THEORETICAL AND EXPERIMENTAL ULTRASONIC CHARACTERIZATION OF ANISOTROPIC PROPERTIES IN CANCELLOUS BONE

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Abstract:

The spatial architecture and multiphasic nature of a porous medium are supposed to strongly influence the propagation of ultrasonic waves. Nevertheless, the relationship(s) between density, microstructure and mechanical properties governing the wave propagation phenomena on cancellous bone is still subject of research. The existence of two different longitudinal waves propagating in both human and bovine cancellous bone has been experimentally demonstrated. In consequence, a poroelastic model precisely predicting the existence of two waves was used to analyze these experimental results. It is here demonstrated that the orthotropic Biot theory is revealed pertinent to describe the acoustic properties as a function of porosity and microstructure geometry in this kind of tissue.

Introduction:

Biot theory of the propagation of elastics waves in a fluid saturated porous solid [1, 2], has been previously used in order to evaluate the ultrasound propagation in trabecular bone [3-7]. In such biphasic media acoustic waves were shown to propagate following two modes with different velocities. *In vitro* experimental studies corroborating the existence of these two waves in cancellous bone are in limited number [4-7] and almost all of them have been restrained to the fast wave analysis [3] or considered cancellous bone as isotropic [4, 5]. The present paper aimed to analyze the wave velocity and attenuation properties of human and bovine cancellous bone into the framework of an orthotropic Biot theory.

Materials and Methods

Fourteen bovine and sixty human trabecular bone samples were tested in vitro, using an immersed transmission method with a single pulse excitation. The parallel-faced cubic samples, with volumes in the cm^3 range were machined from femoral heads of different cancellous bovine specimens and from human femoral head and femoral and tibial condyles. In this study, no specific anatomic location or direction were predefined to prepare the cancellous bone samples. Broadband ultrasound transducers at central frequency of 2,25MHz (6mm OD) were used and were placed in direct contact with the bone specimen. Acoustic wave velocities were measured using a conventional transmission technique whereas the attenuation coefficients were obtained from amplitude spectrum analysis. The marrow was removed from samples, saturated with water and degassed with a vacuum pump prior to the measurement. Weight and volume of each specimen were measured and apparent density was computed. From this value, and assuming a 1.96 g/cc density of the mineralized phase, porosity was calculated.

Experimental Results

In most cases, two longitudinal propagation modes were observed in both human and bovine cancellous bone [9].

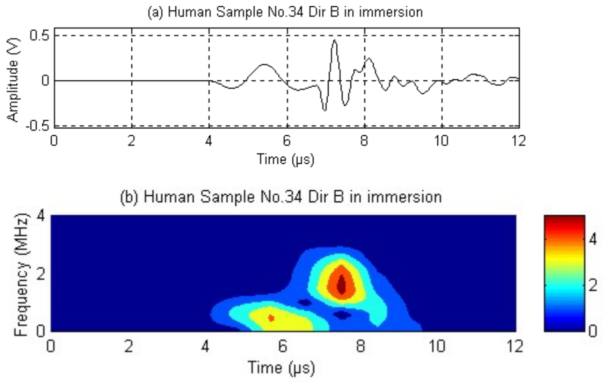

Figure 1 (a) Fast and slow waves observed in a cancellous human bone and **(b)** Spectrogram of the fast and slow waves in the same human sample.

In figure 1a, an acoustic signal transmitted through a human femoral head is presented, where the presence of two distinct waves can be clearly seen. Computed spectrograms from this data (Figure 1b) shows two waves with different frequency components arriving at different time. This demonstrates that the first wave (fast wave) is strongly attenuated at the central frequency of the 2.25 MHz transducer, while the second one (slow wave) is not.

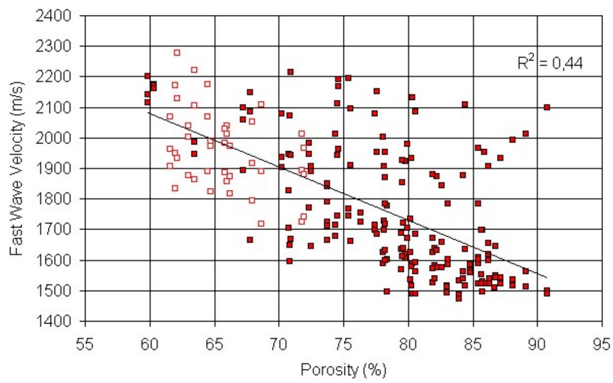

Figure 2 Fast wave velocity measured on human (solid) and bovine (open) cancellous bones.

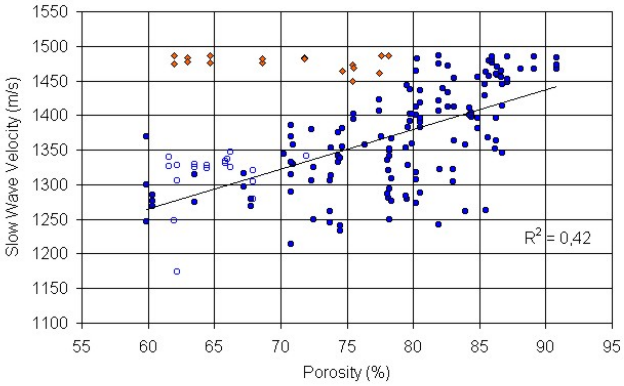

Figure 3 Slow wave velocity measured on human (solid) and bovine (open) cancellous bones. Two different groups of measurements were identified: a first group related to porosity and a second group independent of porosity.

Unfortunately, both waves can be superimposed when analyzed in the time domain and then their identification compromised. In order to overcome this difficulty, a digital filtering procedure was developed, allowing their separation in the frequency domain.

Figure 2 and 3 shows the slow and fast velocities data vs. porosity. Fast wave velocity decrease and slow wave velocity increase with porosity, but in both cases the variability of results is very significant. Both values converge to an unique velocity value similar to the propagation velocity in water alone.

Two bandwidths were defined from spectrogram results to separate fast and slow waves in the frequency domain. In consequence, a slope of attenuation as a function of frequency was defined for each bandwidth as fast and slow FDUA (frequency dependent ultrasound attenuation). In Figure 3 the fast and slow FDUA vs. porosity is presented. Notably, fast wave FDUA measurements exhibit a parabolic behavior as a function of porosity. In any case, nor Velocity or FDUA cannot be accurately predicted with the sole value of local porosity and consequently a structural characterization of the tissue must be taken into account.

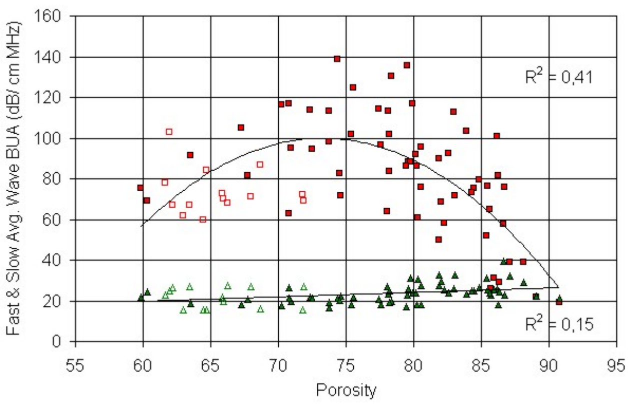

Figure 4 Fast and slow waves FDUA measured on human (solid) and bovine (open) cancellous bones.

Theoretical Model

Biot has proposed two equations describing the dynamics of solid and fluid displacements in a poroelastic composite material [1, 2]. Wave solutions of these equations demonstrate the existence of two longitudinal modes: the faster one corresponds to an in-phase displacement between the solid and fluid phases and the slower one corresponds to the opposite - phase motion.

Into the framework of the orthotropic Biot theory, the fast and slow wave velocities depends on (*i*) 3 fundamental variables: the porosity ϕ, the frequency ω and the media microstructure geometry, and (*ii*) 7 material parameters: the solid mass density ρ^s, fluid mass density ρ^f, Young Elastic coefficient of the solid phase E^s, Poisson ratio of the solid phase ν^s, bulk modulus of fluid phase K^f, fluid dynamic viscosity η and the pore size "a". Note that anisotropy in acoustic properties has been taken into account through the introduction of a Structural Parameter (SP_{ij}) characterizing the microstructure geometry [8].

$$V_{ij}^{(\text{fast1,slow})} = f\left(\phi, SP_{ij}, \omega, \rho^s, \rho^f, E^s, \nu^s, K^f, \eta, a\right)$$

Attenuation of waves propagated in porous media can be considered as the result of (i) loss of energy caused by surface acoustic impedance transition, and (ii) attenuation phenomena related to the propagation through the medium itself (which depends on the sample's size and wave's frequency):

$$A_{\text{dB}} = 10\,log_{10}(A) = 20\,log_{10}(T) - 20\tau d\,log_{10}(e)$$

Here T is the coefficient of transmission between the solid-fluid medium, τ the coefficient of attenuation and d the sample size. It is considered that τ is determined not only by the absorption process in the medium but by a scattering process too. The coefficient of attenuation τ is then defined by addition of the coefficient of attenuation due to absorption $\tau^{(a)}$, scattering $\tau^{(s)}$ and backscattering $\tau^{(b)}$:

The absorption coefficient of attenuation $\tau^{(a)}$ for each kind of wave corresponds to the imaginary part $\Im$ of the square root of solutions of the Biot dispersion equation:

$$\tau^{(a)}_{\text{fast,slow}} = \sqrt{1/\Im^{\text{fast,slow}}}$$

From Nicholson et al [10] and Sehgal & Greenleaf [11] works, the attenuation coefficient due to the scattering phenomena $\tau^{(d)}$ is determined by :

$$\tau^{(d)}_{\text{fast,slow}} = \frac{4\overline{\mu}^2 k^4_{\text{fast,slow}} a^3}{\left(1 + k^2_{\text{fast,slow}} a^2\right)\left(1 + 9k^2_{\text{fast,slow}} a^2\right)}$$

Where $k = 2\pi/\lambda$ represents the wave number and the size of pores "a" corresponds to the diffusers size. It is important to note that the wave inhomogeneities interaction will be different for the fast and slow waves, because of the difference in velocity and wave number associated to each wave for a given frequency. The backscattering coefficient $\tau^{(b)}$ is computed using:

$$\tau^{(b)}_{\text{fast,slow}} = \frac{\overline{\mu}^2 k^4_{\text{fast,slow}} a^3}{2\pi\left(1 + k^2_{\text{fast,slow}} a^2\right)^2} + \frac{3\overline{\mu}^2 k^4_{\text{fast,slow}} a^3}{2\pi\left(1 + 9k^2_{\text{fast,slow}} a^2\right)^2}$$

On the last two equations, the scattering and backscattering phenomena are affected by the mean sound speed fluctuation in the media μ^2, which is computed through [12]:

$$\overline{\mu}^2 = \phi(1-\phi)\left[1 - \phi + \phi\left(\frac{V^{(\text{solid})}}{V^{(\text{fluid})}}\right)^2\right]\frac{\left(V^{(\text{solid})} - V^{(\text{fluid})}\right)^2}{V^{(\text{solid})2}}$$

where $V^{(\text{solid})}$ and $V^{(\text{fluid})}$ stand for acoustic wave velocity in pure component alone.

Discussion

Computed fast wave velocity decrease with porosity, while slow wave velocity slowly increases with porosity, both being in concordance to our experimental results (Figure 5). Fast wave evolution is rather related to a solid phase behavior, while the slow wave is rather related to a fluid phase. Nevertheless, for high values of porosity, both fast and slow wave behaviors are inverted, and the fast wave is rather describing a fluid phase behavior. Moreover, the influence of the structural parameter becomes very important as porosity is increased.

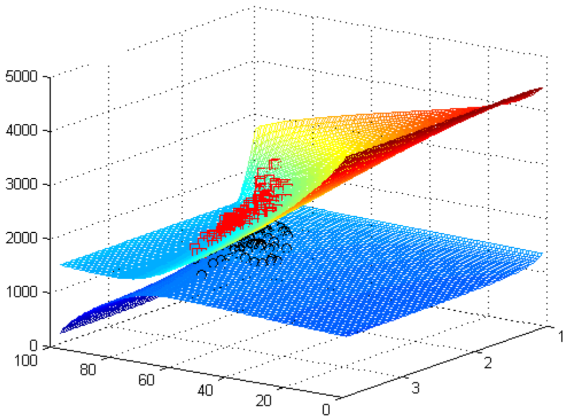

Figure 5 Computed and measured fast and slow waves velocity as a function of porosity and the structural parameter.

The loss of energy by dissipation phenomena, associated to fluid viscosity and thermoconduction effects can be considered as negligible, because of high ultrasonic frequencies experimentally used. On contrary, media inhomogeneities may change the direction of propagation of the wave's energy, resulting in significant changes on amplitude, frequency, velocity and wave direction (diffusion phenomena).

Fast and slow wave attenuations are presented on Figure 6 for a single porosity and different values of the structural parameter SP as a function of frequency. Fast and slow wave attenuation strongly depends upon the frequency of the wave, on one part, and upon the characteristics of the medium (porosity and structural parameter), on the other, thus determining which wave is the less attenuated one and will be more easily detected. For different values of structural parameter one notice the presence of a crossing point between attenuation curves, indicating the frequency where both waves exhibit equal attenuation

Results of the model for fast and slow FDUAs as a function of porosity and SP are showed in Figure 7. Fast wave FDUA follows a parabolic behavior and the slow wave FDUA a low quasi linear increment as a function of porosity, both agree qualitatively with experimental results.

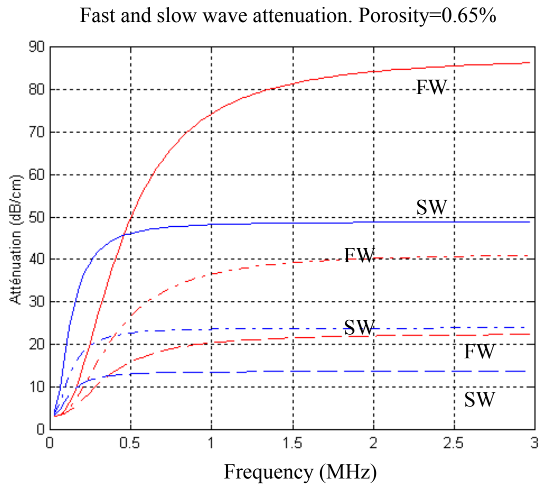

Figure 6 Computed fast (bleu) and slow (red) waves attenuation as a function of porosity and the structural parameter (solid SP_{ii}=1.5, dot dashed SP_{ii}=2, dashed SP_{ii}=2.5).

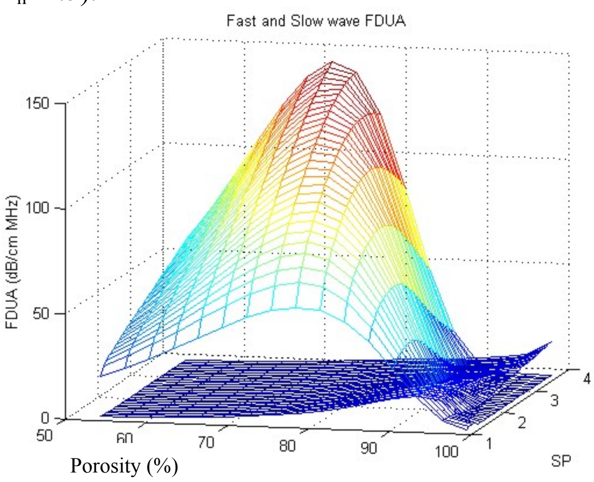

Figure 7 Computed fast and slow waves FDUA as a function of porosity and the structural parameter.

Conclusion

The two longitudinal propagation modes predicted by the Biot poroelastic model were clearly observed and quantified *in vitro*. Fast and slow wave velocities were found to be equally dependent on porosity and the structural parameter. The orthotropic model used here had shown to agree qualitatively and quantitatively with experimental results in terms of measured velocities, improving the understanding of the wave propagation phenomena in cancellous bone when compared to the isotropic Biot approach.

A different attenuation behavior as a function of frequency was found for the fast and slow waves, whose amplitude may be significantly different for a given frequency. The fact that experimental or computed attenuation spectra exhibit a crossing point when analyzed as a function of frequency indicates that there exist a value on frequency for which both waves must have a similar amplitude, and that both waves must be "detectable" in the vicinity of this frequency. This crossing point between fast and slow wave attenuation spectra was observed to be dependent on both porosity and microstructure geometry. Moreover, this result explains the difficulty in observing both waves simultaneously, because the fast wave is the less attenuated one for low frequencies whereas it is the slow one for high frequencies. Special attention must be taken when analyzing results from highly porous samples, where the slow wave measured attenuation could be lower than the attenuation observed for the fast wave. This finding may be a cause of concern when considering *in vivo* measurements of very osteoporotic specimens for which the only measurable velocity may be related to the slow wave instead of the fast one, as generally considered.

This study has shown a very good quantitative and qualitative agreement between experimental and theoretical velocity results. Concerning the attenuation, only qualitative agreement was obtained, possibly because one of the considered attenuation processes is still underestimated. This work represents evidence supporting previous studies suggesting that acoustic wave propagation in cancellous bone is sensitive to both density and media's architectural complexity. For this reason, in vitro ultrasonic exploration technique seems to confirm its strong ability to describe anisotropic mechanical properties in cancellous bone.

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