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5aBB12. Ultrasonic characterization of cancellous bone using three models of trabecular structure

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The semi-empirical scattering models of trabecular bone were developed and examined for their abilities to mimic the frequency dependent backscattering coefficient measured in the cancellous bone. In the simulation of the bone RF echoes the real properties of the bone and experimental conditions were taken into account. Three types of trabeculae mimicking scatterers were considered. First, the bone consisted of cylinders with varying thickness (Gamma distributed) within the population, was assumed. The next two cases accounted for the contribution of thick and thin trabeculae to the total backscattered signal. The second model assumed existence of two populations of the cylindrical scatterers significantly differing in the average value of Gamma distributed diameters. Finally, the mixed model composed of thick and thin trabeculae modeled respectively by cylindrical and spherical scatterers was examined. The last selection resulted from the similarity found between scattering on small sphere and finite cylinder. Calculated echoes demonstrated the usefulness of the mixed model. Frequency dependence of backscattering coefficient agreed well with the experimentally determined dependences. The study showed also that the amplitude histograms calculated using demodulated RF echoes deviate from the Rayleigh distribution when the variation of scatterers' diameters increases.

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Introduction

Ultrasonic examinations of soft tissues, based on the analysis of scattered ultrasonic signal have been successfully applied to characterize and to differentiate tissues [1, 2]. Similarly, signals that have been scattered in trabecular bone contain information about the properties of the bone structure. Therefore scattering-based ultrasonic methods potentially enable the assessment of microscopic structure of bone.

Many investigations have been focused on the measurements and calculations of the backscattering coefficient for trabecular bone and the dependency of that coefficient on frequency [3-8]. It has been demonstrated that using the backscattering model it is possible to estimate some micro-structural characteristics from experimental signals measured in vitro for calcaneal samples [9,10]. Chaffai et al. [11] revealed a significant correlation between broadband ultrasonic backscatter (BUB) and the density and microstructure of the human calcaneal bone in vitro. Also, the ability of ultrasound backscattering to predict mechanical properties of trabecular bone was shown by Hakulinen et al. [12] who proved for bovine bone samples that the integrated reflection coefficient (IRC) and BUB are highly linearly correlated with Young's modulus, ultimate strength and yield stress.

Theoretical studies of ultrasonic scattering by trabecular bone were performed by Wear [8]. The model of a bone, proposed by Wear, consisted of a random space-distribution of long identical cylinders with a diameter much smaller than the wavelength, aligned perpendicularly to the acoustic beam axis. Therefore the scattering by trabecular bone was modeled as scattering of a plane wave by elastic cylinders.

In our previous study [13] we have developed a simulation technique that enabled determination of the ultrasound signal received at the pulse-echo transducer surface after interrogation of cancellous bone. The simulation can be applied for different scattering models of a trabecular structure. Mimicking the bone structure similarly to Wear's model, by a random distribution of long elastic cylinders but allowing for variations of it's physical parameters we have found the departures from the Rayleigh statistics of the scattered signal instantaneous amplitude (envelope) as the variation of cylinders diameters increased [15]. The influence of the variation of mechanical properties of a bone tissue forming the trabeculae was not observed. The departure from the Rayleigh statistics could be expected as the effective amount of scatterers in resolution cell significantly depends on the uniformity of the scatterers. However, the frequency dependence 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 one.

The presented investigations were intended to compare the results obtained with the cylindrical model with the two newly developed models of trabecular bone structure. Both new models accounted for the contribution of thick and thin trabeculae to the total backscattered signal. The first model assumed the existence of two populations of the cylindrical scatterers significantly differing in the mean diameter. The second one was called the mixed model as it was composed of thick and thin trabeculae modeled respectively by cylindrical and spherical elastic scatterers. 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.

Models of trabecular bone

All three models of the trabecular bone structure were simulated as a collection of scatterers (infinitely long, elastic cylinders aligned perpendicularly to the ultrasound beam axis and spherical scatterers), which were randomly (uniformly) distributed in water. Mean values for the mechanical parameters and mean values and standard deviations for the diameters of the trabeculae were determined experimentally using an acoustic microscope [14], or, when needed, were collected from literature. The mechanical properties of scatterers were assumed to be constants and similar to the bone tissue properties.

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 closely matched the Gamma distribution [16]. Accordingly, the diameters values were Gamma distributed for all models described in this paper.

For all bone models 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. For the thin trabeculae the density $\rho = 9/mm^3$ was assumed.

In the *one population model* three values of mean diameters <d> of the trabecula mimicking cylinders equaled 0.05 mm, 0.12 mm and 0.2 mm were considered. In the *two populations model* (fig. 1) three pairs of the cylinder's mean thickness of 0.05 mm and 0.033 mm, 0.12 mm and 0.08 mm and 0.2 mm and 0.13 mm for modeling respectively, thick <d> and thin <d1> trabeculae diameters were used. In the *mixed model* (fig. 2) the thick trabeculae properties remained unaltered while the spheres diameters <d1> were equal to 0.05 mm, 0.1 mm and 0. 14 mm, respectively.

The chosen values of the mean diameters of the sphere assured that the amplitudes of the backscattered signal (at 1 MHz) from the sphere and from the finite, 0.65 mm long thin cylinder [17] of the diameter corresponding respectively to the mean diameters of the thin trabeculae from *two population model* were the same.

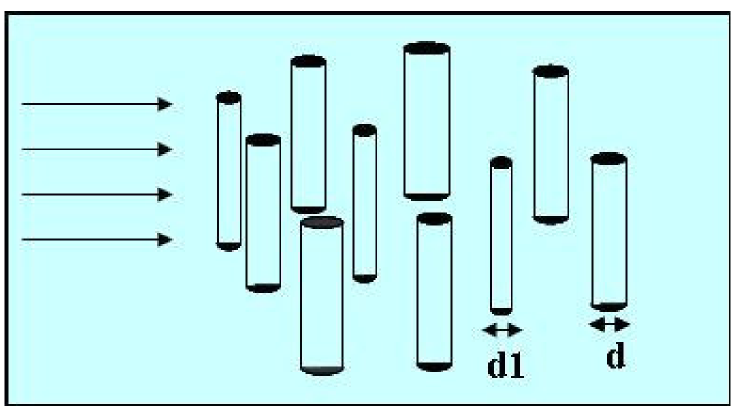

Fig.1 Trabecular bone model consisting of two populations of cylindrical scatterers.

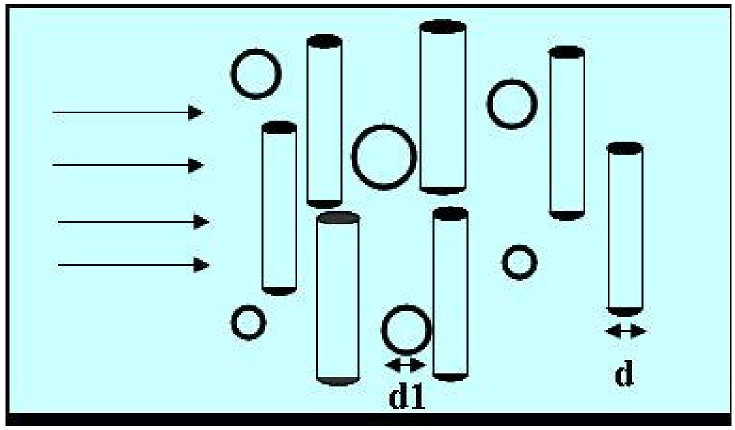

Fig. 2 Trabecular bone model consisting of two populations of cylindrical and spherical scatterers.

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 = $\langle d\rangle/\sigma(d)$) and was equal to 2.7 and 3.2 for simulating thick and thin trabeculae, respectively [18].

The choice of a spherical scatterer for the simulation of a thin trabecula resulted from an exact calculation of the pressure field for the scattering on the finite thin cylinder. The calculations were performed by solving numerically the integral form of the Sturm-Liouville equation that describes scalar wave in inhomogeneous media. The results shown in fig. 3 indicate similarity to the field scattered on the sphere. Also, the frequency (f) dependence of the backscattering coefficient calculated for the scattering on thin cylinders used in the *two population model* was close to the power of 4 that is characteristic to the scattering on the sphere (fig. 4).

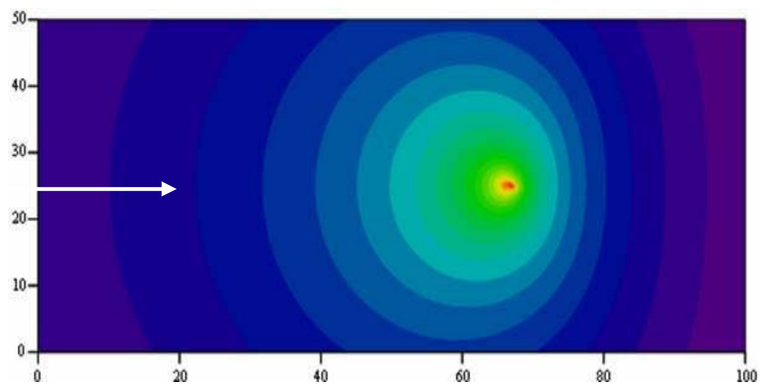

Fig. 3 Pressure field distribution (2dB steps) calculated for 1 MHz plane wave scattered on the finite length (0.65 mm), thin (0.05 mm) elastic cylinder aligned perpendicularly to the ultrasound beam axis. Arrow marks the incidence direction.

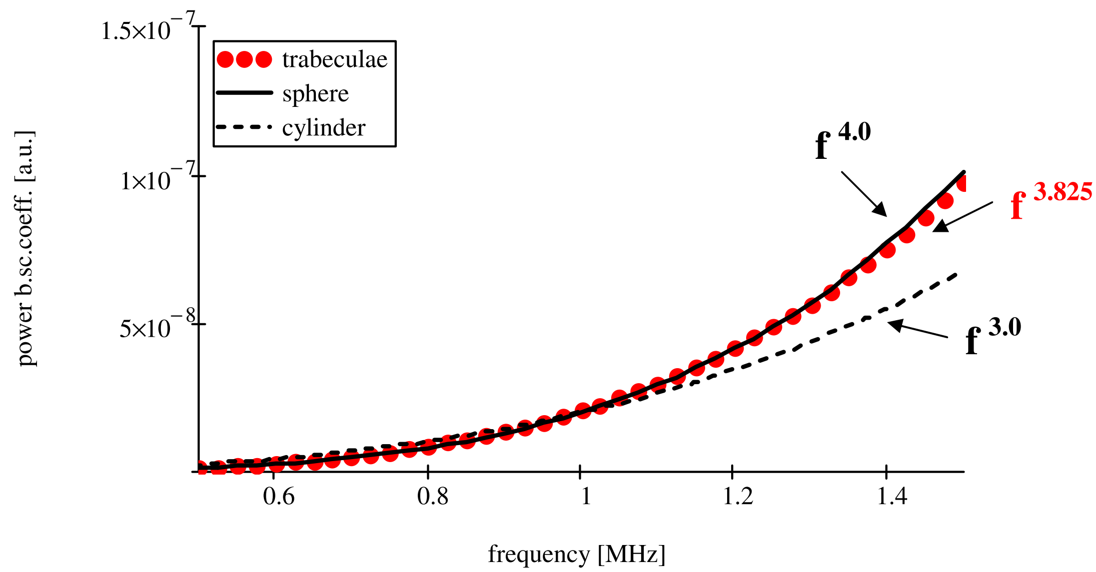

Fig.4 Frequency dependence of the power backscattered coefficient calculated for the finite length cylinder (0.65 mm long, 0.05 mm diameter), infinite thin cylinder and sphere.

Modeling the backscattered signal

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.

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 received signal was simulated by superposition of all of the elementary, individually scattered pulses, taking into account the phase differences caused by each scatterer spatial location associated with the individual cylinder or sphere. The spectrum of the simulated signal was band limited according to the experimentally determined transfer function of the transducer.

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 [19].

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

Using this method the PBSC was calculated by averaging of the 48 simulated spectra <$S_i(f)$> of the echoes which were scattered by a trabecular bone and next by comparing them to 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 next computed, applying volume compensation correction factor C(f) described by the formula given in [19] and under the assumption of non-attenuating medium.

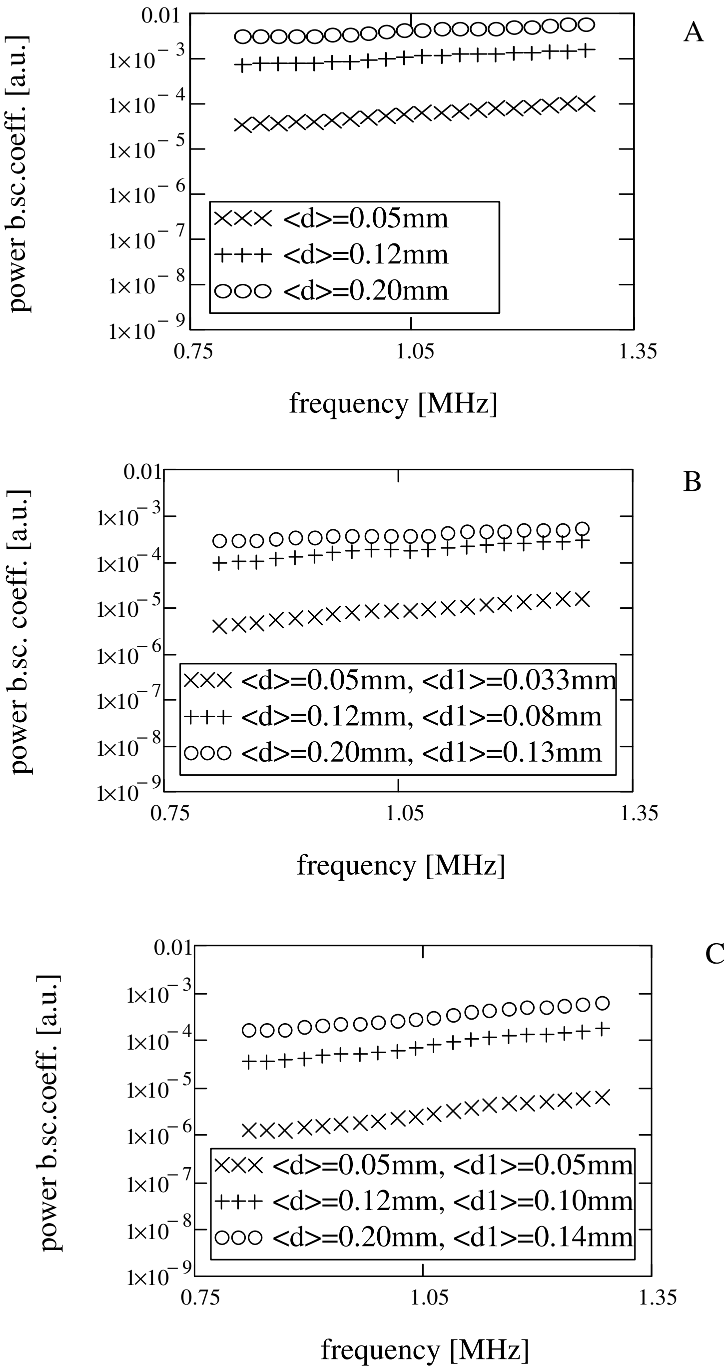

Fig. 5 Power backscattered coefficients calculated from simulated RF-echoes for A/ cylindrical scatterers bone model, B/ model consists of two populations of cylindrical scatterers and C/ mixed model

Next, the values of backscattering coefficient were least-squared fit to frequency f power-law function (Af^{n}) over the bandwidth from 0.8 MHz to 1.3 MHz (Table. 1).

Table 1. The exponents (n) of the power-law function and the coefficients (in brackets) describing the quality of fit of the frequency-dependent backscattered coefficient determined for three bone models.

thick scatterers diameters	Cylindrical model	Two population cylindrical model – thin scatterers diameter and (n)	Two population mixed model - thin scatterers diameter and (n)
<d>=0.05mm	**2.587** (0.998)	<d1>=0.033mm, **2.978** (0.988)	<d1>=0.05mm, **3.853** (0.978)
<d>= 0.12 mm	**1.789** (0.991)	<d1>=0.08mm**, 2.306** (0.976)	<d1>=0.1mm, **3.693** (0.961)
<d>= 0.20 mm	**1.603** (0.996)	<d1>=0.13mm, **1.416** (0.958)	<d1>=0.14mm, **2.961** (0.946)

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 ($\sigma(A)$) 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.

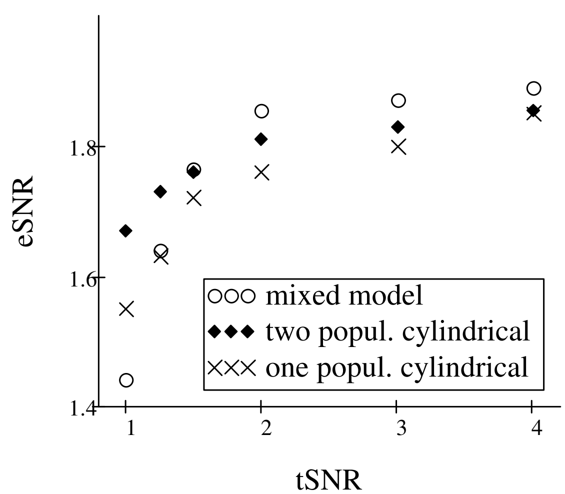

Fig. 6 The eSNR coefficient versus tSNR coefficient calculated using the one population model of a bone (crosses), assuming a two population cylindrical model (squares) and two population model with cylindrical and spherical scatterers (open circles).

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> = 0.033 mm for cylindrical model and <d1> = 0.05 mm for mixed model. The frequency dependence of the

PBSC is clearly seen in fig. 5. 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 exceeding 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.

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. 6). For all models of bone starting from tSNR=2, the eSNR values stabilized and were close to the value assigned to the Rayleigh distribution.

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 investigating the ultrasound scattering in cancellous bone.

Acknowledgements

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