A STUDY OF ULTRASONIC WAVE PROPAGATION IN BONES

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***Abstract*— In the present work the propagation of ultrasonic waves in human bones is modeled by Biot equations introducing in them viscoelasticity so as to take into account attenuation mechanisms; different models for the latter are introduced and compared. Also, Biot equations are numerically solved using two dimensional finite elements. How different porosities affect elastic moduli, phase velocities, visco-dynamic and intrinsic attenuation is also studied.**

***Keywords*— Cortical and trabecular bone, Low frequency, Biot theory, Finite elements.**

I. INTRODUCTION

Osseous tissue forms the variety of bones that make up the skeletal system. The matrix is partially organic (collagen fibres in which osteocytes are embedded) and partially inorganic (mineral salts with calcium as the most important mineral). Because of its structure, bone tissue is found in two different types, Compact Bone and Cancellous or Trabecular Bone. Compact bone is very dense and strong, found on the outmost portions of all bones as a protective layer. It contains numerous osteons or Haversian Systems with a central channel through which blood vessels and nerves pass. Surrounding this channel there are multiple concentric layers of tissue known as lamellae. On the other hand, Cancellous Bone is lightweight and spongelike; the interconnected bony pieces forming this characteristic structure are called trabeculae. Trabecular bones have relatively large hollows filled by bone marrow and adipose tissues. Therefore, the relative volume fraction of solid in both structures is different; bone portions with volume fraction of solids below 70% are classified as trabecular, and over 70 % as cortical (Cowin, 1999; Smit *et al.*, 2002; Barkmann *et al.*, 2003; Bossy *et al.*, 2004; Buchanan *et al.*, 2004; Bossy *et al.*, 2005). Biot (1956 a,b,c) established a theory of propagation of elastic waves in a medium composed of a porous elastic solid saturated by a simple and viscous fluid phase. He showed the existence of a shear wave and two compressional waves, a high velocity one (wave of the first kind or Type I wave) corresponding to in-phase motion of solid and fluid and a low velocity one (wave of the second kind or Type II wave) associated to out of phase motion between solid and fluid. These compressional waves had been observed in laboratory experiments with bones, see for example Lakes *et al.* (1986); McKelvie and Palmer (1991); Kacsmarek *et al.* (2002); Lee *et al.* (2002); Cardoso *et al.* (2003).

Numerical simulation of ultrasonic wave propagation in bones using Biot theory has been reported since several years ago by many authors -see Haire and Langton (1999); Hughes *et al.* (2003); Lee *et al.* (2003); Buchanan *et al.* (2004); Fella *et al.* (2004); Wear *et al.* (2005) to name some of them-, but still there are open questions to be answered, as the reader can see below. The aim of this report is to analyze the propagation of ultrasonic waves in human bones and study how different porosities affect elastic moduli, velocities and intrinsic attenuation. Biot theory is used for two dimensional numerical simulation where bones are considered as a biphasic poroviscoelastic material. It is important to remark that the upper bound for the involved frequencies is reached when the corresponding wavelength becomes of the order of the porous size. Experiments involving frequencies beyond this limit must be treated within a different theoretical frame, as stated by the author of the theory (Biot, 1956c).

Following Mellish *et al.* (1989) and Hughes *et al.* (2003), the typical pore radii (mean values and standard deviations) are 0.285 ± 0.050 mm for young normal bone and 0.455 ± 0.130 mm for aged and osteoporotic bone. Bossy *et al.* (2005) reports an average trabecular spacing ranging from 0.5 mm to 2.0 mm; therefore Biot theory cannot be used with bones for frequencies greater than 750 kHz.

Keeping in mind that Biot's theory is applicable at wavelengths much longer than the pore size (corresponding to frequencies within the 0–750 kHz range), and that the Type I and shear waves have a behaviour similar to those in an elastic solid, with high phase velocities, low attenuation and little dispersion, it is necessary to establish the critical frequency f_c that determines whether or not Poiseuille flow occurs. When the frequency range is below f_c, the relative motion of the fluid in the porous is of the Poiseuille type; the coupling between solid and fluid is preeminently viscous, leading to a slow wave of diffusive nature. The assumption of Poiseuille is not established for the higher frequency range $f_c \leq f$; in this regime inertial coupling dominates over the viscous one leading to a truly propagating slow compressional wave. Johnson and Plona (1982) showed that the latter cannot propagate if the viscous skin depth