SOFT TISSUE-MIMICKING MATERIALS WITH VARIOUS NUMBER OF SCATTERERS AND THEIR ACOUSTICAL CHARACTERISTICS

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For the study of the temperature increase in the soft tissues irradiated by a low-power ultrasound [1], soft tissue-mimicking materials can be used. The phantoms have been produced based on an aqueous solution of agar, oil, and glass beads microparticles. The RF signals collected in the experiments enabled evaluation of the acoustic properties of phantoms with different number of strong scatterers (concentration varied from 0 to 30 pcs/mm^3). Speed of sound (SOS) determined for the phantoms was similar to the value typical of soft tissue (about 1540 m/s). To determine attenuation coefficient the semi-transmission method has been used. Attenuation coefficient value varied from 0.5 to 1.1 dB/(MHz cm), depending on the number of scatterers. It was shown that the phantoms stored for 6 months preserved their acoustical properties and were usable for further experiments. It was found that within the total attenuation, the part corresponding to scattering can be distinguished.

INTRODUCTION

To design the hyperthermia medical procedures, precise identification of all phenomena occurring during irradiation is required and the relationship between the parameters of transmitted ultrasonic pulse and its effects on the tissue must be studied and considered in great detail. The opportunity of non-invasive monitoring of treatment providing the control of local tissue temperature *in situ* enables the development of number of various types of therapies and diagnostic methods.

Experimental studies on the rate of temperature increase of soft tissue *in vitro* under irradiation with a low-power beam are carried out in the Ultrasound Division IFTR, [1, 2]. The temperature was measured with thermocouples. The RF signals were collected during the heating process. Since it was not possible to repeat the heating experiment on the same sample of soft tissue (beef liver was used), soft tissue-mimicking materials with designed scattering characteristics were prepared. Created tissue-mimicking materials are intended for the experiments concerning the influence of temperature increase on the received ultrasonic signals.

1. SOFT TISSUE-MIMICKING MATERIALS

The main requirements for the soft tissue phantom is its similarity to living tissue in terms of acoustic properties: density of about 1.0 g/cm^3, the speed of sound about 1540 m/s, linear dependence on frequency of the attenuation and attenuation coefficient value of about 0.5 dB/(cm MHz), backscattering coefficient the order of 10^{-5} – 10^{-2} MHz in the frequency range from 2 to 7 MHz, and the acoustic impedance 1.5^6 – 1.75^6 kg/(m^{2}s).

1.1. PRODUCTION OF SOFT TISSUE-MIMICKING MATERIALS

Since the phantoms are intended for the experiments performed in the temperature range from 37 ^{o}C up to 50 ^{o}C, it is necessary to use the components characterized by melting temperature higher than 50 ^{o}C. Agar has a higher melting point in comparison to gelatin. Moreover it exhibits temperature hysteresis: melting point at 85 - 90 ^{o}C whereas solidification point at 32 – 50 ^{o}C. This quality provides the gel stability at relatively high temperatures. For this work soft tissue phantoms were produced following one of the recipes proposed by Madsen [3]. To prepare the phantom, the suspension prepared of 1 liter of deionized water at room temperature and 154 g of agar was stirred and heated in a water container at 90 °C, to dissolve the agar powder completely and to obtain clear solution. In order to increase the attenuation and scattering of the ultrasonic wave in the phantoms glass microparticles were added (model 59200-U, Supelco, Bellefonte, PA, USA, diameter r=75±5μm). Table 1 presents glass beads material properties.

Tab.1. Material properties of the glass beads.

Material	Diameter	Density	Speed of sound
Glass	75±5 μm	3000 kg/m^3	5300 m/s

The Phantom A consisted only of a mixture of oil, agar; the phantoms B and C differ in the number of glass beads (see Tab. 2), which are uniformly distributed. The concentration of scatterers in patterns B and C were determined by the following formula:

$$N = \frac{m}{\frac{4}{3}\pi r^3 \rho V}, \quad (1)$$

where m is the mass of glass beads in the mixture, which occupies a volume V.

Tab.2. Phantoms A, B and C description.

Phantom	Glass beads concentration [psc/mm^3]	Glass beads volume fraction [%]
A	0	0
B	6	0.13
C	30	0.66

Fig. 1 presents a picture of Phantom A without glass scatterers and Phantom C with is clearly visible scatterers.

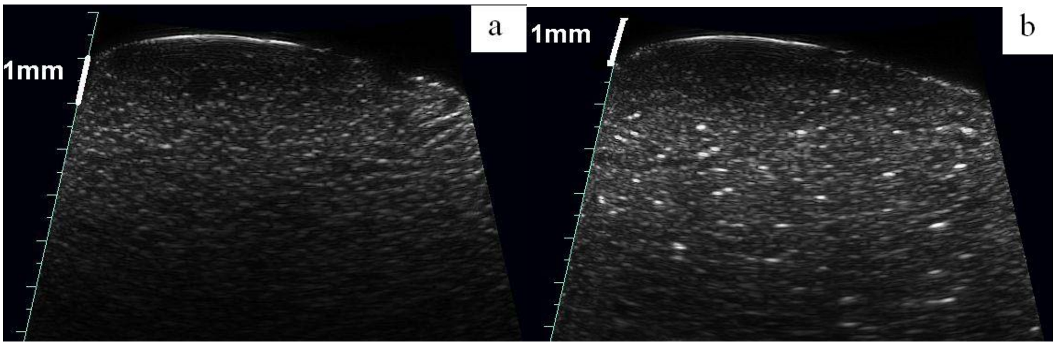

Fig.1. Picture (7mmx7mm) taken by ultrasound imaging system with high resolution probe of 30 MHz central frequency: a) Phantom A - without glass beads, b) Phantom C - containing beads.

2. ULTRASOUND PROPERTIES OF SOFT TISSUE-MIMICKING MATERIALS

The tissue-mimicking materials have been tested regarding ultrasonic properties: speed of sound (SOS), attenuation coefficient (α) and backscattering coefficient (η). The data for determining the acoustic parameters of phantoms A, B and C were collected three times within 6 months with an interval of 3 months.

For the generation and reception of ultrasonic pulses the transmitter-receiver JSR Ultrasonics DPR 300 Pulser/Receiver was used and Imasonic head (center frequency 6MHz, diameter 9 mm, the focal length 62 mm). The received RF signals were recorded with oscilloscope (Agilent Technologies type DS09104A).

2. 1. SPEED OF SOUND

The speed of sound for each phantom was determined by semi-transmission method. The results are shown in Tab. 3. It can be concluded that the amount of glass beads did not significantly affect the speed of sound in the phantoms it is similar to the average value of the soft tissue (1540 m/s).

Tab.3. Average speed of sound of the phantoms during six months.

Measurement		Average speed of sound, [m/s]		
		Phantom A	Phantom B	Phantom C
1	Within a week from preparation	1529	1541	1521
2	Within 3 months from preparation	1536	1545	1540
3	Within 6 months from preparation	1551	1562	1555

2. 2. ATTENUATION COEFFICIENT

The attenuation coefficient was determined by semi-transmission method. The frequency dependent attenuation $\alpha(f)$ was calculated following the formula:

$$\alpha(f) = \frac{-10}{\Delta z} \log_{10}\left[\frac{B(f)}{A(f)}\right], \qquad (2)$$

where $A(f)$- the amplitude spectrum of the signal obtained after propagating through the phantom submerged in water, and $B(f)$- the amplitude spectrum of the reference signal.

Comparison of the amplitude of the reflected signal from the reflector is shown in Fig.2. Dependence of the attenuation vs. frequency obtained with the formula (2) is shown in Fig. 3. (dashed line) and it is approximated by linear regression (solid line). Attenuation coefficient is determined as a slope of the linear-fit.

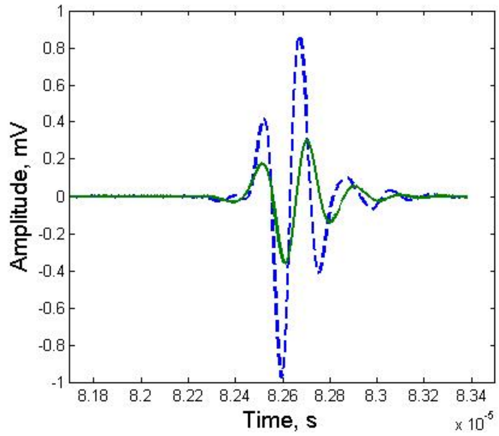

Fig.2. The recorded echo-signal after propagating along the same distance: (solid line) demineralized water and Phantom A in propagation path, (dashed line) only demineralized water in propagation path.

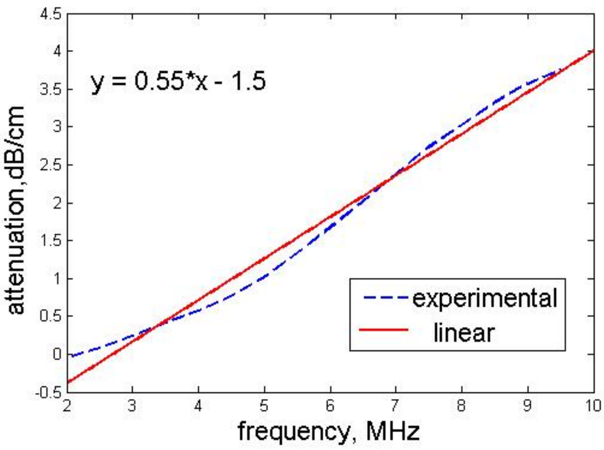

Fig.3. Determined from the experiment dependence of attenuation vs. frequency for phantom A (dashed line) and linear regression fit (solid line).

Tab.4. Attenuation coefficient of the phantoms during six months.

Measurement		Attenuation [dB/(cm MHz)]		
		Phantom A	Phantom B	Phantom C
1	Within a week from preparation	0.50	0.70	1.1
2	Within 3 months from preparation	0.54	0.74	1.1
3	Within 6 months from preparation	0.55	0.75	1.3

2. 3. BACKSCATTERING COEFFICIENT

Backscattering coefficient was determined following the equation proposed by O'Donnell and Miller [4] on the basis of prior work of Sigelman and Reid [5]:

$$\eta(f) = \frac{P_S}{P_W} D(f) A(f), \tag{3}$$

where P_S is averaged phantom power spectrum P_W is averaged reference power spectrum. $D(f)$ describes diffraction compensation and $A(f)$ attenuation compensation.

Diffraction compensation was calculated with the equation by Ueda and Ozawa [6]:

$$D(f) = \frac{(kR)^2}{8\pi d\left[1 + \left(\frac{kR^2}{4Z}\right)^2\right]}, \tag{4}$$

where k is the wave number, R is the transducer radius and d is length of the applied window, Z is the distance between the transducer and the center of the window.

Compensation from attenuation was performed with O'Donnell and Miller equation [4]:

$$A(f) = e^{4a(f)x} e^{4a'(f)x'} \left[\frac{2a'(f)c_S \tau e^{a'(f)c\tau}}{e^{a'(f)c_S\tau} - e^{-a'(f)c_S\tau}}\right] \tag{5}$$

where x and x' depict water and phantom thickness respectively. Similarly $a(f)$ and $a'(f)$ are attenuation coefficients of water and phantom and c, c' depicts speed of sound in water and phantom respectively, τ is time duration of the applied window.

Since backscattering coefficient vs. frequency dependence can be approximated by the power law function, experimental data were approximated by:

$$\eta(f) = bf^n \tag{6}$$

Obtained exponents for the phantoms were: for A: n=2.78, for B: n=3.85 and for C: n= 4.14. Values for phantoms B and C close to 4, refer to scattering by sphere. But exponent value for phantom A depicts that the shape of scatterers is different from sphere and may be caused by inhomogeneities in gel resulting from oil scatterers. Determined of experiments based on the dispersion coefficient of frequency and approximating the exponential function are shown in Fig. 4.

3. STATISTICS OF BACKSCATTERED SIGNAL

After filtering the noise the RF signals from phantoms were used to determine so-called effective number of scatterers M given by the formula [7]:

$$M = \frac{2}{r^4 - 2}, \tag{7}$$

where r is the fourth moment of the distribution. Calculations proved that phantoms microstructure can be described by K-distribution. Effective number of scatterers M is the shape parameter of K-distribution.

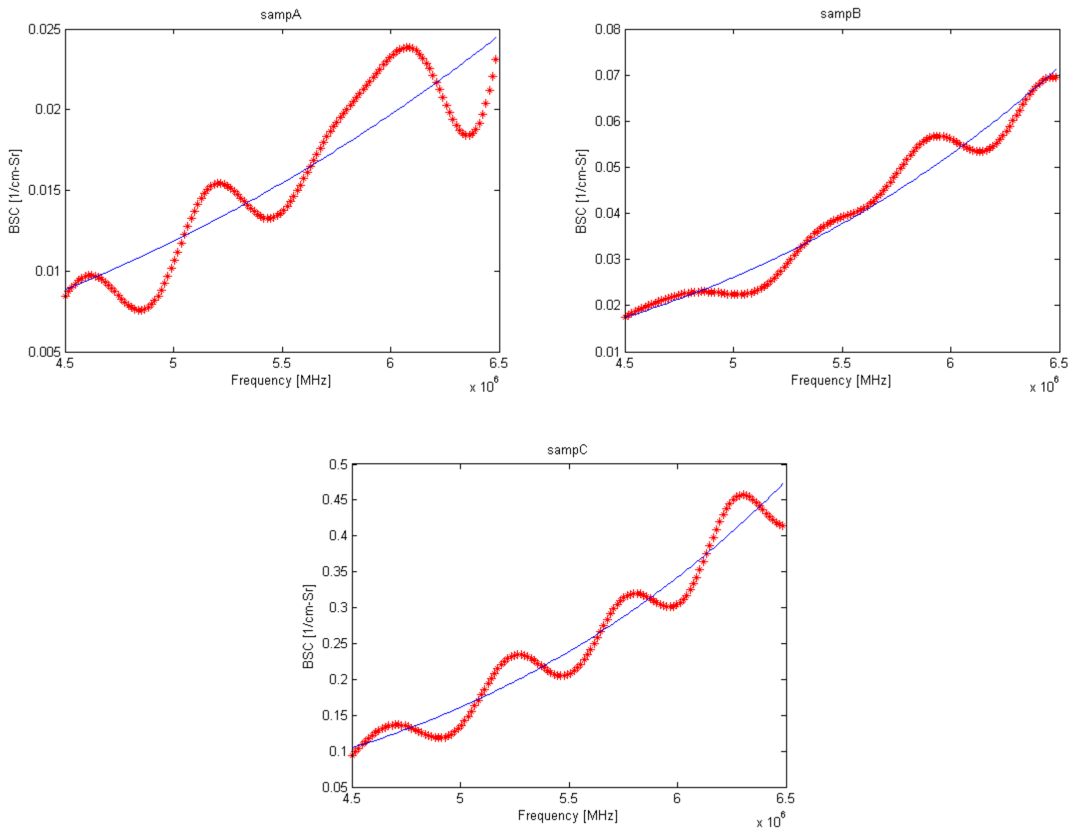

Fig.4. Experimentally determined backscattering coefficient vs. frequency (dashed line) and power law fit (solid line).

3. 1. STATISTICS AMPLITUDE ENVELOPE AND CHANGE IN THE STRUCTURE SOFT TISSUE-MIMICKING MATERIALS

Recorded RF signals for each phantom were analyzed in order to bind the statistical properties of the amplitude envelope with the changes in the structure of the medium. Calculated effective number of scatterers M=1.94, [7] for the phantom B describes the medium with a relatively small number of strong scattering objects. This number increases by two orders of magnitude for phantom A and C, what is related to the similarity of the shape of the histogram to the Rayleigh distribution. Figures 5 - 7 show the results obtained for phantoms A, B and C.

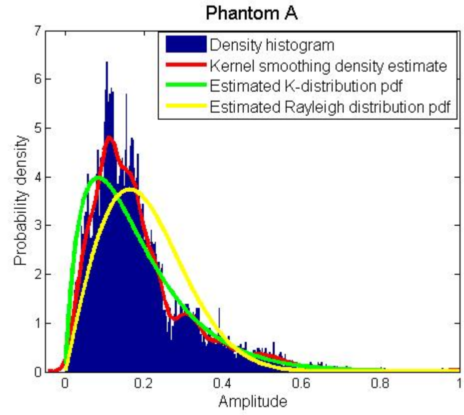

Fig.5. Phantom A, the shape parameter 1.24, the scale parameter 9.70.

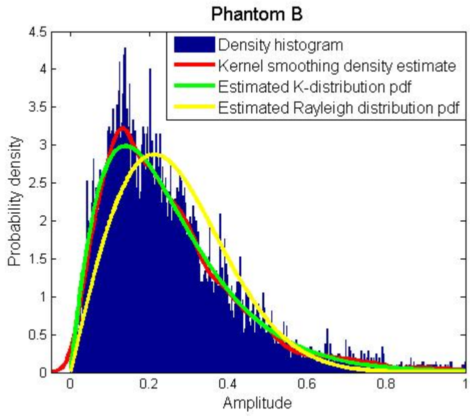

Fig.6. Phantom B, the shape parameter: 1.94, the scale parameter: 8.88.

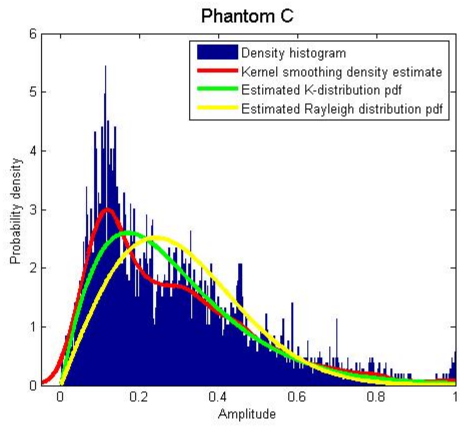

Fig.7. Phantom C, the shape parameter: 2.298, the scale parameter: 8.88.

4. RESULTS

Examined tissue phantoms have similar acoustic properties to soft tissue. Acoustic properties changes due to heating process can be used to measure the temperature of examined material. It has been observed that the attenuation increases with the number of glass beads. Parameters of K-distribution calculated for the phantoms may form the basis for differentiating materials containing various number of scatterers. Both the results summarized in Table 3, 4 and the data obtained from the statistical analysis of the amplitude envelope of the signal lead to the conclusion that the number of scatterers and their distribution are strongly correlated with the speed of sound, attenuation and scattering characteristics as determined from the distribution K.

Future work is going to be focused on correlating temperature increase with statistical characteristics changes of the signal received from the area exposed to low-power ultrasound. The further experimental work will concern measurements during heating process of tissue phantoms. Then already determined acoustic properties of various phantoms and the number of reproducible results will be large enough to enable reliability assessment of statistical methods.

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