Bones characterization with ultrasound

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Introduction

Most of the publications concerning ultrasonic bone investigations describe the experiments performed in transmission mode. Also, the commercially available ultrasonic densitometers utilize the signals transmitted through the bone. Two acoustic properties of a trabecular bone are measured. The slope of the frequency-depended attenuation is known as broadband ultrasonic attenuation (BUA) and speed of sound (SOS). Usually, the measurements are performed on a heel bone - calcaneus. This bone is well suited for ultrasonic investigations. It is composed mainly of a trabecular bone and it is easily accessible. The thickness of the cortical shell and overlying soft tissue is relatively low and the shape of the bone assures good penetration of ultrasound. Acoustic results were often verified by comparing the bone mineral density - BMD (g/cm^2) assessed by X-ray densitometry. It was shown, that the bone density can be measured by ultrasound as well as with X-rays and that the bone fracture risk of elderly women can be predicted based on ultrasonic results.

In our approach we were searching for new indicators of trabecular bone properties. Two of them, the shift of an amplitude spectrum of a transmitted wave and a TSC (Trabecular Structure Cross section) function were found to be good candidates for further study.

Instrumentation

We built a system for in vivo heel examination. The system consisting of a pair of wideband, flat, composite transducers (diameter = 25mm) was operating at a central frequency equal to 0.58 MHz.

Transducers were mounted in small tanks filled with water. The wall of the tank opposite to the transducer face was made of a thin latex membrane. The foot under examination was placed between the tanks. By positioning the acoustic heads (1mm step) the area of measurement could be selected. Then, by increasing the pressure in the tanks, the heel was surrounded by a " water balloon", which fits the foot shape. Good transmission at the skin/rubber interface was assured by applying ultrasonic coupling gel.

The transmitting/receiving system was driven by a computer. The transmitter was developed in our laboratory. It generated the burst-like signal of a one period duration at the center frequency of 0.5 MHz and peak-to-peak amplitude of 100V. The pulse repetition rate was equal to 1kHz. Signals from the receiving transducer were amplified by a wide band receiver (0.1MHz - 1MHz) and were next captured by an A/D converter (12 bit, 20 MHz). Up to 32 successive echoes were averaged and stored in the computer for further processing. In order to assure the shortest possible ultrasonic pulse (the wide band transmission) a set of transmitting-receiving transducers was carefully designed. A great effort was put into eliminating any spurious reflections coming from the backing of a transducer, which could disturb scattered waves. Both transducers could operate in transmission and receiving modes.

The following set of data was collected for each patient: 1° The reference signal, which is a signal transmitted through water only, 2° the signal transmitted through the heel, 3° the signal reflected from the heel, and 4° the signal scattered from the selected heel area, corresponding to the position of trabecular bone.

The transmitted signals were used for BUA, shift of the spectrum and velocity evaluation. The reflected signal allowed us to select the trabecular bone area. The scattered signal was used for trabecular structure cross-section function determination.

Measurements

The ultrasonic measurements were performed on two groups of patients of the Warsaw Osteoporosis Center (Warsaw, Poland). The approval of Local Ethical Review Board was obtained prior to the measurements. Always, the left heel was examined. For the first group (32 women, age 46-84) the transmitted ultrasonic signals were recorded. The second group (54 women, age 35-88) was examined with backscattered waves. Recorded signals were processed according to the described procedures and the BUA coefficient, shift of the signal spectrum and TSC function were calculated.

For the both groups the left hip BMD was measured using a Hologic QDR-4500A apparatus. The BMD values were compared with the ultrasonic results.

Pearson's correlation coefficient and probability p-value, which describe the significance of the correlation, were used to assess the dependences between ultrasonic bone status indicators and BMD.

Transmission mode - attenuation study

Signals transmitted through the water and through the heel were used to calculate the frequency-dependent attenuation and a shift of signal spectrum. The ratio of amplitude spectrum of a signal transmitted through bone and through water determines the attenuation. The slope of the attenuation curve for a given frequency range defines the BUA. Attenuation is given in dB instead of dB/m because it is measured for a whole heel and not for a unit length of tissue. BUA values were calculated for all transmission data and these coefficients were correlated with bone mineral density.

Transmission mode - frequency "shift" study

The frequency-dependent attenuation influences the spectrum of transmitted pulses. Since the higher frequencies in the spectrum are more attenuated than the lower ones, the spectrum moves to the lower frequencies. We found it interesting to determine the shift of the frequency of the spectrum (Δf) for the signal transmitted through the trabecular bone and through the water only. Values of the frequency shift were correlated with spine and hip BMD.

Reflection mode study

In transmission mode the generated wave amplitude – $U_0(f)$ is subjected to reflections at water-tissue and tissue-cortical bone interfaces and to attenuation. In backscattering mode the received waves are additionally reflected by trabecular structure and the amplitude of the reflection depends on a local backscattering coefficient - $R(f)$. Assuming the same overall transmission coefficient at the water-tissue-bone interface for both sides of a heel, the transmitted -$U_T(f)$ and backscattered in a bone center -$U_R(f)$ signals amplitudes can be described in the following way: $U_R(f)=U_T(f)*R(f)$

For U_R collected from the middle of the bone, the ratio U_R/U_T yields R. Comparing the amplitude spectra of transmitted and scattered signals the frequency dependence of $R(f)$ is obtained (TSC-Trabecular Structure Cross section function – integrated $R(f)$).

The spectrum of a back-scattered signal contains many random peaks and valleys and it cannot be used directly for TSC function calculation. Instead we have used the following averaging method to smooth out the spectrum. First the part of the signal corresponding to trabecular bone was selected. Then it was divided (multiplied by semi- Gaussian window) into 16 partly overlapping sections, each 6 μs long. The length of the section was equal to the length of a transmitted pulls while the number of sections was limited by the thickness of a trabecular part of a heel bone. For each section the amplitude spectrum was calculated. Using BUA coefficient, the spectra were compensated for attenuation changes resulting from the shift of the section from the middle of the bone. Finally, the averaged spectrum was calculated and compared with the transmission wave spectrum yielding the TSC function. The TSC function was divided into several frequency ranges. Next the integrals of TSC over several frequency ranges were calculated giving numerical values (ITSC). ITSC coefficients were correlated with BMD data and BUA coefficients.

Conclusions

The ultrasonic results correlated with hip and spine BMD values are summarized in Tab 1. We must stress at the beginning that a limited number of cases allows us to state only a weak hypothesis and conclusions.

	BUA	**Δf**	**ITSC 0.6 - 0.7 MHz**
BMD -hip	**corr =0.66 p = 0.005**	**corr =0.75 p =0.0008**	**corr =0.64 $p=10^{-5}$**
BUA		**corr = 0.96 $p = 10^{-5}$**	**corr =0.75 $p=10^{-6}$**

Tab.1 Pearson correlation coefficients (corr) and probability value (p) for ultrasonic and BMD measurements results.

BUA was calculated over the 0.3 MHz - 0.7 MHz frequency range. A moderate correlation with BUA was obtained (corr = 0.66, p = 0.005 for hip BMD). On examining the results, we have found for some attenuation-frequency curves serious deviations from linear dependence on frequency. In these cases, BUA that is a slope of a linear regression curve does not describe properly the attenuation. In our opinion a positioning error causes such behavior of the attenuation-frequency curve.

The mean frequency shift Δf was found to be better correlated with BMD than BUA (corr= -0.75, p =0.0008 for hip BMD). These two indicators BUA and shift Δf, are strongly correlated (corr = 0.96) because they describe the same phenomenon. We believe that BUA and Δf can be used with the same efficiency but our results show that the mean frequency estimation was more robust to positioning errors when the flat transducers are used.

The TSC function found from the backscattered signal was increasing rapidly at higher frequency (0.6MHz-0.7MHz) and the best correlation of integrated TSC was found for integration over this frequency range (corr = 0.64, $p=10^{-5}$). We believe that the backscattered energy depends on bone micro architecture and describes the trabecular bone connectivity. The total bone mass increases with a number of trabeculae and/or with the single trabecula thickness increase. That explains the correlation of scattering with BMD. On the other hand, the micro architecture of the bone can also change to some extent without mass variation. The moderate correlation of integrated TSC with BUA (corr = 0.75, $p = 10^{-6}$) suggests that the bone-transmitted wave interaction and the bone-backscattered wave interaction are due to slightly different properties of the trabecular bone.

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