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Ultrasonic characterization of trabecular bone: Two scatterers' population model

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Abstract

The paper describes the computer simulations allowing investigating the properties of the ultrasound pulse-echo signal, as it is received on the transducer surface after scattering in trabecular bone. A novel computer simulation model provides better understanding of ultrasonic scattering in porous bone structure and it can be also used to yield an ideal environment in which, the effects of various parameters (scatterer mechanical and geometrical properties, scatterer' concentration), the shape of incident wave and experimental conditions influencing the scattering of ultrasonic waves in trabecular bone structure can be examined individually. The results proved that the computer simulation has a particular relevance in studying scattering in cancellous bone which may be approximated as a collection of two populations of scatterers, cylindrical and spherical that imitate thick and thin trabeculae respectively.

Keywords: bone modeling; scattering simulation; osteoporosis; trabecular bone

1. Introduction

"Bone sonometry" is an accepted technique for diagnosis of osteoporosis. It is based on sound transmission through the examined bone, which enables the determination of the frequency-dependent attenuation coefficient well correlating with bone density. However, the applicability of transmission techniques for *in vivo* measurements is limited to peripheral bones only. Also, the evaluation of bone strength requires not only the knowledge of its density but also of its microscopic structure.

Ultrasonic examination of soft tissue, based on the analysis of scattered ultrasonic signal was successfully applied to characterize and to differentiate the tissue. Therefore, it could be anticipated that the analysis of the ultrasound signals that have been scattered in trabecular bone should be useful in assessment of the microscopic architecture of the investigated bone.

Several studies have been focused on the measurements and calculations of the backscattering coefficient of the trabecular bone and its dependency on frequency. It has been demonstrated that the use of the backscattering model enabled an assessment of density and microstructural characteristics from experimental data obtained from the

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calcanal samples measured in vitro. Specifically, Chaffai et al. [1] reported a correlation between the broadband ultrasonic backscatter (BUB), density and microstructure of the human calcanal bone in vitro. The ability of ultrasound backscattering data to predict the mechanical properties of trabecular bone has been demonstrated by Hakulinen et al. [2] who determined that integrated reflection coefficient (IRC) and BUB in bovine bone samples were linearly correlated with Young's modulus, ultimate strength and yield stress.

Theoretical studies of ultrasound scattering by trabecular bone were performed by Wear [3]. His bone model consisted of a random space-distribution of infinitely long identical cylinders with a diameter much smaller than the wavelength, aligned perpendicularly to the acoustic beam axis and insonified by a plane wave. The scattering by trabecular bone was modeled as scattering by the elastic cylinder.

In our previous study [8] we have developed the new trabecular bone model consisted of two populations of scatterers having different physical dimensions and also allowing the mechanical properties of the scatterers to be varied. The received pulse-echo signals were simulated by superposition of all of the elementary, individually scattered pulses, taking into account the phase differences caused by each spatial location associated with the individual cylinder. Two groups of cylindrical scatterers, significantly differing in mean thickness were assumed for modeling thick and thin trabeculae. The importance of thin interconnecting trabeculae in the bone scattered signal was demonstrated. However, the frequency dependences of the power backscattered coefficients calculated using modeled signals differed from the published experimental results [3]. Whereas these results show the frequency exponent exceeding the value of 3 in the case of simulated results the dependence was below the cubic.

The power backscattered coefficient calculated numerically for the plane acoustic wave scattered on the finite length elastic cylinder aligned perpendicularly to the incidence axes shows the frequency dependence similar to the one representing scattering on the sphere. For example, for cylinder length and thickness equal to 0.65mm and 0.08mm, respectively the frequency exponent of the backscattering coefficient calculated for 1MHz frequency at 50 mm distance from the cylinder was equal to 3.825.

In this paper we have modeled the scattering on thick trabecula by scattering on infinite elastic cylinder and the scattering on thin trabecula by scattering on elastic sphere [4]. The investigations were intended to compare the results obtained with the cylindrical model with those determined with the mixed, consisted of cylindrical and spherical scatterers, model. As in the previous study the frequency dependent backscattering coefficient of the modeled bone structure were analyzed and the statistical properties of the simulated echoes for varying parameters of the bone models were examined.

2. Simulations: Modeling the structural properties of trabecular bone and backscattered signal

The trabecular bone was modeled as a collection of scatterers (infinitely long, elastic cylinders aligned perpendicularly to the ultrasound beam axis and spherical scatterers), which were distributed in water. The coordinates that defined the locations of scatterer on Z-axis were assumed to be randomly distributed (uniform distribution). Along with Z-axis coordinate, the random value *r* for each scatterer was generated. This value was describing the distance of the scatterer from the Z axis and was used to account for the influence of the emitted field structure produced by the interrogating pulses. In order to simulate the signal received at the transducer we have applied the 1D geometry model as a direct consequence of the 180^{o} angular scattering (backscattering) assumption.

All simulations were carried out with a transmitted pulse waveform identical to the pulse emitted by a pulse-echo transducer used to collect the empirical densitometric data. Also the 2D pressure field distribution in the transducer focal zone was incorporated in simulations.

Mean values and standard deviations for the mechanical parameters and diameters of the trabeculae were determined experimentally using an acoustic microscope [5], or, when needed, were collected from literature. Variations in the structural properties of cancellous bone were modeled by changing the mean value and variance of scatterers' diameters. Experimentally determined thickness distributions of trabeculae were reported to be right-skewed and the data published followed well the Gamma distribution. Accordingly, in the model described here the thickness values were Gamma distributed.

The backscattered signal that was received at the pulse-echo transducer surface after scattering in trabecular bone structure was simulated in the following way. First, each scatterer (trabecula) was considered as a secondary source of an ultrasound wave. Then, each scatterer's backscattering coefficient was modified by a field coefficient that depended on the position of the scatterer considered and the distribution of the field generated by the pulse-echo transducer. Next, the spectrum of each individual pulse scattered from each cylinder was obtained as a product of the emitted pulse spectrum and the modified, complex backscattering coefficient of the scatterer. The pulse-echo transducer signal on receive was simulated by superposition of all of the elementary, individually scattered pulses, taking into account the phase differences caused by each spatial location associated with the individual cylinder or sphere. The spectrum of the simulated signal was limited according to the experimentally determined transfer function of the transducer.

3. Results

Analysis of the simulated transducer responses to bone backscattered waves was performed in order to calculate the frequency dependence of the power backscatter coefficient (PBSC). This coefficient was determined following the substitution method [6].

$$PBSC(f) = \frac{\langle S_i(f)\rangle \cdot C(f)}{S_p(f)} \qquad (1)$$

Using this method the PBSC was calculated by averaging the 48 simulated spectra $<S_i(f)>$ of echoes which were scattered by a trabecular bone and by comparing them with those obtained from the plane reflector $S_p(f)$ (calibration spectrum). Each echo corresponded to another random location of the scatterers but was assigned to have the same statistical properties of the bone model.

The frequency-dependent coefficient was then computed, applying volume compensation correction factor $C(f)$ described by the formula given in [6] and under the assumption of non-attenuating medium. Next, the values of backscattering coefficient were least-squared fit to frequency f power-law function ($Af^{\,n}$) over the bandwidth 0.8MHz to 1.3MHz.

Also, the model described was used to examine the structural properties of a bone in order to determine their influence on the statistics of the backscattered signal envelope and to determine what structural characteristics could lead to non-Rayleigh statistics. In the case of Rayleigh distribution the ratio of the mean signal amplitude (<A>) to the standard deviation of amplitude (σ(A)) is constant and equals to $(\pi/(4-\pi))^{1/2} \approx 1.913$. In the following this ratio is referred to as envelope SNR (eSNR). Each of the eSNR coefficients was obtained in the following way: likewise in the backscattering coefficient calculations, forty-eight RF-echoes from the trabecular bone were simulated. For each simulated RF backscatter the envelope was determined using Hilbert transform. The amplitude data from all forty-eight envelopes were then used to calculate the eSNR coefficient. Deviations of eSNR from the value corresponding to Rayleigh distribution (1.913) were considered as the departure from the Rayleigh statistics.

For all simulations the same density value (amount of scatterers per unit volume) of thick trabeculae equal to $\rho=3/mm^3$ was used. This density value is equivalent to 86% porosity calculated for a constant length (4 mm) and diameter (0.12 mm) of trabeculae. Also, the mechanical properties of scatterers were assumed to be constants and similar to the bone tissue properties.

The echoes signal used to calculate the backscattering coefficients were simulated using three pairs of thickness of 0.05mm and 0.033mm, 0.12mm and 0.08mm and 0.2mm and 0.13mm for modeling thick $<d>$ and thin $<d1>$ trabeculae, respectively. The variation of trabeculae thickness was described by the thickness SNR coefficient (tSNR) defined as a ratio of the mean thickness to the standard deviation of thickness (tSNR = $<d>/\sigma(d)$) and was equal to 2.7 and 3.2 for simulating thick and thin trabeculae, respectively [7].

The statistical properties of the backscatter envelopes were investigated assuming identical values of thickness SNR varying from tSNR=1 to tSNR=4 for both, thick and thin trabeculae. Calculations were performed for $<d>$ = 0.05 mm and $<d1>$ = 0.033mm. The trabecular density values of $\rho= 3/mm^3$ and $\rho=9/mm^3$ for thin trabeculae were used.

In all simulations the mean amplitude of echoes calculated for backscattering on the spherical scatterers was adjusted to be equal to the mean amplitude echoes determined for scattering on appropriate thin cylinders considered in cylindrical model.

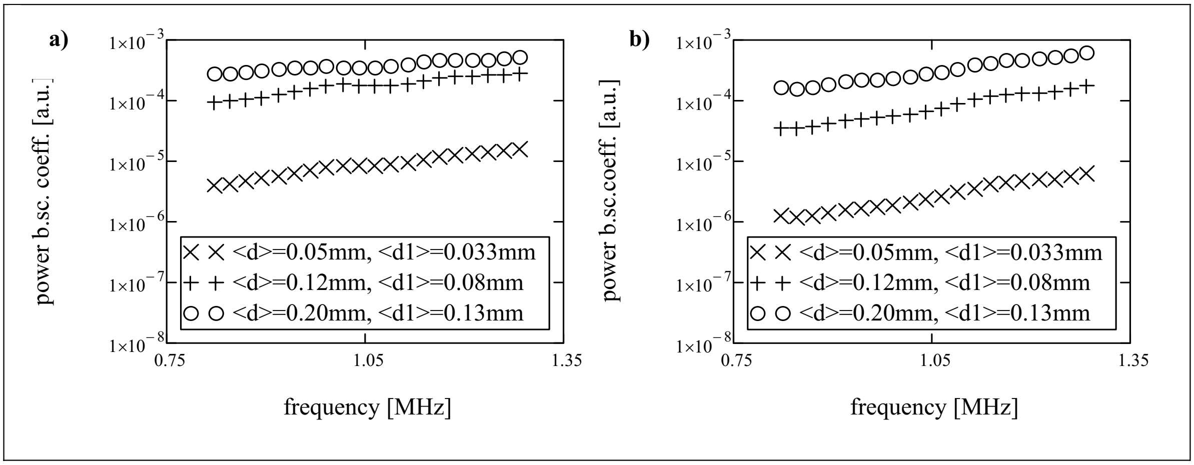

Fig.1 Dependence of power backscattering coefficients (PBSCs) calculated from simulated RF-echoes for: a) cylindrical model of bone, b) mixed model of bone.

The frequency dependence of the PBSC is clearly seen in Fig.1. When the spherical scatterers were used to describe thin trabeculae (mixed model of bone) the exponents *(n)* of the power-law function fitting the frequency dependence of backscattering coefficient increased to the value over 3 (see Table 1). For the smallest of the concerned spherical scatterers, outnumbering three times an amount of thick cylindrical trabeculae the value of n equal to 3.853 was achieved.

Table 1. The exponents (n) of the power-law function and the coefficients (in brackets) describing the goodness of fitting of the frequency-dependent backscattered coefficient determined for the two bone models. Thick trabeculae density ρ= 3/mm3

Scatterers diameters	Thin trabeculae density ρ= 3/mm^3		Thin trabeculae density ρ= 9/mm^3	
	Mixed model of bone	Cylindrical model of bone	Mixed model of bone	Cylindrical model of bone
<*d*>=0.05mm <*d1*>=0.33mm	3.156 (0.943)	2.786 (0.906)	3.853 (0.978)	2.978 (0.988)
<*d*>= 0.12 mm <*d1*>=0.08mm	2.781 (0.911)	2.006 (0.955)	3.693 (0.961)	2.306 (0.976)
<*d*>= 0.20 mm <*d1*>=0.13mm	2.787 (0.921)	1.725 (0.912)	2.961 (0.946)	1.416 (0.958)

For the mixed model of bone and big variation of trabeculae thickness the departure from Rayleigh distribution of the signal envelope values is very pronounced (Fig 2 b). For both models of bone starting from tSNR=2 the eSNR values stabilized and was close to the value assigned to the Rayleigh distribution.

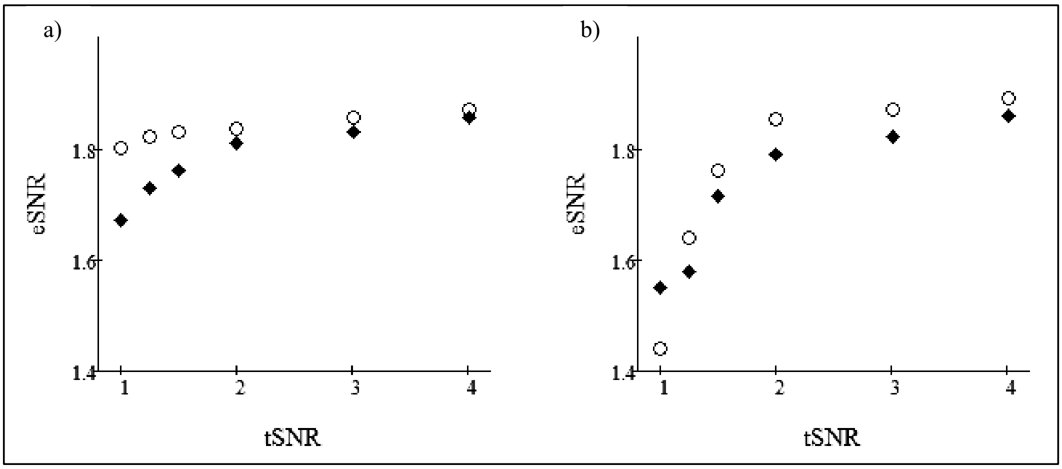

Fig.2 The eSNR coefficient versus tSNR coefficient calculated: a) using the cylindrical model of a bone (thick and thin trabeculae modeled by cylinders), and b) mixed model (cylinders and spheres) with equal amount of the thin and thick scatterers (squares) and with the thin scatterers outnumbering three times an amount of thick scatterers (open circles).

4. Conclusions

The proposed mixed model of trabecular bone allows each of the parameters important in the diagnosis of osteoporosis, including the physical dimensions and shape of the scatterers to be examined separately. It was shown that the physical dimensions, such as size and shape of the individual scatterers, exerted influence on frequency dependence and on the statistics of scattered signals.

Again, the importance of thin interconnecting trabeculae in the bone structure model was demonstrated.

Both, the backscattering coefficient and statistics of the backscatter envelope have changed when the population of thin cylinders was replaced with the population of spherical scatteres to create the mixed model of bone.

It was shown that introducing of spherical scatterers increased significantly the value of the exponent *(n)* of the power-law function approximating frequency dependence of backscattering coefficient. The mixed model approximates well the exponent values closely to those calculated from the experimentally measured bone backscattering. Variation of scatterers dimensions cause bigger variation of backscattering coefficient for spherical than for cylindrical scatterers. Thus, the drop of eSNR coefficient with the decrease of tSNR is much more rapid in the case of modeling the thin trabeculae with spherical scatterers. The results presented above indicate that the model proposed can potentially provide clinically useful information about the bone status and can be applied as a tool for investigation the ultrasound scattering in cancellous bone.

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