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Application of an effective medium theory for modeling ultrasound wave propagation in healing long bones

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ABSTRACT

Quantitative ultrasound has recently drawn significant interest in the monitoring of the bone healing process. Several research groups have studied ultrasound propagation in healing bones numerically, assuming callus to be a homogeneous and isotropic medium, thus neglecting the multiple scattering phenomena that occur due to the porous nature of callus. In this study, we model ultrasound wave propagation in healing long bones using an iterative effective medium approximation (IEMA), which has been shown to be significantly accurate for highly concentrated elastic mixtures. First, the effectiveness of IEMA in bone characterization is examined: (a) by comparing the theoretical phase velocities with experimental measurements in cancellous bone mimicking phantoms, and (b) by simulating wave propagation in complex healing bone geometries by using IEMA. The original material properties of cortical bone and callus were derived using serial scanning acoustic microscopy (SAM) images from previous animal studies. Guided wave analysis is performed for different healing stages and the results clearly indicate that IEMA predictions could provide supplementary information for bone assessment during the healing process. This methodology could potentially be applied in numerical studies dealing with wave propagation in composite media such as healing or osteoporotic bones in order to reduce the simulation time and simplify the study of complicated geometries with a significant porous nature.

1. Introduction

The study of wave propagation in porous media such as cancellous bone and fracture callus is a challenging research field since scattering is predominant giving rise to material dispersion of velocity and attenuation. Wave dispersion due to porosity is difficult to be investigated alone since it is usually accompanied by geometry-induced dispersion. The underlying mechanisms of wave dispersion and attenuation in bone have been studied experimentally and computationally by several research groups. Many authors aiming at the ultrasonic assessment of cancellous bone have reported phase velocities that decrease with frequency, a phenomenon known as negative dispersion [1–4]. Specifically, Bauer et al. [1] investigated this phenomenon by performing through transmission measurements in a cancellous bone phantom. Negative dispersion was observed at specific spatial locations of the plate at which the attenuation coefficient was increasing linearly with frequency. Anderson et al. [2] used the modified Biot–Attenborough model to simulate multiple-mode wave propagation in cancellous bone. It was found that negative dispersion can arise when signals consisted of overlapped fast and slow waves are analyzed as a single longitudinal wave. Another study [3] presented a nonlocal version of Biot's theory of poroelasticity to investigate the dependence of the phase velocity and attenuation for both porosity and frequency variation. It was found that the phase velocities exhibit a negative dispersion where the magnitude of dispersion is strongly dependent on porosity. It was also shown that the Lamb modes show negative dispersion when predicted by the nonlocal poroelastic theory. In [4], trabecular bone was assumed to be a composite medium consisting of infinite cylinders immersed in a saturating matrix. The generalized self-consistent method was used to describe the homogeneous effective material by considering two concentric cylinders immersed in the medium. The authors suggested that scattering effects are responsible for the negative dispersion, whereas the frequency dependence of the absorption coefficient results in an increase in dispersion. However, the factors which affect the variability of the phase velocity and lead to the observed abnormal negative dispersion in cancellous bone are not yet fully understood.

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Another research field that has not been addressed so far neither theoretically nor numerically is the ultrasonic evaluation of the porous nature of callus during the healing process. Several research groups have studied ultrasound wave propagation in healing bones by performing measurements of the velocity and attenuation of the first arriving signal (FAS) and fewer by investigating the propagation of guided waves. The problem has been addressed in 2D and 3D numerical studies with simplified or more complex geometries and material properties. In particular, in [5] the callus tissue was modeled as a 2D, one-phase homogeneous and isotropic material. It was found that the FAS velocity and the attenuation depend on the plate thickness and fracture geometry suggesting that it corresponds to a guided mode. In addition, in [6] the callus was modeled as a homogeneous, 2D medium and two different geometries were examined. The FAS velocity was found to decrease during the first healing stages and gradually increased at later healing stages approaching the values of intact bone. More recently, Machado et al. [7] performed a 2D computational study in which the callus consisted of six different tissue types with material properties evolving during healing. The velocity of the FAS and the signal energy loss were measured using four numerical daily-changing models of callus. It was found that the FAS velocity increased during healing, while the callus composition could not well explain the changes in energy attenuation. In our previous works [6,8,9], the propagation of guided waves has been extensively studied as an indicator of bone healing in combination with measurements of the FAS velocity. Fracture healing was simulated as a three-stage process and the callus tissue was modeled as a 2D inhomogeneous material consisting of six distinct ossification regions [8]. In all these studies [6,8,9], the Finite Differences Method (FDM) was used in order to simulate the 2D wave propagation problem. The same model of the callus was later incorporated in a 3D Finite Element (FE) computational study [9], where intact and healing bones were simulated as isotropic and anisotropic media, as well. These studies indicated that guided waves depend on bone anisotropy and irregularity in geometry as well as on the material and geometrical changes of callus that occur during the healing process. On the other hand, the FAS velocity was not influenced by the irregularity and anisotropy of the bone for a given frequency. In a more recent study, Papacharalampopoulos et al. [10] investigated how the microstructure of bone affect guided and Rayleigh waves by performing simulations using the Boundary Element Method (BEM). However, the microstructure and porosity of the callus tissue have not been considered so far.

Several multiple scattering theories have been proposed aiming at the quantitative determination of wave dispersion and attenuation phenomena induced by a random distribution of inhomogeneities-scatterers in composite media [11–16]. The so-called self-consistent theories use self-consistent expressions derived from the solution of the single scattering problem in order to estimate the frequency dependent phase velocity and attenuation coefficient. Recent theoretical studies dealing with the quantitative determination of wave dispersion and attenuation in cancellous bone have been based on multiple scattering theories. Here one can mention the representative works of Haïat et al. [4,17] and Molero et al. [18]. In the analytical studies of Haïat et al. [4,17], multiple and independent scattering theories were presented to derive the frequency dependence of phase velocity. Molero et al. [18] proposed an analytical approximation of the Waterman and Truell's [19] corrected model to conduct phase velocity predictions. In these studies, the theoretical results were found to be in agreement with experimental data in bone mimicking phantom samples [20]. However, for increasing scatterers' volume concentrations the theoretical results were found to diverge from the experimental findings. Another approach based on the self-consistent theories is the iterative effective medium approximation (IEMA) of Aggelis et al. [21]. Comparisons of the phase velocity and the attenuation coefficient calculated theoretically using IEMA with experimental findings in various nonhomogeneous media have shown the significant efficiency and accuracy of the methodology even in cases of scatterers with volume fractions as high as 50%. To our knowledge, multiple scattering theories have not been exploited so far to investigate how the porous nature of callus can influence the evolution of scattering effects during bone healing.

In this study, we investigate wave scattering phenomena induced by the porous nature of callus and we model ultrasound wave propagation in healing long bones by using IEMA. First IEMA is applied to the cancellous bone mimicking phantoms presented in [20], and the results are compared with experimental and theoretical findings [17,18,20] in order to examine the effectiveness of the methodology. Then, group velocity and attenuation predictions are performed for the callus region of healing bones in the frequency range from 24 to 1200 kHz. The material and geometrical properties of the callus tissue were obtained from a sheep study [22] using serial scanning acoustic microscopy (SAM) images corresponding to different consolidation weeks. Subsequently, we present 2D healing bone models having the original material properties of callus derived using SAM, and the equivalent homogeneous and isotropic numerical models with the effective material properties derived from IEMA. For comparison purposes FAS velocity measurements and guided wave analysis were performed. Finally, the effective material properties and the attenuation coefficient derived from IEMA are incorporated in BEM computational models of healing long bones representing different healing stages. The propagation of guided waves is investigated in the time–frequency domain.

The novelty of our work consists in that (a) multiple scattering theories, although recently incorporated in the ultrasonic evaluation of cancellous bone, have not been used so far in the monitoring of bone healing, (b) this is the first systematic study investigating the evolution of scattering effects in the callus region at different healing stages based on realistic material and geometrical properties derived from SAM images, and (c) the proposed methodology can contribute to the reduction of the simulation time in complicated geometries through the development of simple, homogeneous and isotropic computational models of healing bones, which however have equivalent geometrical and material properties with the original composite medium.

2. The IEMA for composite materials and particle suspensions

In this section we briefly describe IEMA which was originally presented in detail in [21,23] and we compare the theoretical wave dispersion and attenuation predictions in cancellous bone mimicking phantoms to those taken either experimentally or theoretically through other multiple scattering theories. According to [21], IEMA is a single theoretical model that predicts effectively wave dispersion and attenuation in composite materials, suspensions and emulsions through an iterative computational procedure which is simple and easily implemented especially for the case where the material inhomogeneities are considered as spherical inclusions. Moreover, it provides reasonable results for a wide range of particle concentrations and wavenumbers.

The main idea of the method is very simple and it is based on the hypothesis that a plane wave propagating in nonhomogeneous media such as healing bones can be considered as a sum of: (a) a mean wave travelling in the medium with the dynamic effective properties of the composite and (b) fluctuating waves derived from the multiple scattering of the mean wave by the material inhomogeneities. Then, at the direction of the propagating plane wave, one can say that the dynamic effective properties of the nonhomogeneous material are those corresponding to a mean