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Influence of the precision of spectral backscatter measurements on the estimation of scatterers size in cancellous bone

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Abstract

The goal of this study is to propose a model for the ultrasonic frequency-dependent backscatter coefficient in femoral cancellous bone. This model has been developed with success to predict backscatter in human calcaneal bone [Jenson, Ultr. Med. Biol. 2003]. A weak scattering model is used and the backscatter coefficient is expressed in terms of a Gaussian autocorrelation function of the medium. The backscatter coefficient is computed and comparison is made with experimental data for 37 specimens and for frequency ranging from 0.4 to 1.2 MHz. An excellent agreement between experimental data and predictions is found for both the magnitude and the frequency-dependence of the backscatter coefficient. Then, a nonlinear regression is performed for each specimen, and the mean trabecular thickness is estimated. Experimental data and theoretical predictions are averaged over the 37 specimens. We also find a close agreement between theoretical predictions obtained using the Gaussian autocorrelation function (scatterer size $= 134 \pm 15$ μm) and the mean trabecular thickness (Tb.Th $= 132 \pm 12$ μm) derived from the analysis of bone 3-D micro-architecture using high-resolution micro-tomography. However, the correlation between individual experimental and estimated Tb.Th values is moderate ($R^2 = 0.44$). The performance of the estimator are limited mainly by two factors: interference noise due to random positioning of the scatterers and attenuation. We show that the fundamental limitation of our estimator due to the speckle noise is around 5 μm for trabecular thickness estimation. This limitation is lower than the observed biological variability which is around 30 μm and should not be a limiting factor for individual prediction. A second limitation is the tremendous attenuation encountered in highly scattering media such as cancellous bone, which results in highly damped backscatter signals. The compensation for attenuation is difficult to perform, and it may be a critical point that limits the precision of the estimator.

1. Introduction

The complex micro-architecture of trabecular bone plays an important role in the biomechanical properties of bone. Hence, the ability to non-destructively characterize the micro-architecture of the trabecular network would be useful for the evaluation of pathologies, such as osteoporosis, that affect this component of bone.

Trabecular bone is a highly porous and heterogeneous medium, composed of a solid matrix (mineralized collagen) of interconnected trabeculae (diameters ranging from 50 to 200 μm) filled with a fluid-like medium (marrow in vivo, water in vitro). The mean pore size ranges from 1000 to 2000 μm. Trabecular bone is a scattering medium, and measurements of the ultrasonic backscatter coefficient of the human calcaneus have been performed by different groups, both in vitro [1–3] and in vivo [4–6].

Ultrasonic backscatter measurements at the calcaneus have recently been studied for their potential directly to assess the microstructure of trabecular bone (e.g., trabecular thickness and trabecular number density) [2,6–9]. We have proposed in a previous study to use a weak scattering model to predict the backscatter coefficient at the heel bone [7]. An inversion scheme was developed to estimate the mean scatterer size. We reported a good agreement between estimated scatterer size and trabecular thickness obtained from analysis of 3-D reconstructed micro-architecture.

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The goal of this study is to extend the previous results and to propose a model for the ultrasonic frequency-dependent backscatter coefficient in femoral trabecular bone. Ultrasound measurements of backscatter coefficient are performed on slices of human femoral trabecular bone. Scatterer size are estimated using nonlinear regression between experimental data and predicted data obtained with the weak scattering model and a Gaussian autocorrelation function to describe fluctuations of acoustical impedance in bone. The 3-D micro-architecture of bone specimens is investigated using high-resolution synchrotron radiation micro-tomography and the trabecular thickness is derived from the analysis of bone 3-D micro-architecture. Finally we compare estimated scatterer size to trabecular thickness and discuss the limitations of the proposed inversion scheme.

2. Material and methods

2.1. Theoretical background: model of backscatter coefficient

We assume that cancellous bone can be modeled as randomly-positioned impedance fluctuations contained within an otherwise acoustically uniform material. The two materials are supposed to be fluid, i.e., we neglect mode conversions and shear wave propagation in the bone material. We make the assumption that the incident wave is locally plane. We consider observations at large distances from the scattering volume. We also assume that the amplitude of the scattered wave is much smaller than that of the incident wave. Following these approximations, the scattered pressure filed can be written using the Born approximation. If we now assume that the medium may be considered as isotropic, and that the second order statistical properties of spatial impedance fluctuations of the medium can be described by a Gaussian autocorrelation function, then the backscatter coefficient may be written as [7,10]:

$$\sigma_{\mathrm{b}} = \left(\frac{k^4 V_{\mathrm{s}}^2 \bar{n} \gamma_0^2}{16\pi^2}\right) e^{-2k^2 d^2}, \tag{1}$$

where d is the correlation length of the medium, $V_{\mathrm{s}} = (2\pi d^2)^{3/2}$ is the volume of a scatterer, k is the wavenumber; γ_0^2 is the mean square fluctuations in medium properties and $\bar{n}$ is the volume fraction of scatterer. To write Eq. (1), we have considered only the incoherent contribution to the scattering cross-section. Coherent scattering includes the contribution of scattering from the front and back surfaces of the scattering volume and from inside the scattering volume (e.g., when the scatterers are periodically distributed within the scattering volume). Coherent scattering from front and back surfaces will be removed experimentally by time windowing of the backscatter signal in experimental measurements. Given the quasi random distribution of the trabeculae, we assumed weak incoherent scattering from the distribution of scatterers.

2.2. Bone specimens

Measurements were performed on 31 slices of pure trabecular bone with parallel faces and thickness 1 cm. Specimens were obtained from human proximal femurs. They were defatted and vacuum-degassed under water in a desiccator before ultrasonic measurements.

2.3. Ultrasonic measurements

Ultrasonic measurements were performed in immersion using a pair of focused broadband transducers (1 MHz center frequency, 29 mm in diameter, focal length of 35 mm, V391, Panametrics Inc, Waltham, MA). The beam width at half maximum was approximately 3 mm. The −20 dB frequency bandwidth was 0.4–1.2 MHz. Emission and reception of the signals were performed using a plug-in ultrasonic pulser–receiver, amplifier and digitizer (SFT 4001H PCI, Sofratest, Ecquevilly, France). Both transducers were mounted coaxially, separated by twice the focal length, in a through-transmission normal incidence configuration. The measured specimen was placed in the focal zone. Two stepping motors mounted on a crossed slide assembly moved the specimen transversally in the ultrasonic beam. Transmitted and backscattered radio-frequency (rf) signals were recorded along 2-D scans in steps of 1 mm (Motion Controller – MM4006 – Newport, Irvine, CA). The size of the scans were chosen to fit the sample size. Radio-frequency signals were amplified, time averaged and digitized at 60 MHz.

The transmitted signals were computed to obtain the slope of the frequency-dependent attenuation so called normalized BUA (nBUA, dB/MHz cm), using a through-transmission method that has been widely described elsewhere [11–13].

The backscattered signals were computed to obtain the backscatter coefficient. Measurements were performed using a substitution method [14]. First, a reference echo was acquired on a plane reflector (steel plate) placed at a distance equal to the position of the scattering volume of the specimen under study. Then, an echo signal was acquired from the scattering of the incident pulse onto a bone specimen. This signal was time-weighted using a Hamming function in order to keep only the part of the signal backscattered from a volume approximately 8 mm in length placed in the center of the specimen. Then the backscatter coefficient $\sigma(f)$ was calculated by computing the ratio of the frequency power spectrum of the time-gated echo signal to the power spectrum of the reference signal. Corrections were made to compensate for attenuation using BUA measured at the same position in the transmission experiments, Hamming gate function and frequency-dependent scattering volume (diffraction). The detailed calculation may be found in a previous paper [14]. With this method, the intrinsic backscatter coefficient of the scattering volume is obtained, and it is independent of the charac-