STATISTICAL PROPERTIES OF PULSE-ECHO SIGNAL BACKSCATTERED IN TRABECULAR BONE

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The paper considers the application of statistical properties of backscattered ultrasonic signal for assessment of the trabecular bone status. Computer simulations were conducted to investigate the properties of the ultrasound pulse-echo signal, as it is received on the transducer surface after scattering in trabecular bone. Results indicated that while for the well-defined trabeculae properties within the simulated bone structure the signal envelope values are Rayleigh distributed the significant departures from Rayleigh statistics may be expected as the thickness of trabeculae become random. The influence of the altering of mechanical properties of the bone tissue building the trabeculae on the signal statistical parameters was unnoticeable. The initial experiments confirming some cases of departure from Rayleigh statistics for envelopes of backscattered signals are also discussed.

INTRODUCTION

Ultrasonic signals scattered in trabecular bone contain information about the properties of the bone structure. Therefore, the scattering-based methods potentially enable the assessment of microscopic structure of bone. In addition, very important zones of human skeleton (due to osteoporosis hazard) are detectable by the backscattering-based techniques, where previously these have been inaccessible for transmission-based measurements.

Many investigations have been focused on the measurements and calculations of the backscattering coefficient for trabecular bone and the dependency of that coefficient on the frequency [1]-[6]. It has been demonstrated that ultrasound backscatter measurements have the ability to discriminate patients with osteoporosis from controls [2]. Theoretical studies of ultrasonic scattering by trabecular bone were performed by Wear [6]. 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 modelled as scattering of a plane wave by elastic cylinder.

In this paper, a more realistic computer simulation is introduced. To describe a cancellous bone the Wear's scattering model was applied with modifications that allow for changes of mechanical and geometrical properties of individual trabeculae as well as for their spatial density variation. Also, this paper proposes a new approach to ultrasonic bone examination, based on statistical analysis of the pulse-echo signal that is received on the transducer surface after scattering in trabecular bone structure.

1.STATISTICS OF THE SCATTERED SIGNAL ENVELOPE

Statistical parameters of acoustic signals backscattered in soft tissue or grained materials make it possible to examine the characteristics of the internal structure of the scattering medium, as they depend on the number, location and size of the scattering cross-sections of scatterers playing the role of secondary sources of the scattered signal [7]-[9]. Similarly, it can be assumed that the trabecular bone backscattered wave consists of a number of individual scatterings on the single trabecula, and the received signal is a result of the summation of these partial components.

The central limit theorem [10] shows that for a large number of randomly distributed scatterers within the resolution cell, the value of instantaneous amplitude of RF signal generated on the transducer surface is Gauss-distributed, with the mean value equal to zero and the signal envelope values (A) are Rayleigh distributed.

When the scattering cross-sections of individual scatterers are random, the actual number of scattering centres located within the area of measurements should be substituted with the effective number. When alterations of scatterers' cross-sections become more stochastic (their variance increases), the effective number of scattering centres decreases, and in some cases, it may reach value substantially lower than the real number of elements. In such case, the assumptions of the central limit theorem are not fulfilled, and the deviations in distribution of the signal amplitudes from the Rayleigh model are visible [11],[12].

Metabolic illnesses of bones affect the structures of cancellous bones [13]. They may change the average spatial density of trabeculae and cause the local density fluctuations, as well as change the distribution of material and geometrical parameters of trabeculae. Such variations in the scattering structure could lead to changes in distribution for the envelopes of RF echo signal received from the bone. Therefore, the recorded signal amplitude distribution could be used for monitoring the alterations in the structure of cancellous bones, assuming that the effective number of trabeculae in the resolution cell is sufficiently low.

This paper tries to answer the questions, how much alterations in the cancellous bone structure may affect the effective number of trabeculae within the resolution cell, and whether such alterations may cause significant and measurable changes in the statistics of the envelopes of signals received on the transducer, during ultrasonic pulse-echo examination of a bone.

The envelopes of backscattered signals (either measured or calculated) were used to calculate the MSR coefficient defined as a ratio of the mean $<A>$ to the standard deviation (σ) and to calculate amplitude histograms. The theoretical value for the MSR = $<A>/\sigma$ for Rayleigh distribution equals $(\pi/(4-\pi))^{1/2} \approx 1.913$. Any deviation of MSR from this value can be considered as deviations from the Rayleigh statistics. The histograms were compared with the appropriate Rayleigh probability density function.

2. NUMERICAL GENERATION OF THE BACKSCATTERED SIGNAL ENVELOPES

A. *Scattering Model of the Cancellous Bone*

The trabecular bone was modelled as a collection of long, elastic cylinders, randomly distributed in water, with diameters much smaller than the wavelength, aligned perpendicularly to the ultrasound beam axis. The signal that is received on the transducer surface after scattering in trabecular bone structure was simulated in the following way: Every cylinder (trabecula) was considered as a secondary source of an ultrasonic wave. Each cylinder was associated with a complex backscattering coefficient. The value of this coefficient was defined on the basis of the theory of scattering of ultrasound from elastic cylinder [14] and depended on the cylinder diameter (d), mechanical properties of the cylinder and immersion liquid and frequency of the probing wave. The distance between the scatterers and transducer was assumed to be large compared to the size of scatterers. A spectrum of every elementary pulse scattered from a cylinder was obtained as a product of the emitted pulse spectrum and the complex backscattering coefficient of the scatterer. The receiving transducer action was simulated by superposing all the elementary scattered pulses, taking into account the phase differences that result from various locations of individual trabecula. The model assumes that the effects of multiple scattering are negligible.

Variations of the structural properties of cancellous bone were modelled by changing the spatial density of cylinders and changing the mean value and variance of cylinders diameters and their mechanical properties, such as velocity of both longitudinal and transverse waves and density.

B. *Data for Simulations*

Mean values and standard deviations for mechanical parameters and diameters of the trabeculae were determined experimentally by means of acoustic microscope, or were adopted in accordance with reference publications. The velocity of transverse wave was assumed for calculation as equal to 0.53 of the velocity for the respective longitudinal wave that corresponds to Poisson ratio = 0.3.

In the bone model, coordinates that define the locations of trabeculae were random (uniformly distributed). The results of measurement of mechanical parameters of trabeculae (velocity and density) reported by author [16] were used again to assess their statistical properties. The histograms of velocity and density values showed that they are Gauss distributed. Thus, the Gauss distribution was assumed for these parameters distribution in simulations. Thickness distributions of trabeculae are right-skewed as reported in experimental studies [15], [17]. The published trabecula thickness distributions fit the Gamma distribution well. Therefore, trabecula thickness values in the bone model were Gamma distributed.

C. *Procedures of Simulations*

Every simulation consisted of one RF-line, of 512 samples corresponding to a bone structure depth of 35 mm, and sampled at the rate of 10 MHz. Statistical properties of the backscattered signal were calculated in every case on the basis of 32 independent spatial arrangements of trabeculae (32 RF-lines = 16384 amplitude values) whereas geometrical and mechanical properties of trabeculae were kept unchanged as input parameters of the simulations. For the calculation of MSR coefficient all 16384 amplitude values were used.

The study investigated the impact of three parameters that define structural properties of trabecular bone. These included: (1) spatial density of trabeculae; (2) significant change in one of physical parameters of trabecula, such as density, velocity of longitudinal and transverse waves, or diameter; and (3) variation of physical parameters defined by standard deviations from their mean value.

Fig.1 Simulated RF echo-signal scattered in trabecular bone

D. *Simulation Results*

1) *The Impact of Cancellous Bone Porosity*: The sensitivity of simulated signal envelopes to bone porosity was investigated assuming a constant length and diameter of trabeculae, equal to 4 mm and 0.12 mm, respectively. These geometrical parameters define the volume of trabecula (cylinder) that together with the assumed value of bone porosity, enables to calculate the spatial density of trabeculae. The mechanical properties of the bone tissue were also fixed (ρ=1900 kg/m^3, v=3800 m/s). Porosity of bones ranged from 90% to 99.5%. This range corresponds to a change of the number of scatterers in the volume of measurements (30 mm^3) from 70 to about 3. Finally, for the simulated signals, histograms of signal amplitudes and the values of the MSR coefficient were calculated.

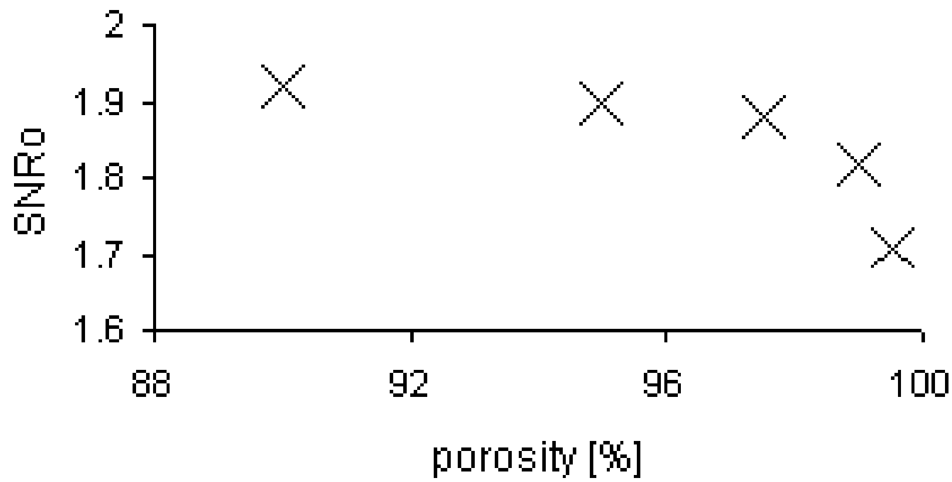

Fig.2 The dependence between the MSR_o factor and structural porosity

It was found (Fig.2) that within the range of trabecular bone porosity from 90% to 98% the MSR_o parameter is nearly constant and equals to 1.91. This means that the number of scattering centres in the volume of measurements is large and the amplitude of the backscattered signal is Rayleigh distributed. Only when the porosity was really high (99%, N=7) the assumptions of the central limit theorem were not fulfilled and the rapid decrease of the MSR_o value was observed. Virtually no case was observed when trabecular structure represented only 1% of cancellous bone volume.

2) *The Impact of Material Properties and Thickness of Trabeculae*: The second part of simulations was carried out to determine how the mechanical properties of bone tissue constituting the trabeculae and the varying thickness of trabeculae affect statistics of backscattered signals. One of the consequences of the assumed model of trabecular bone and backscattered signal generation is that the simultaneous and equal change in material properties of all trabeculae affects only the amplitude of simulated signals. The statistical properties of the backscattered signals should remain unchanged.

The scattered signals were simulated for two average densities of trabecular tissues (<ρ>=1900 kg/m^3 and <ρ>=1200 kg/m^3), two average values of velocity of longitudinal wave (<v>=3200 m/s and <v>=3800 m/s) as well as for two average thicknesses of trabeculae (<d>=0.12 mm and <d>=0.05 mm). All the distributions (Gauss for mechanical properties and Gamma for the thickness) featured high ratio of the mean to the standard deviation. For every simulation pass, only one parameter was altered. Other parameters were assumed as constant and equal to the values for non-pathological tissues (ρ=1900 kg/m^3, v=3800 m/s, d=0.12 mm).

As expected, the obtained results show that the properties of bone tissue material which constitute trabeculae, have practically no influence on the statistical properties of the backscattered signal. Similarly, alterations of average thickness (diameter) of trabeculae induce no changes in the nature of scattering (calculated MSR values were ranging from 1.89 to 1.90 for all simulations).

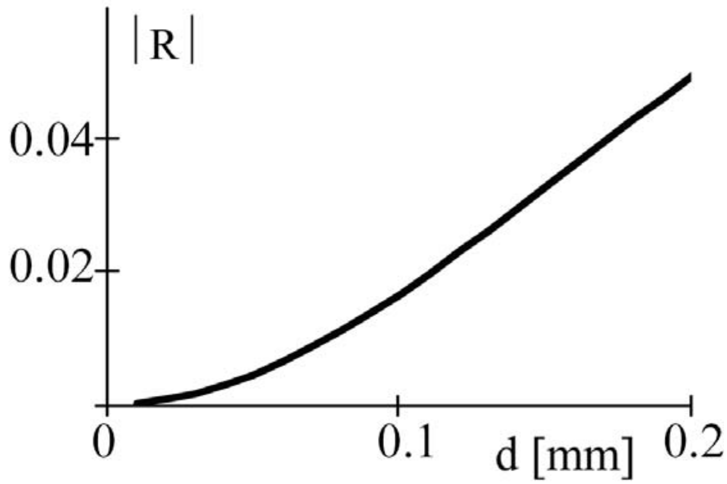

Fig.3 Amplitude - |R| of the backscattering coefficient calculated for varying diameter (d) of the scattering cylinder. Frequency = 1 MHz

Substantial drop of average amplitude for the backscattered signal associated with the decrease of average trabecula thickness, was observed. A strong relationship between the value of backscattering coefficient and the cylinder diameter is shown in Fig. 3. This result coincides with both theoretical expectations and experimental results that were obtained by Wear [18] in his studies dedicated to the investigation on the backscattering coefficient for cancellous bone at frequency of 0.5 MHz. The signal amplification is however expected to have no influence on its statistical properties and the value of MSR factor.

3) *The Impact of Statistical Spread of Values Defining Trabeculae*: The third part of simulations was aimed at investigating how the variation of the parameters defining trabeculae, affects the backscattering of ultrasonic waves and consequently how the statistical properties of amplitudes of that signal are modified.

First, the simulations were performed with constant values of thickness and length of trabeculae equal to 0.05 mm and 4 mm, respectively. The variation of random, Gauss distributed values of mechanical properties of trabeculae were simulated by modifying the standard deviation values for density (from σ=100 kg/m^3 to 400 kg/m^3) and velocity (from σ= 100 m/s to 500 m/s) while keeping the mean values constant and equal to 1500 kg/m^3 and 3500 m/s, respectively. Simulations were carried out for porosities of 97.5% and 99%.

Calculated values of the MSR coefficient clearly indicate that the spread of velocity and density values of the trabecula material (even for unrealistically high porosity of 99%) has nearly no impact on statistical properties of the backscattered signal (MSR value ranged from 1.89 to 1.91).

In the next step of simulations, the material properties of the bone tissue were kept constant (1900 kg/m^3, 3800 m/s respectively for density and velocity), while the impact of randomness of Gamma-distributed trabecula thickness values on the scattered ultrasonic signal was investigated. Thickness of trabeculae in cancellous bone is affected by a number of factors such as the anatomical size of bones, their age, character and scale of transferred loads and metabolic illnesses of the osseous system. These illnesses have also a substantial impact on the variation of trabecula thickness. Images from an acoustic microscope as well as optical images of samples of osteoporotic cancellous bones show both trabeculae with thickness that corresponds to non-pathological bones as well as atrophic trabeculae with much less thickness.

Simulations were carried out for three values of bone porosity, namely 99%, 97.5%, and 95%. To restrict the effect of structural parameters of bones to mere variation of their thickness, the simulation used the assumption of the constant average thickness (<d>=0.05 mm). The value of standard deviation of the thickness varied in the range of σ = 0.004 mm ÷ 0.05 mm.

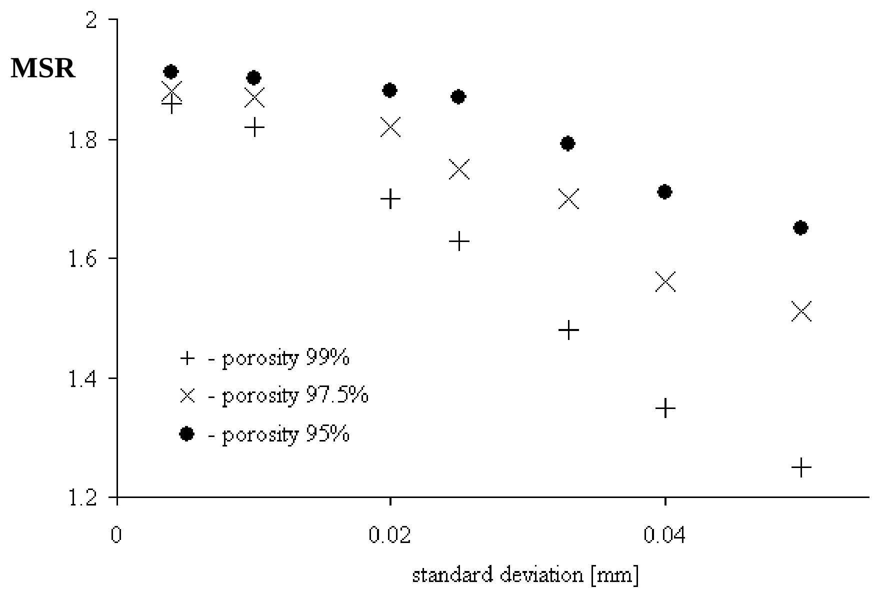

Fig.4 The MSR factor calculated using the envelopes of simulated signals that were backscattered in the trabecular structure. Thickness of trabeculae was Gamma distributed with the mean = 0.05mm and variable value of standard deviation (σ)

Substantial impact of trabecula thickness variation on the statistical properties of amplitudes for the backscattered signal is clearly visible for all the considered porosities (Fig.4). At the very beginning, the decreasing of the MSR value is insignificant (for low values of standard deviation of thickness σ = 0.004 mm ÷ 0.01 mm). The degradation of trabeculae (caused by metabolic illnesses) enhances variation of trabecula thickness. As thickness variation increases, the value of the MSR factor rapidly drops. That phenomenon concerns variations of the standard deviations within the range of σ = 0.02 mm – 0.05 mm.

Alterations of trabecula thickness result in variations of the backscattering coefficient. Thus, the spread of trabecula thickness values is equivalent to the spread of the backscattering coefficient. The more random variations of the backscattering coefficient are, the more significant decrease of the effective number of scatterers in the volume of measurements, occurs. This leads to deviations in distribution of signal envelopes from the Rayleigh distribution

3. EXPERIMENTAL DETERMINATION OF THE STATISTICS OF BACKSCATTERED SIGNAL

A. *Sample Preparation*

The measurements were performed on human heel bones (calcaneus). Upon consent of the Ethical-Deontological Board, three heel bones were obtained from cadavers that significantly differed in age (1 – 34 y, 2 – 40 y, and 3 - 80 y). The part of a cortical bone was removed, leaving a direct access to porous bone structures within the area of measurements. Then the tissues of bone marrow and blood were taken away by suction. Finally the bones were subjected to the lyophilization process until full dehydration of the trabecular structure was achieved. Before ultrasonic examination, the bones were refilled with water under vacuum.

B. *Ultrasonic Measurements*

Ultrasonic measurements were performed in water with a low-focusing transmitting-receiving transducer (diameter -15 mm, focal length - 86 mm, 10 dB frequency bandwidth - 75%) operating with centre frequency of 1MHz. The pressure field emitted by the transducer was determined experimentally using the technique described in [19]. Measured field revealed a uniform, well-defined acoustic beam in the vicinity of the focal plane. The measured beam width (5 mm, 10 dB) and the length of the emitted signal (2 μs) determined the resolution cell volume equal approximately to 30 mm^3.

The pulse signals were transmitted using Arbitrary Function Generator Le Croy 9101 and RF Power Amplifier E&I 325 LA and backscattered signals were received with RITEC BR-640A amplifier and sampled and stored with Agilend Infinium Oscilloscope (20MHz, 12 bit resolution). One after the other, the bones were placed in a water tank and backscattered echoes were acquired across 21 mm by 9 mm scan plane with a displacement between RF lines of 3 mm. The distance between the transducer and the bone was adjusted in each case, where the focal plane was situated approximately 5 mm beneath the bone surface. In addition, the average BUA coefficient and phase velocity of the longitudinal acoustic wave was determined for each bone basing on the technique described by Laugier [2]. The velocity value is necessary for the proper compensation of attenuation.

Measurements were performed with the ultrasound beam axis perpendicular to the direction of main orientation of the trabecular network, which corresponds to the clinical configuration.

C. *Signal Processing*

High attenuation of ultrasonic waves in cancellous bones essentially affects statistical properties of the backscattered signal. The signals backscattered from the internal bone microarchitecture were compensated for attenuation prior to the evaluation of the statistics of their envelopes. To this end, the frequency-dependent attenuation coefficient (α) was determined separately for each recorded RF signal line. Its value was derived from the log-ratios of the amplitude spectra calculated for segments of signal backscattered at various depths in the examined bone [9]. The cepstral smoothing technique was applied to eliminate random changes of spectrum amplitude [9], [20].

Finally, the signal envelope was calculated using the Hilbert transformation. Each envelope was normalized by dividing by its mean value. Exemplary waveforms of backscattered signal before and after compensation are shown in Fig.5. Typically, 20 waveforms were recorded (sampling 20 MHz, 12 bits) for every specimen. Statistical analysis consisted of calculations of histogram and MSR value for the amplitude values determined from all 20 envelopes of RF lines recorded for a specific specimen.

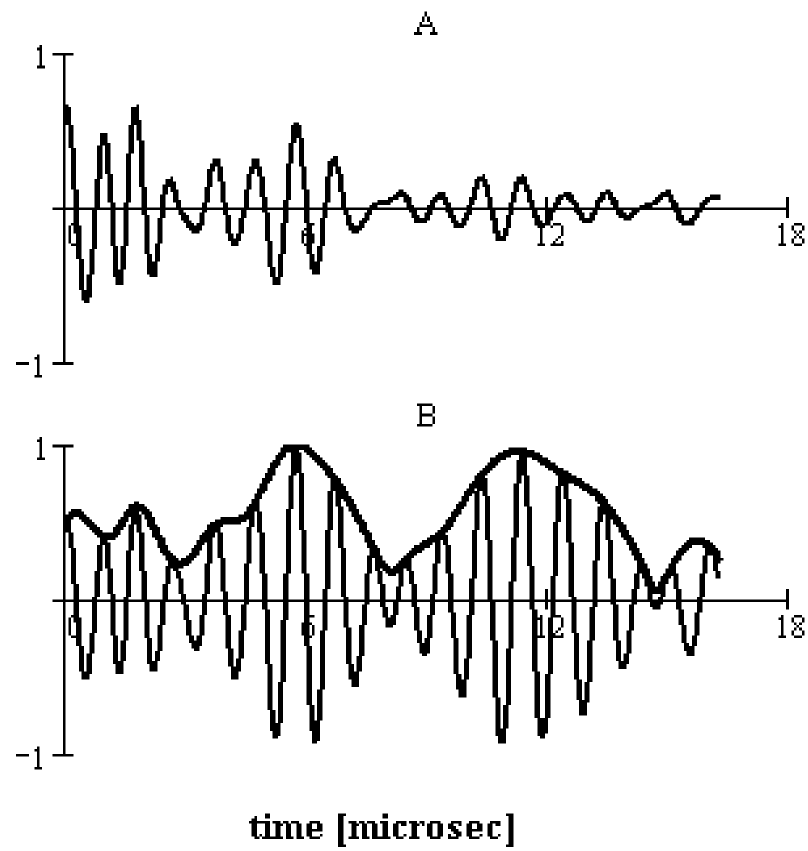

Fig. 5 The RF signals scattered in trabecular structure of the heel bone. A – original signal, B – signal compensated for attenuation together with the signal envelope

D. *Results of Measurements of Cancellous Bone Properties.*

The specimens of bones were characterized by the average values of BUA coefficient (1 - BUA=16 $dBMHz^{-1}cm^{-1}$; 2 - BUA=21 $dBMHz^{-1}cm^{-1}$; 3 - BUA= 12 $dBMHz^{-1}cm^{-1}$). The measured data reflect differences in spatial density of trabeculae or their thickness (or the both parameters at the same time).

The measured backscattered signals were corrected by applying attenuation compensation. Next their envelopes were determined. All the signals taken for the particular specimen were used to determine statistical parameters of the specimen. The values of MSR calculated for individual specimens (1 – MSR =1.92, 2 – MSR =1.93 and 3 – MSR =1.70) suggest that for the bones with rather high density of the trabecular structure (given by high values of the BUA parameter), distributions of amplitudes for the backscattered signals are very close to the Rayleigh distribution. The results support Wear's findings [21]. In the case of the sample with the lowest value of the BUA, deviation from the Rayleigh distribution can be noticed and the difference amounts to 11% of MSR value. The value of the BUA parameter for that specimen (12 $dBMHz^{-1}cm^{-1}$) is not very low, indicating that the spatial density of trabeculae for this sample is relatively high. These results suggest that the deviations of the amplitude distribution from the Rayleigh model may result from the bone structure alteration, rather than from a low number of trabeculae within the resolution cell.

4. CONCLUSIONS

The results of measurements indicate that for trabecular structures that can be regarded as nonpathological (high values of BUA), the amplitude of backscattered signal is Rayleigh-distributed. Departure from the Rayleigh distribution (MSR=1.70) was found for the backscattered signal amplitude, recorded for the bone specimen with the lowest BUA factor. This specimen was taken from the oldest donor (80 y), and one can assume that trabecular structure of the bone was substantially deteriorated at least due to the age.

The performed simulations have revealed that the variable trabecula thickness in structure of cancellous bone is the main reason for the decrease of the MSR value calculated for amplitudes of backscattered signals. Mechanical properties of the tissue constituting the trabeculae and the spread of these parameters have no impact on the statistics of the backscattered signal amplitude. The backscattered coefficient of trabecula significantly depends on trabecula thickness. Thus, the considerable spread of thickness values represent a primary reason for significant variation of backscattered coefficient values. Eventually, the volume of measurements comprises a number of constituents that variably affect the final result of backscattered echoes addition, which leads to formation of instantaneous amplitude values. The number of constituents essentially contributing to the final signal (trabecula with large thickness, defining the effective number of scattering centres) is lower than the total number of the constituents within the resolution cell. Backscattered signals that are produced under such conditions present substantially increased variance of their amplitudes, which leads to decrease of the MSR factor and departures of the amplitude histograms from the Rayleigh model.

The method proposed in this article utilizes the information about structural properties of bone. The MSR factor for backscattered signal envelopes is insensitive to bone density, expressed as mean trabecula thickness or density of the bone tissue. The usefulness of presented approach has to be verified experimentally. If confirmed, the MSR value could be used to differentiate between the bone structures with well-defined trabecula thickness and the structures with diffuse values of trabecula dimensions.

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