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Computational Methods of Ultrasound Wave Propagation in Healing Long Bones

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Summary

Quantitative ultrasound has attracted significant interest in the evaluation of bone fracture healing. Animal and clinical studies have demonstrated that the propagation velocity across fractured bones can be used as an indicator of healing. Researchers have recently employed computational methods for modeling wave propagation in bones aiming to gain insight into the underlying mechanisms of wave propagation and to further enhance the monitoring capabilities of ultrasound. In this paper we review the computational studies of ultrasound wave propagation in intact and healing bones.

Introduction

Quantitative ultrasound has been extensively used in the assessment of osteoporosis and the evaluation of fracture healing. The so-called axial transmission technique has been suitable to examining long bones, such as the tibia and radius. In the context of bone healing, a transmitter and a receiver are placed over the skin on each side of the fracture site. The velocity of ultrasound waves propagating along the long axis of bone is determined by the transit time of the first-arriving signal (FAS). Animal [1-3] and clinical studies [4-5] have demonstrated that the propagation velocity across fractured bones gradually increases during healing and when bony union is achieved, the velocity exceeds 80% that of the contralateral intact bone. Simple experiments on immersed acrylic plates [6] have been carried out to investigate the dependence of the FAS velocity on the fracture gap width and depth.

The recent use of computational methods for modeling wave propagation in bone has played a significant role in the understanding of the underlying wave propagation phenomena and has also helped to interpret experimental and clinical measurements. Although most of the related works have focused on the assessment of osteoporosis, a growing number of studies have extended to the context of bone healing. The subject of this review is to present the current knowledge obtained from the use of computational methods for the ultrasonic monitoring of bone healing.

Computational Studies on Models of Intact Cortical Bone

Computer simulations were initially used to investigate the nature of the FAS wave and to determine the relationship between its velocity and the thickness of the

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cortical bone[7,8]. The primary objective was to evaluate the ability of FAS velocity measurements to diagnose osteoporosis and to interpret previous experimental and clinical findings [2,9]. Osteoporosis in long bones is mainly characterized by reduced cortical thickness and increased porosity in the endosteal region and therefore velocity measurements should be able to reflect these structural changes. All studies [7,8,10], except one [11], have been limited to two-dimensional (2-D) models in which the bone is simply simulated by an elastic isotropic plate with varying thickness. Solution to the 2-D linear elastic wave propagation problem has been obtained numerically based on the finite-difference method. It has been demonstrated that when the plate thickness, d, is larger than the wavelength in bone, λ_{bone}, the FAS wave corresponds to a lateral wave (also known as a P-head wave) which propagates along the subsurface of the medium at the bulk longitudinal velocity. When $d/\lambda_{bone} \leq 1$, the velocity of the FAS wave is no longer independent of the plate thickness, but decreases with it. For very thin plates, typically $d/\lambda_{bone} < 0.4$, the FAS wave propagates as the lowest order symmetric plate mode (S0 Lamb mode) with velocity being a non-linear function of d. A more recent three-dimensional (3-D) study on a cylindrical model [11] supplemented these findings by demonstrating that no significant differences exist between 3-D and 2-D models in terms of the FAS velocity. They further showed that the lateral wave travels only along a thin periosteal layer with depth ranging from 1.6 mm for 500 KHz to 1.1 mm for 2 MHz.

From the above it is deduced that traditional velocity measurements are generally sub-optimal in terms of their sensitivity to alterations that occur in deep cortical layers. To this end, researchers have used 2-D simulations to investigate whether the velocity of Lamb waves can provide an enhanced approach to characterizing cortical bone. The principle behind this is that Lamb modes propagate throughout the plate thickness and thus their characteristics depend on both the material and geometrical properties of the medium. It has been shown that generally two dominant modes could be identified in the signals; the fastest one corresponds to the S0 Lamb mode, whereas the slowest one to the lowest-order antisymmetric Lamb mode (A0 mode). Assuming that guided modes in a plate agree closely to the waves propagating in the cortical shell, researchers have showed through *ex vivo* and *in vivo* studies[8] that the velocity of an A0-type mode could better discriminate between healthy and osteoporotic bones.

Computational Studies on Models of Healing Long Bones

The first computational study of ultrasound propagation in a healing long bone was published in[12]. A 2-D model of an elastic isotropic plate (4 mm thick, with bulk longitudinal and shear velocities of 4063 m/s and 1846 m/s, respectively) was developed. A 2-mm fracture gap was modeled at middle of the plate's length and the consolidation of callus was simulated by a simple 7-stage process. The callus tissue was assumed to be homogeneous and isotropic with properties evolving throughout the stages. Axial transmission of ultrasound was simulated by two longitudinal transducers placed in direct contact with the plate's upper surface. Two broadband excitation signals were examined with central frequencies of 500 KHz and 1 MHz resulting in 8-mm and 4-mm wavelengths in bone, respectively. The bone plate was assumed to be in vacuum (free plate) neglecting thus the presence of soft tissues. Solution to the elastic wave propagation problem was achieved using the finite-difference method. Analyzing initially the simulated signals obtained from the intact plate, it was proved that the FAS wave propagated as a lateral wave. When the callus was incorporated in the model, the FAS remained a lateral wave. At the first stages, the FAS velocity was low due to the large difference in velocity between the callus and the cortical bone, whereas as the properties of callus increased the velocity was gradually approaching that of intact bone. The FAS velocity at each stage was exactly the same independently of the excitation frequency.

In a subsequent study by the same group [13], the model of the healing bone was enhanced by assuming the callus tissue to be an inhomogeneous material consisting of six different ossification regions (Fig. 1). The healing course was simulated by a three-stage process in which the properties of each region evolved corresponding to various soft tissue types that participate in the healing process. In addition, three different cases of boundary conditions were investigated. In the first, the healing bone was assumed immersed in blood which occupied the semi-infinite spaces over the plate's surfaces (Fig. 1a). In the second case, the soft tissues were modeled as two 2-mm thick layers of blood loading each surface, whereas in the third, the upper surface was again loaded by a layer of blood, while the lower by a different fluid simulating the bone marrow (Fig. 1b). It was found that at the first stage the FAS velocity decreased from that in the intact plate, remained the same up to the second stage, and then increased at the third stage. No significant differences were observed in the FAS velocity between the various boundary conditions cases. The fact that the velocity remained constant between the first and the second stage possibly indicates that the propagation of the FAS wave was only affected by the material that filled the fracture gap, which was the same for those two stages. From the above it becomes clear that although FAS velocity measurements monitor the healing process, the FAS wave cannot reflect changes that occur in the whole structure of the callus tissue.

The second issue addressed by this series of studies was the use of guided waves as an alternative means of monitoring bone fracture healing. A time-frequency (t-f) methodology was followed for the representation of the propagating guided modes. The method was first applied to the signals obtained from the free intact

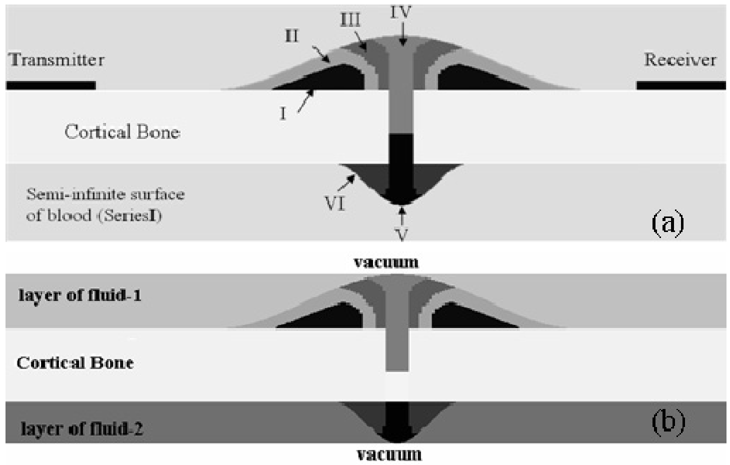

Figure 1: 2-D model of a healing bone in which the callus tissue consists of six ossification regions (denoted by capital Latin numbers). (a) The bone is immersed in blood, and (b) two layers of fluids load the upper and lower surfaces of the bone.

plate model. Mode identification was performed using group velocity dispersion curves predicted by the Lamb theory. Among multiple modes that were detected, the S2 and the A3 Lamb modes were found to dominate. When applying different boundary conditions, the analysis was performed with the use of the modified dispersion curves. As opposed to the lateral wave, the effect of the boundary conditions on the simulated modes was significant. T-f analysis of the signals from the simulated stages showed that both the properties and the geometry of the callus affected the dispersion of the theoretically-anticipated Lamb modes. The modes were gradually reconstructed towards the theoretical ones during the consolidation of callus.

The above simulation studies were further extended to more realistic conditions by considering the 3-D geometry and anisotropy of the bone and the callus tissue [14]. First, a hollow cylinder was examined for two cases of elastic symmetry: isotropy and transverse isotropy. Next, the real geometry of an intact tibia was modeled. The model of the healing tibia incorporated the callus which was modeled as in[13]. Axial transmission was performed using a broadband 1-MHz excitation. The bone was considered free of tractions on the inner and outer surfaces. Solution to the 3-D elastic wave propagation problem was performed using the explicit elastodynamics finite element analysis. Concerning the intact models, it was observed that the FAS wave corresponded to a lateral wave and its velocity was not affected by the irregular shape of the cortex and remained almost the same between isotropy and anisotropy. On the other hand, the geometry and anisotropy of bone had a major effect on the propagation of high-order modes. For both material symmetry cases, the high-order modes in bone were significantly different from those observed in the cylindrical model and from those predicted by the tube theory. The effect was less pronounced on the dispersion of the fundamental modes, i.e. the longitudinal $L(0,1)$ and the flexural $F(1,1)$ tube modes. For the fractured tibia, it was that FAS velocity could not reflect the material and mechanical changes that occur in the whole structure of callus which is in accordance with the findings of the 2-D studies[12,13]. Conversely, guided waves were sensitive to both the geometry and the properties of callus. Although no quantitative results were extracted, it was suggested that monitoring of fracture healing could be enhanced by analyzing the characteristics of the higher-order modes, such as the $L(0,5)$ and $L(0,8)$ tube modes.

In another simulation study [15], it was investigated whether the amplitude of the FAS wave could be used for monitoring purposes. The authors used a 2-D model of a fractured plate immersed in water. The fracture gap was also filled with water and various gap sizes were examined. The transmitter was positioned on the first segment of the fractured plate while the receiver was progressively shifted from the start of the fracture to some distance from it over the second segment. Simulation of axial transmission at 200 KHz was performed using the finite difference method. The curve of the FAS amplitude plotted against the transducer separation showed a characteristic variation. This amplitude variation was explained on the grounds of interference between reradiated and scattered/diffracted waves at the fracture. The reduction in the FAS amplitude increased with the fracture gap. The authors argued that in real fractures the consolidation of the callus could be reflected in the amplitude measurements due to changes in acoustic impedance mismatch.

Conclusions

The introduction of computational methods into bone research has significantly extended our knowledge on the mechanisms of ultrasound propagation in healing long bones. It seems that the use of guided waves can supplement traditional velocity measurements and improve the monitoring capabilities of ultrasound. However several issues need to be further addressed, such as the effects of material attenuation, different fracture geometries, etc., preferably in conjunction with clinical measurements on real fractures.

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