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Theoretical and experimental study of the ultrasonic attenuation in bovine cancellous bone

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ABSTRACT

In this study a theoretical approach for the estimation of ultrasonic attenuation is proposed. The approach combines two models which take into account both absorption and scattering. Attenuation due to absorption is studied by using the Biot's analytical model whereas that due to scattering is described by means of a generalized weak scattering model which is formulated for binary mixtures. The scattering model takes account of the density fluctuation of the porous medium in addition to the propagation velocity fluctuation. For the calculation of the attenuation coefficient due to absorption, experimental values have been used to link size of pores to porosity. The theoretical results have been compared with experimental data obtained on bovine cancellous bone samples filled with water. Using an immersion acoustic transmission method, the ultrasonic attenuation has been measured at a frequency range between 0.1 and 1.0 MHz for 12 bovine cancellous bone samples with a porosity range between 40% and 70%. The prediction of attenuation with this model appears to correspond more closely to its experimentally observed behavior. This study indicates that scattering is the predominant mechanism which is responsible for attenuation in trabecular bone. Furthermore, it shows that the density fluctuations contribute significantly to the phenomenon of attenuation and cannot thus be neglected.

1. Introduction

Nondestructive methods using acoustic waves are now commonly used for cancellous bone characterization [1]. They avoid damage of the material during the characterization and permits reproducibility of the measurements. Numerous studies have focused on developing ultrasonic techniques for trabecular bone characterization and osteoporosis diagnosis [1,2]. From the quantitative evaluation of the ultrasonic parameters, these techniques allow predicting the loss of bone mass and the deterioration of the microarchitecture. The loss of bone mass is due to ageing process or osteoporosis. It involves an increase in porosity, thinning or even a total disappearance of some trabecular elements and a disturbance of continuity of the structure. The porosity of cancellous bone has been considered as a criterion for the prediction of osteoporosis [2]. Therefore, it is interesting to study the change of attenuation versus porosity. The diagnosis methods of bone tissue using ultrasound are generally based on the assessment of the velocities and attenuation of the propagating ultrasonic waves, in order to determine the acoustic or geometrical parameters of the bone by in vivo or in vitro measurements [3]. The propagation mechanisms of ultrasound in trabecular bone are not well understood and are still investigated by many researchers. As it was proven that ultrasound attenuation is mainly due to both absorption and scattering by this material [3], it is of interest to understand the relative contributions of each.

Trabecular bone is an anisotropic, composite, porous and heterogeneous medium. It is complex and composed of a solid matrix (mineralized collagen) of interconnected trabeculae (size ranging from 50 to 200 μm for human bone) filled with a fluid-like medium (marrow in vivo, water in vitro). The mean pore size ranges from 0.2 mm to 3.0 mm [4]. The interaction of the incident ultrasonic wave with the porous medium, which is composed of the bone frame saturated with fluid, causes essentially two mechanisms of attenuation: absorption and scattering. It is difficult to separate these two contributions starting from ultrasonic measurements. The absorption results from the energy dissipation by viscous friction at the solid-fluid interface, in the solid and in the fluid themselves. The solid trabeculae are likely the main cause for waves scattering in trabecular bone. This is due to the disparity in the acoustic properties between the mineralized trabeculae and the saturating fluid. This scattering results in a frequency dependent velocity and attenuation of coherent waves [5]. The scattering

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is related to the characteristics of the scatterer (elastic properties, size, number and spacing between solid trabeculae). It reflects the microarchitecture parameters of the material [6]. Generally, the relative roles of absorption and scattering in trabecular bone are still not well understood. We propose, in this study, to use theoretical approaches to model the ultrasonic attenuation by the trabecular structure of the bone and to compare the variation of the attenuation coefficient versus frequency or porosity with that evaluated from experiments on samples of bovine bone. We aim to assess the validity of these approaches and to obtain predictions of the influence of structure on the acoustic properties of the cancellous bone.

2. Biot's theory

The Biot theory [7,8] describes elastic wave propagation in a fluid saturated porous medium. It was developed to predict the acoustical properties of fluid saturated porous rocks in the context of geophysical testing but has been extensively used to describe the wave propagation in trabecular (cancellous) bone. It accounts for the motion of the fluid and of the solid. It models the elastic, inertial and viscous coupling between the fluid and the solid and predicts a simultaneous propagation of three kinds of waves. These are two compressional waves of different velocities (the fast wave and the slow wave) and one shear wave. The fast wave (first kind) corresponds to the solid and the fluid moving in phase and the slow one (second kind) corresponds to the solid and the fluid moving out of phase. Fast and slow waves were identified independently in bovine trabecular bone by Hosokawa and Otani [9]. The difficulty in the use of this model is the large number of characteristic parameters of the medium that are not necessarily easily measured. For cancellous bone, some of structural parameters can be directly evaluated neither in vitro nor in vivo. In the present study, the parameter values of the Biot model for the bovine cancellous bone were taken from the works of Williams [10] and Hosokawa and Otani [9]. Furthermore, the ultrasonic parameters are sensitive to the anisotropy of cancellous bone [11], while the underlying physical mechanisms, for this phenomenon, remain not fully understood [12]. In order to account for acoustic anisotropy in cancellous bone, some modifications have been made on the Biot's model by introducing empirical angle-dependent input parameters. This anisotropy is attributed, on one hand to the variation in the elastic moduli of the skeletal frame with respect to the trabecular alignment and, on the other hand to the anisotropic pore structure [13].

The intrinsic bulk modulus K_s of the solid material constituting the skeletal frame is calculated from Young's modulus E_s of the solid material by assuming it as isotropic [10]:

$$K_s = E_s/[3(1-2\nu_s)], \tag{1}$$

where ν_s is the Poisson's ratio for solid bone. A power law was used to relate the Young's modulus of the trabecular frame (E_b) to the volume fraction of bone ($1-\Phi$) and to the Young's modulus of the solid bone (E_s) [14]:

$$E_b = E_s(1-\phi)^n, \tag{2}$$

Φ is the porosity and n is a parameter that depends on the trabecular structure and on the direction of testing; n varies from 1 to 3 [14]. In the case that this structure is considered as isotropic $n = 1$ [10]. The bulk modulus K_b and the shear modulus of the skeletal frame N are given respectively by $K_b = E_b/[3(1-2\nu_b)]$ and $N = E_b/[2(1+\nu_b)]$, where ν_b is the Poisson's ratio of the skeletal frame [10]. The value of n can be determined by curve fitting of the phase velocity as a function of porosity to the experimental data. Williams [10] has found an exponent $n = 1.23$ in bovine cancellous bone with an oriented columnar structure (i.e., for wave propagation in a direction parallel to the predominant trabecular alignment), and $n = 2.35$ for a random structure. Hosokawa and Otani [9,15] have obtained $n = 1.46$ in the direction parallel to the trabeculae of bovine cancellous bone, and $n = 2.14$ in the perpendicular direction. Lee et al. [12], modeled the influence of angle dependency of the elastic properties on sound propagation direction of cancellous bone by using the relation:

$$n(\theta) = n_1 \ \cos^2(\theta) + n_2 \sin^2(\theta). \tag{3}$$

($n = 1.23$ for $\theta = 0°$) and (for $n = 2.35$ for $\theta = 90°$). These values correspond to the directions of wave propagation, which are parallel or perpendicular to the predominant trabecular alignment, respectively and are consistent with the work of Williams [10].

The geometric tortuosity of the medium is an important parameter in Biot's theory. It represents the squared ratio of the mean path length through the porous frame to that of the direct path. It plays an important role in the propagation through cancellous bone since it affects the inertial coupling between the fluid and the solid. Aygün et al. [13] introduced an anisotropic pore structure into Biot theory by using an empirical expression for the angle and porosity dependency of the geometric tortuosity. The proposed heuristic form of this tortuosity is:

$$\alpha_\infty = 1 - r\left(1 - \frac{1}{\phi}\right) + k_T \cos^2(\theta), \tag{4}$$

where r and k_T are coefficients which can be adjusted. These parameters are chosen so that the assumed angle-dependency function, α_∞, is consistent with the expected variation of the fast wave speed in the considered propagation direction [13]. It should be mentioned that $k_T = 0$ if the isotropic case is considered.

According to the Biot's theory, the equations that reflect the interaction dynamics by coupling both inertial and viscous behavior of the fluid and solid phases, and which characterize the dispersion and attenuation of the waves propagating in a porous medium, lead to the following expressions of the propagation velocities [10].

$$V^2_{slow,fast} = \frac{2(PR-Q^2)}{\Delta \pm \left(\Delta^2 - 4(PR-Q^2)(\overline{\rho_{11}}\,\overline{\rho_{22}} - \overline{\rho_{12}}^2)\right)^{0.5}}, \tag{5}$$

where $\Delta = P\cdot\overline{\rho_{22}} + R\cdot\overline{\rho_{11}} - 2Q\cdot\overline{\rho_{12}}$. The signs ± in the denominator mean that v^2_{fast} will be obtained when "–" is selected, and v^2_{slow} when "+" is selected. The parameters P, Q and R are the elastic moduli. They are expressed as functions of the coefficient K_f, K_s, K_b and N where K_f is the bulk moduli of the fluid [7,8]. The "mass coefficients" ρ_{ij} are defined in terms of porosity and density. They are related to the densities of the solid phase ρ_s and of the fluid phase ρ_f by [8]: $\overline{\rho_{11}} + \overline{\rho_{22}} = (1-\phi)\cdot\rho_s$ and $\overline{\rho_{12}} + \overline{\rho_{22}} = \Phi\cdot\rho_f$ respectively. The coefficient $\overline{\rho_{12}}$ represents the mass coupling parameter between the fluid and solid phases. It may be written to account for frequency dependency as:

$$\overline{\rho_{12}} = [1-\alpha(\omega)]\phi\cdot\rho_f, \tag{6}$$

where $\alpha(\omega)$ is the dynamic tortuosity defined by Johnson et al. [16]. In the high frequency approximation (frequencies above 100 kHz), the coefficient $\overline{\rho_{12}}$ can be written in the following form [16]:

$$\overline{\rho_{12}} = \phi\cdot\rho_f[1-\alpha_\infty] - \frac{Z}{\sqrt{i\cdot\omega}}, \tag{7}$$

where

$$Z = \frac{2\cdot\phi}{\Lambda}\sqrt{\rho_f\cdot\eta}. \tag{8}$$