A Stratified Model for Ultrasonic Propagation in Cancellous Bone

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Abstract: A new approach for modelling ultrasonic wave propagation in cancellous bone is presented. Cancellous bone is idealised as a system of bone/marrow layers, and an established theory for propagation in stratifed media is applied. Two compressional modes, analogous to fast and slow waves of Biot's theory, are examined *in vitro* using bovine bone samples over a range of angles, in terms of a slowness surface. A clear anisotropic behaviour is seen and qualitative agreement with theory is excellent. The stratified model is a simplification of cancellous bone, but it offers potential for future research.

INTRODUCTION

Of the two types of bone in the skeleton, "cortical" and "cancellous", the latter is a porous matrix of calcified strands, called trabeculae, saturated with fatty marrow. The trabecular structure forms along stress trajectories in response to mechanical loading, often with a dominant orientation, and bone responds anisotropically to both mechanical stimulus and to ultrasound.

Ultrasound is a promising and inexpensive tool for assessing bone condition, but research is needed before it can assist clinical decision-making. A thorough theoretical understanding of propagation in cancellous bone may lead to ultrasound being optimally applied. Biot's theory (1) for elastic wave propagation in fluid-saturated porous media has been applied by previous authors (2), but the structure is assumed to be isotropic. This paper discusses an alternative model for ultrasound in cancellous bone that accounts for anisotropy.

ACOUSTIC PROPAGATION IN STRATIFIED MODEL OF CANCELLOUS BONE

The cancellous architecture has been idealised as a system of parallel calcified plates (3). Ultrasonic propagation in a system of bone/marrow layers (Figure 1) was investigated by applying Schoenberg's theory for stratified media (4), which describes propagation for arbitrary frequency and angle. For incident wavelengths much greater than the structural period, two compressional waves, analogous to the fast and slow waves of Biot's theory, propagate at all angles except normal incidence, subject to an angular inertial coupling effect.

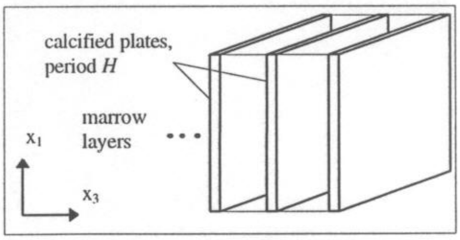

FIGURE 1. Stratified idealisation of cancellous bone

Acoustic wave propagation is examined in terms of a "slowness vector", *s*, defined as the ratio of wavenumber to frequency, ω. A period ($0<x_3<H$) contains an elastic solid (compressional speed, V_s, shear speed, V_{sh}) and an ideal fluid (density, ρ_f, sound speed V_f), where $h_f = (1-h_s)$ is the porosity. For harmonic waves $\exp j(s_1 x_1 - \omega t)$, the parallel component of slowness, s_1, is related to the normal component, s_3, by

$$\left(s_3^2 / \langle\rho\rangle\right) - \left[h_f\left(V_f^{-2} - s_1^2\right) / \rho_f + h_s\left(V_s^{-2} - s_1^2\right) / \left(1 - V_{pl}^2 s_1^2\right)\right] = 0, \qquad (1)$$

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where $\langle\rho\rangle$ is a thickness-weighted average density and V_{pl} is the speed in an elastic plate, $2(1-V_{sh}^2/s^2)^{1/2}V_{sh}$. Propagation in layers may be represented by the slowness surface, which is the locus of the slowness vector, s, around 90°, or, which may be constructed as s_3 versus s_1 from equation (1).

Bovine bone samples (30 x 30 x 13 mm) were taken from the tibial epiphysis, with the dominant trabecular axis running both parallel and normal to the square cross-section, with marrow intact. Two 1 MHz-resonant 2.5 cm diameter transducers were suspended in a water tank at a fixed separation. The sample was aligned between the transducers and could be rotated in 5° increments. A pulse of 1 MHz centre frequency was transmitted through the sample, and the output was acquired at 10 Ms/s by a digital oscilloscope.

Phase velocity and refraction angle were calculated using equations of Plona *et al.* (5). Fast and slow wave slowness surfaces were constructed over 90° as the inverse of the phase velocity at 1 MHz, with a maximum error in slowness of 14% owing to time series truncation. Experimentally derived surfaces were compared with those predicted from equation (1) (Figure 2), using the parameters in Table 1, chosen to give the best fit to experimental data within limits quoted in the literature, normalised for fluid slowness.

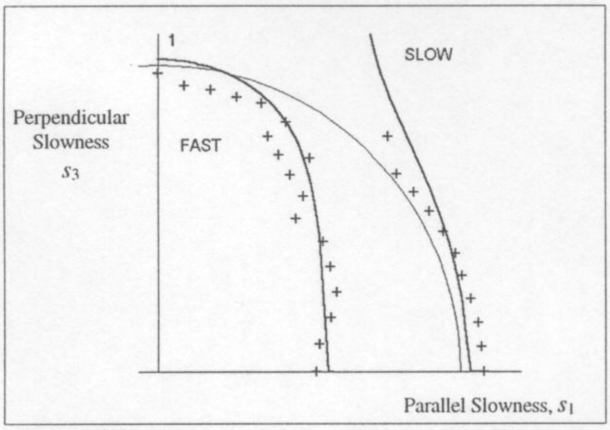

FIGURE 2. Slowness surfaces: Experiment + , Theory -

TABLE 1. Parameters for stratified model of bone / marrow layers

Density of bone, ρ_s	1900 kg/m^3	**Compressional Speed in bone, V_s**	2900 m/s
Density of marrow, ρ_f	950 kg/m^3	**Shear Speed in bone, V_{sh}**	1800 m/s
Porosity, h_f	0.65	**Speed in marrow, V_f**	1500 m/s

Qualitative agreement was good. The theory predicts two distinct contours: the inner surface corresponding to the fast wave, and the outer to the slow wave. The fast wave was observed over the whole angular range, but the slow wave was only observed between 0° - 50°. Fluctuations in the curves thought to be due to truncation of the time series during processing. These results demonstrated the anisotropic nature of ultrasound in cancellous bone. Although the stratified model is a simplification of cancellous bone, it has potential for future application to this problem.

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