. Shear waves are related to the shear modulus and torsional strength of bone which are important factors in the bone fracture. This study focuses on the measurement of axially transmitted shear waves in thin cortical bone plates with different thicknesses. Ultrasonic waves radiated at different incident angles in the axial direction of the bone plate were detected and characterized. Results were discussed with a FDTD simulation of the wave propagation.

2. Samples and Experiments

Previous studies have shown similarities in the wave velocities measured in plate and tube bone samples[2)]. In this study, plate samples were used. Three plates were fabricated from the cortical bone of bovine femora. The thicknesses are t = 1.0, 1.6 and 2.0 mm. All samples have an approximated length of 63 mm in the axial direction (the direction of the body weight) and width of 26 mm in the tangential direction.

One cycle 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). By moving the transmitter, a distance of 10 mm was scanned along the axial direction of the bone plate at step size of 0.1 mm. Experiments were performed at incident and receiving angles from 10º to 60º (each 10º and 15º) and keeping the same conditions shown in Fig. 1.

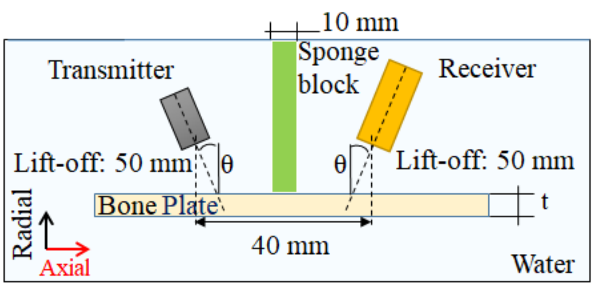

Fig.1 Experimental system.

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Using the time-of-flight (ToF) technique, velocities were calculated as the gradient of the line described by a point of the signal being detected at different time while moving the transmitter. Dispersion curves, phase velocity versus frequency of the experimental data, were obtained using a 2D-FFT.

3. Simulation of the Wave Propagation

In order to understand the wave propagation, similar conditions were simulated using the FDTD method[3)]. A 2D model was built considering an isotropic and homogeneous bone medium; sound attenuation was not considered. The spatial resolution 37.5 µm and the time resolution 6.6 ns, both satisfied Courant's stability condition. In addition, Higdon's boundary condition was used[4)]. The transmitted signal with a Hanning window was a single sinusoidal wave at 1 MHz. Longitudinal wave velocity of 4000 m/s for bone and 1500 m/s for water were assumed[5)]. Shear wave velocity in bone was assumed as 1800 m/s. One emitter and six receivers separated 2 mm from each other were set at angles of 15º, 30º, 45º and 60º. The wave velocities and the dispersion curves were obtained following the above experimental method.

4. Results and Discussion

The B-scan images of the 1.0 mm sample at angles of 15º, 30º, 45º and 60º are shown in Fig. 2. The observed waveforms from the simulation are shown in Fig. 3 at the same conditions. Waves arriving at different time, suggested the existence of basically two waves (among other attenuated waves), the first observed at incident angles smaller than 30º and the second at angles larger than 30º.

As the first approach, wave velocities were determined considering the waves arriving at the indicated time in Fig. 3, these waves correspond to the waves that strike the bone model at the same initial incident angle. First arriving waves at 45° and 60° (according to the simulation) seems to come from the wave radiated from the edge of the transmitter and therefore were neglected. Obtained experimental and simulation wave velocities (using four distinct pick points of the wave to estimate the ToF) are shown in Fig. 5.

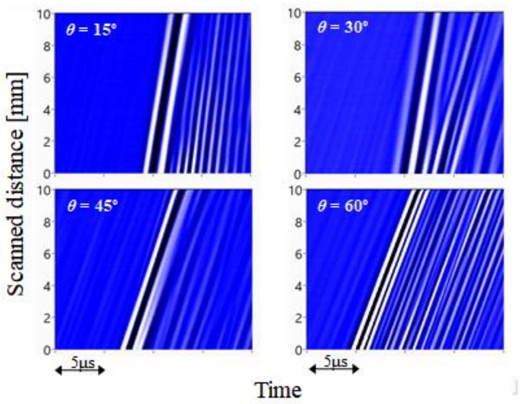

Fig. 2 B-scan of experimental measurements.

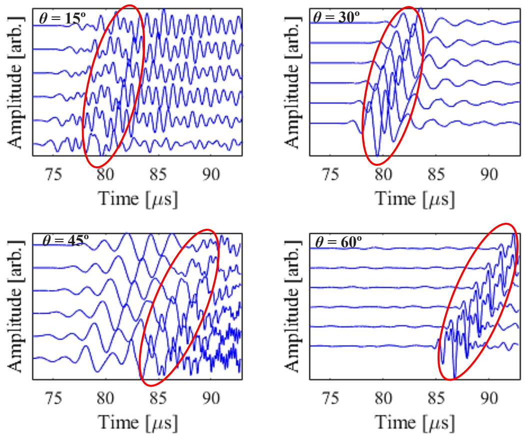

Fig. 3 Observed waveforms at different receivers. (Simulation)

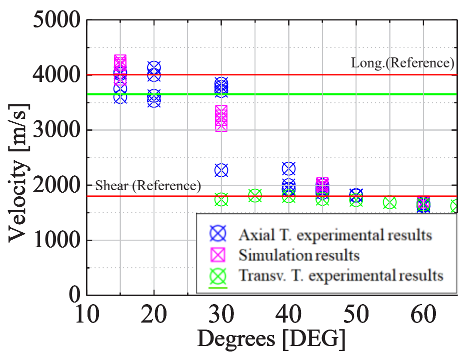

Fig. 4 Estimated wave velocities.

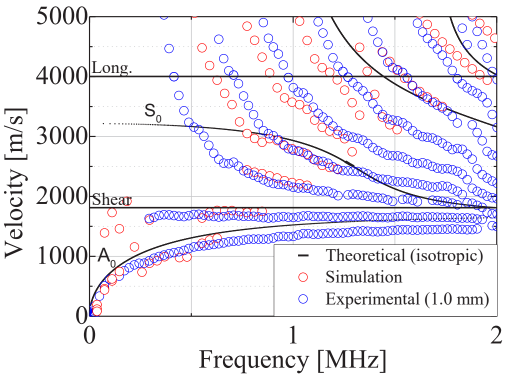

Fig. 5 Dispersion curves 1.0 mm plate at θ = 60º.

As it was expected, depending on the incident angle, two velocities were mainly determined. For angles smaller than 30º, close to the longitudinal wave critical angle θ = 22º, a velocity of 3710 m/s (averaged value under 30º) corresponding to the longitudinal wave velocity and for angles larger than 30º a velocity of 1870 m/s (averaged value over 30º), which corresponds to shear wave velocity were obtained. In the 30º case, both longitudinal and shear waves can be detected.

Similar results of shear wave velocities could be observed when comparing with results of a transversal transmission measurement[6] in the radial-axial plane of the plate performed by rotating the plate. Additionally, a longitudinal wave velocity of approximately 3650 m/s was also confirmed with a transversal transmission measurement along the axial direction of the plate. Isotropic simulation results showed good agreement with the experimental measurements performed in the anisotropic medium of the bone plate.

Signals were farther analyzed as the second approach. Plate conditions were favorable to originate Lamb waves, specially, in the thinnest sample (1.0 mm). The relation between velocity and frequency was determined by transforming the experimentally measured time-domain signals using a 2D-FFT method. Obtained dispersion curves from the 1.0 mm sample are shown in Fig. 6. Dispersion curves were more visible at 60º, this is reasonable, since close to 72º, the antisymmetric zero-order mode A_0, (considering a thickness of 1.0 mm and frequency of 1 MHz) is excited. Dispersion curves extracted from the simulation of the isotropic model are slightly affected, and almost overlap the experimental curves in the lower order modes.

5. Summary

Shear and longitudinal wave velocities were sucessfully characterized using axial transmission technique in various bone plates in the MHz range. Simulation results which consider isotropic conditions of the bone were in good agreement respect to the experimental results.

References

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