Bone scanner for examination
of deeply located trabecular bones

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Abstract – **The ultrasonic scanner dedicated for acquiring the RF echoes, backscattered from the trabecular bone, was developed. The device is based on the concept of minimizing of electronics and computations executed solely in the main computer processor and the graphics card. The electronic module of encoder-digitizer – executing all the transmission and reception functions – is based on a single low-cost FPGA chip. The scanner is equipped with the mechanical sector scan probe with a concave transducer with 50 mm focal length, center frequency of 1.5 MHz and 60 % bandwidth at – 6 dB. The example of femoral neck bone examination shows that the scanner can provide ultrasonic data from deeply located bones with the ultrasound penetrating the trabecular bone up to the depth of 20 mm. It was also presented that the RF echo-data acquired with the scanner allow for the estimation of sound attenuation in trabecular bone.**

I. INTRODUCTION

Osteoporosis induced by aging and as a side effect of certain drugs is a serious public health problem. It is a skeletal system disease characterized by low bone mass and architectural deterioration of trabecular bone structure. In consequence the bone fragility and a susceptibility to fracture increases. The lack of adequate means for early detection of bone deterioration is the most critical issue in the problem of diagnosing and monitoring osteoporosis therapy in general and in minimization of side effects of pharmaceutical treatment on skeletal system.

"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 (nBUA - normalized Broadband Ultrasound Attenuation) well correlated with bone mineral density (BMD), that in turn is an important predictor of fracture risk. However, the applicability of transmission techniques for *in vivo* measurements is limited to peripheral bones, in practice to calcaneus. Also, the evaluation of bone strength requires not only the knowledge of its density but also of its microscopic structure.

The analysis of ultrasonic echoes scattered on the soft tissues have been successfully applied for tissue characterization [1, 2]. Similarly, the trabecular bone backscatter contains information about the properties of the bone structure. 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. Moreover,

the scattering techniques enables acquiring the ultrasonic data from the bones located deep in the body. An overview of technological development applied to assess bone strength *in vivo*, including investigations of trabecular and cortical bone, and use of transverse transmission, axial transmission as well as reflection techniques, was published by Laugier [3].

The femoral neck bone fracture often occurs in osteoporosis and leads to severe complications. Therefore, assessment of femoral bone microstructure and condition is important and essential for the osteoporosis diagnosis and treatment monitoring. Up to now the *in vivo* measurements of a proximal femur were carried out only in transmission [4].

We have developed the ultrasonic scanner dedicated for acquiring the RF echoes, backscattered from the trabecular bone *in vivo*. Moreover, the bone scanner provides data not only from calcaneal bone but from the deeply located bones e.g. femoral neck. The B-scan image of the investigated structure is displayed facilitating the bone location and proper adjustment of the receiver gain. Light and easy to manipulate scanner probe allows the operator for recording the ultrasonic signals from the optimal projection. The applicability of the scanner for the data acquisition from trabecular bones was validated in *in vivo* experiment [5].

II. MATERIALS AND METHODS

A. Bone scanner hardware

The discussed scanner is designed for the trabecular bone examination and is the modified version of previously developed a high-frequency µScan device operating at 30 MHz frequency and dedicated for skin lesions visualization [6]. The attenuation of ultrasound in the trabecular bone is much higher than in the soft tissue. Therefore, the probing frequency is in the range of 1 MHz, and consequently the sampling frequency was reduced from 200 MHz down to 20 MHz. In our case the useable frequency was centered around 1.3 MHz. An analog input low-noise amplifier, a variable gain amplifier and a linear gain power output amplifier were optimized for 0.5–3.0 MHz range and mounted on a separate analog module.

The device is based on the concept of minimizing the custom electronics hardware moving the computation to the PC main processor and the graphics card. The electronic module of encoder-digitizer (Fig. 1), executing all the transmission and reception functions, is based on a single low-cost FPGA chip (Xilinx® Spartan 3 XC3S200).
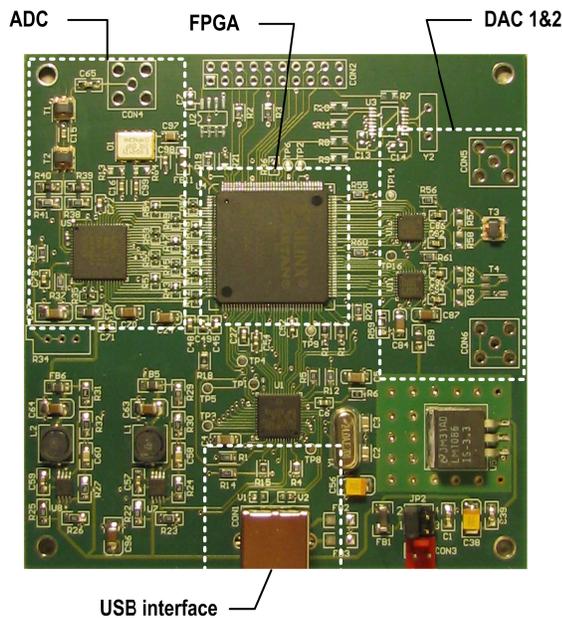
Fig. 1. The encoder-digitizer board photo of size 90 mm x 90 mm.

The transmission involves the use an arbitrary waveform generator with a 14-bit DAC operating at 20 MSPS speed. The acquisition is performed using a 12-bit ADC also working at 20 MSPS. The digital RF echo signal is transmitted to PC via USB 2.0 interface.

The analog section (Fig. 2) was designed using discrete parts as a separate module. The analog gain has two stages of adjustment: main gain control and Time-Gain Compensation. Linearity of the analog chain is crucial for the reliable determination of the frequency dependent attenuation coefficient. The output signal from the receiver was measured for the input signal with the fixed amplitude but varying frequency. At the frequency range 0.5–3.0 MHz the gain variation of frequency is less than 1 dB while for the range 1.0–1.5 MHz (the frequency range of attenuation measurement) the scanner gain is almost constant (0.3 dB variation). The TGC is controlled by an arbitrary waveform generator, built using a 14-bit DAC. The effective gain (up to 80 dB) results from the sum of the main gain setting and the actual value of the TGC varying with depth. The gain and the values of the TGC were calibrated (in dB) in order to allow recovery of the absolute value of ultrasonic echoes, which is necessary for the applied algorithms of the attenuation estimation. The encoder-digitizer module enables the encoded excitation by the arbitrary transmit signal generator and the linear power amplifier. The implemented function of the FPGA supports also the transmission of a sequence of two codes (e.g. Golay codes). The time compression algorithm of codes was implemented in the software.

B. Signal processing of the ultrasound echoes

Typical diagnostic medical ultrasound devices utilize waves at the frequency of 1–15 MHz. The transmitted ultrasonic wave, mainly in the form of a train of short pulses, propagates in the tissue and is reflected from the tissue inhomogeneities. The received echoes are initially amplified and filtered in an
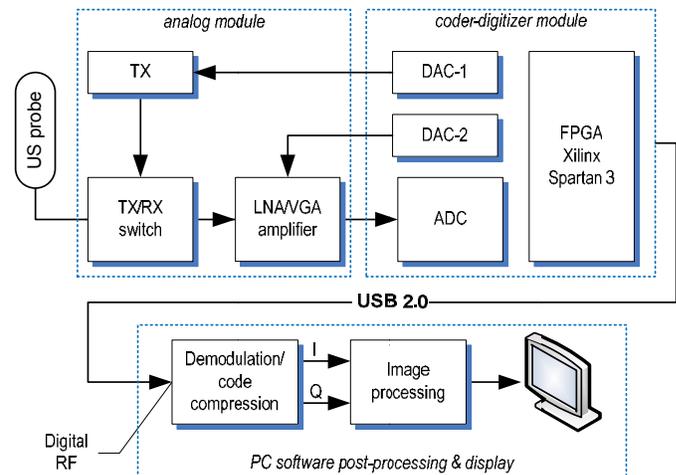

Fig. 2. Block diagram of the encoder-digitizer module.

analog circuitry. Afterwards, they are digitized using ADC usually with 12 bit of resolution. The received high frequency echoes are the amplitude and phase modulated carrier frequency signals. Afterwards these signals are demodulated and shifted down to the baseband frequency. The demodulated echo signals are further processed depending on the application.

In our scanner all digital RF signal processing functions were implemented in the software domain and distributed between the CPU of the PC and the graphic card processor (GPU) based on their specificity. On the CPU side the Intel® Integrated Performance Primitives library was used for the implementation of digital signal processing functions. The sector geometry conversion function is required to obtain a correct display of an image, generated by the sector probe, and it is executed by a graphics processor. Direct access and real-time processing of the raw RF ultrasonic echoes enable implementation of various parametric imaging algorithms.

The speed of the RF signal processing allows for the real-time imaging at the frame rate up to 10 images/s (limited by USB transfer issues) both in the standard burst transmission and in the encoded transmission mode. For example in the case of Golay coding it requires two complementary sequences transmitted per scan line and an additional time for compression. The software enables saving the data files with B-mode image and the raw RF data, as well as the TGC curve. Further these data sets can be post-processed in the Matlab®/Mathcad® environment.

C. Ultrasonic probe

The scanner was equipped with the probe with mechanically wobbling concave transducer (center frequency – 1.5 MHz, focal length – 50 mm, diameter – 16 mm, 60 % bandwidth at – 6 dB) producing the sector scan within ±14 deg. The probe was connected to the scanner via the 1.5 m long coaxial cable. The operating frequency could vary from 1.0 MHz to 1.7 MHz. The choice of the frequency range was a trade-off between the attenuation in bone and the size of the transducer and its backing damping. The pressure field emitted by transmitting transducer at 1.3 MHz was measured using the wideband membrane hydrophone (Sonora Medical

Systems, Longmont, CO, USA), and is shown in Fig. 3. The Mechanical Index assessed for the transmitted pulse was equal to 0.41. The probe was designed for collecting the echoes scattered from the deep bones, located approximately 35 mm beneath the body surface.

III. APPLICATION TO BONE EXAMINATION *IN VIVO*

A. Experimental procedure for deep bones examination

The experiments were carried out with the approval of Local Ethical Review Board. Bones were insonified with one period long sinusoidal signals of 1.3 MHz frequency. Five volunteers (age about 30) were examined. Data were recorded in trigonum femorale area approaching the bone though the skin, subcutaneous tissue and the muscles (iliopsoas and rectus femoris). Optimal location of the investigated bone within acoustic field is presented in Fig. 3. The system gain together with the Time Gain Compensation were carefully adjusted to obtain uniform brightness within the ROI in trabecular bone B-scan image (Fig. 4a). This procedure highly increased the dynamic range of the registered RF echoes what is presented in Fig. 5.

B. Attenuation determination from RF backscatter

The attenuation coefficient was determined using the spectral difference technique based on a comparison of the amplitude spectra of the backscattered signals recorded before and after propagation through the chosen section of the medium. As the TGC controlled gain depends on the depth, this gain must be compensated prior to the evaluation of attenuation. For each B-scan different TGC slope was used. Thus, the TGC curve for each sample of the RF-echo signal was recorded and adequate correction was performed. Next, the attenuation correction was applied according to the developed procedure. First, the selected part of the scattered echo-signal was divided into m partially overlapping segments 5 µs long and separated by $\Delta t = 4$ µs. The useful length of backscattered echoes was limited to 15–25 µs what corresponds to 11–18 mm depth in the bone. Typically, 3-4 segments were used. The RF echo in these segments was Fourier transformed. Afterwards the calculated spectra were corrected for the effect of focusing. The correction procedure, similar to the method proposed by Bigelow et al. [2]., was used. The compensation was carried out using amplitude spectra of

Fig. 4. B-scan images of femoral neck obtained with the scanning plane parallel to the bone axis with distance from the transducer and ROI marked (a). X-ray image with the projection scheme (b).

echoes obtained from a rigid plane reflector located in water at various axial distances from the source. Thus, for each component of the spectrum the variation of its amplitude with the distance from the focus was assessed and the appropriate correcting function was calculated. Afterwards, the partial attenuation coefficients $\alpha_i(f)$ (coefficients obtained with two adjacent windows) were estimated from the log-ratio of both corrected spectra. Next, the $\alpha_i(f)$ coefficients were averaged over all m segments, and finally the averaging was also performed over all considered echo lines (40–50) yielding the averaged, frequency depended attenuation $\alpha(f)$ of the examined bone (Fig. 6).

Fig. 5. Example of raw RF signal (solid line) from ROI (Fig. 4a) with applied TGC correction curve (dashed line) (a). The same line compensated from TGC (b). A – cortical bone reflection, B – trabecular bone scattering.
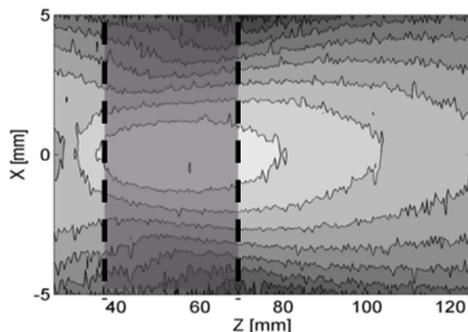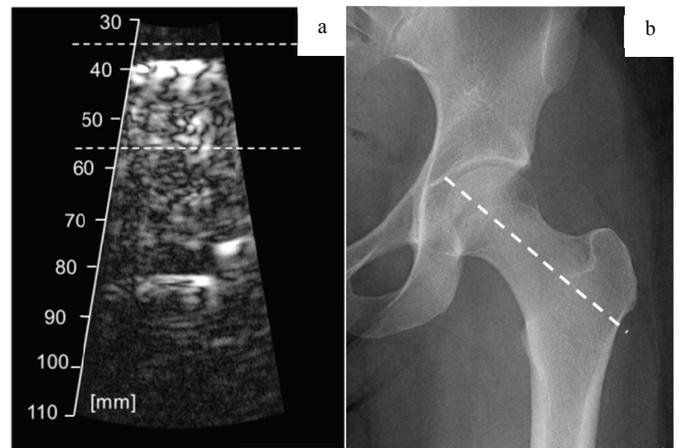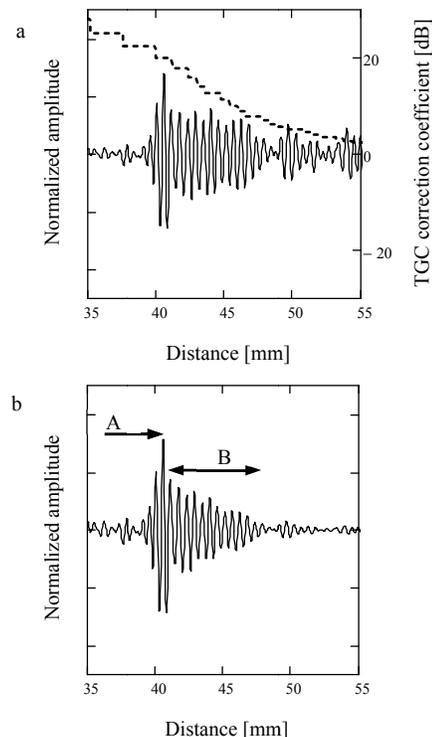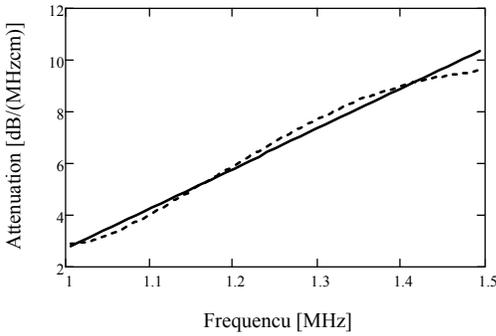
Fig. 3. The pressure field emitted by the transducer with a sine pulse excitation (isobars separated by 2 dB steps). Optimal location of bone is limited by dashed lines. z denotes distance from the transducer.

Fig. 6. Example of frequency dependent attenuation α(f) measured in femoral neck (dashed line) is plotted together with linear regression approximation (solid line). Attenuation coefficient = 15.5dB/(MHz·cm).

IV. RESULTS

The experimental measurements showed that the scanner could be used for collecting the backscatter from the trabecular bones located deep in the body. Mean nBUA values obtained from *in vivo* measurements of femoral neck for each volunteer are presented in Table I together with the standard deviation (SD). They were derived from the four successive examinations of each investigated bone.

V. DISCUSSION AND CONCLUSIONS

The novel versatile ultrasonic scanner, dedicated for the study of bones, was developed. The scanner enables the *in vivo* acquisition of the RF echoes from the trabecular bone. The B-scan image, accompanying the acquired RF data proved, to be useful in determination of the bone location as well as the gain setting. The TGC gain curve is recorded together with ultrasonic data allowing the post recovery of the absolute magnitude of RF echoes.

The experimental measurements carried out in the femoral neck have shown that the scanner is useful for collecting the backscatter from the trabecular bone located deep in the body. It was proved that RF echo-data can be applied for the trabecular bone properties assessment. Results are in the range of nBUA determined *in vitro* for femoral bone using the transmission technique [7]. Rather high standard deviation is probably caused by the difficulty in localizing the very same volume of tissue for each measurement.

There are some intrinsic difficulties of scattering measurements in trabecular bone [8]. The impedance mismatch between the trabeculae and surrounding bone marrow is high, resulting in strong scattering of the ultrasound and considerable variability of the echoes magnitude. Additionally, at the frequency in the range of 1.0 MHz high ultrasound attenuation limits the depth of the wave penetration into the bone and the useful backscattered signal is relatively short (15-25 µs). The applied averaging procedures cannot efficiently reduce the stochastic nature of the signal spectrum what results in some randomness of the calculated attenuation coefficients. It is appropriate to note that attenuation coefficients measured in the transmission mode are also often overestimated due to the effects of the phase cancellation on

TABLE I
nBUA OBTAINED FROM IN VIVO MEASUREMENTS
OF FEMORAL NECK TRABECULAR BONE

Volunteer	nBUA [dB·cm⁻¹·MHz⁻¹]					
	Left leg			Right leg		
	Mean	SD	Min-Max	Mean	SD	Min-Max
1	5.6	2.2	3.2 – 9.0	6.7	1.7	3.9 – 8.0
2	11.9	6.2	5.3 – 19.5	8.6	2.1	5.0 – 10.4
3	20.0	6.1	10.3 – 26.8	13.3	3.1	9.7 – 17.3
4	9.4	2.1	7.0 – 12.4	13.4	1.1	11.6 – 14.6
5	10.3	3.1	6.8 – 15.2	12.7	3.0	8.6 – 17.0

the receiving transducer. In the case of deep bones, the ultrasonic wave travels relatively long distance in the soft tissue and is strongly reflected and refracted by cortical bone that is much more irregular than the calcaneal bone surface. Interaction between the ultrasound and the soft and hard tissue introduces pulse spectrum variation that should be considered in attenuation calculation.

An issue of reliable determination of the bone attenuation from the ultrasonic backscatter requires more theoretical and experimental investigations. That was beyond the scope of this study. In this work, the scanner that can provide *in vivo* ultrasonic data from deeply located trabecular bones was described. These data will be beneficial in developing the processing techniques designed for the estimation of attenuation, thus improving the accuracy of assessing the bone properties.

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