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GENERATION AND PROPAGATION OF SHEAR WAVES IN INHOMOGENEOUS RUBBER-LIKE MEDIA

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ABSTRACT

Elasticity parameters of solid tumors are quite different from ones of the normal tissue. These inhomogeneous inclusions modified phase and amplitude of shear waves propagating in tissue. We propose to employ focused ultrasound for remote excitation of shear waves inside tissue and track them in area of interest. The excited shear waves were in a form of unipolar pulses with duration defined by time of shear wave propagation through the focal waist. Experiments were performed in tissue-like phantoms with artificial inclusions in the form of thin layer and cylinder with shear modulus several times exceeding the modulus of surrounding media. It was demonstrated that position and dimensions of the inclusions can be determined with accuracy of several percents. Shear modulus of biological tissue is modified by the HIFU procedure. In real-time lesion development can be monitored by measuring a temporal profile of the shear wave excited by the same transducer employing for HIFU. In particular, a growth of the shear modulus inside lesion results in decreasing of shear pulse duration and its peak shear displacement. It was demonstrated that temperature in the focal zone of HIFU transducer can be evaluated with accuracy of 5 degrees.

INTRODUCTION

Imagine of soft tissue elasticity for medical diagnostics is a field of interest in the past two decades. Several techniques were proposed for non-invasive measurements of shear modulus distribution inside soft tissue. In this work we employed focused ultrasound for shear wave excitation.

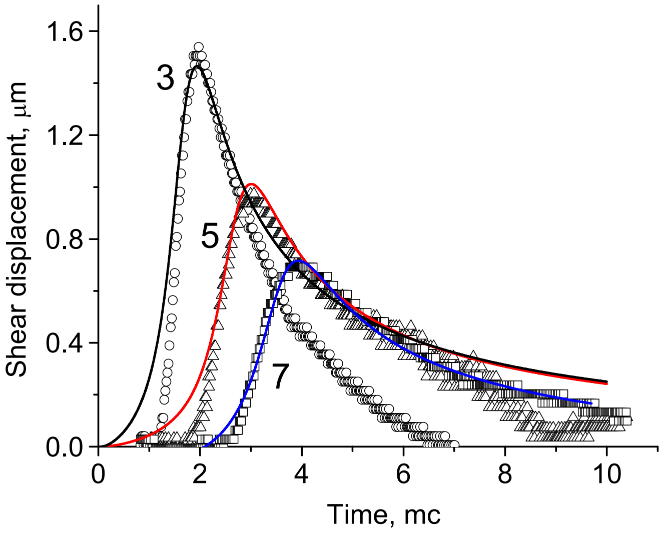


Figure 1.-Experimental profiles of shear pulses (symbols) recorded in a homogeneous sample at distances of 3, 5, and 7 mm (numbers near the curves) from the axis of the ultrasonic beam. The solid lines represent the results of calculation for a shear viscosity of 0.3 Pa s.

The temporal profile of the shear wave excited by ultrasonic pulse looks like an unipolar pulse (Fig. 1) which peak value is a function of the absorbed sound intensity, the burst duration τ_i and it is inversely proportional to the square root of the shear modulus μ_t: $u_{\max} = \frac{f(\alpha, I_0, \tau_i)}{\sqrt{\mu_t}}$, where α is the sound absorption coefficient, I_0 is the intensity of sound on the axis [1,2]. The peak of shear displacement propagates with a shear wave velocity: $c_t = \sqrt{\mu_t / \rho}$, where ρ is the density of medium. The duration of the pulse is defined by time of shear wave travelling through the focal waist. The peak displacement is reduced with travelling distance due to cylindrical divergency and attenuation resulted from the shear viscosity. The shear viscosity can be measured from the experimental profiles measured at different distances from the axis of ultrasonic beam. Measurements of a peak shear displacement and time delay of the shear wave arrival could provide information about the shear modulus distribution. The main advantage of this approach is the ability to excite shear waves remotely in different parts of soft tissue.

MATERIALS AND METHOD

An experimental setup is shown in Fig.2. Optically transparent polymer sample *3* was positioned in the focus of a 3-MHz piezoelectric transducer *1* driven with the electric pulses from the generator *2*. Both the sample and the ultrasonic transducer were placed into the tank filled with degassed water. Optical detection of the shear displacements originated due to ultrasonic pulse absorption was employed. The beam of He-Ne laser *4* was focused by the lenses on the small opaque particle embedded inside polymer sample. The photodiod *5* detected the light intensity transmitted through the sample. The digital oscilloscope Tektronix 3032 (*6*), synchronized by the burst from the generator acquired data from the photodiode. Medium motion produced by the shear wave resulted in the particle movement and corresponding variation of the photodetector current. The typical sensitivity of the detection scheme was about 100 mV/µm.

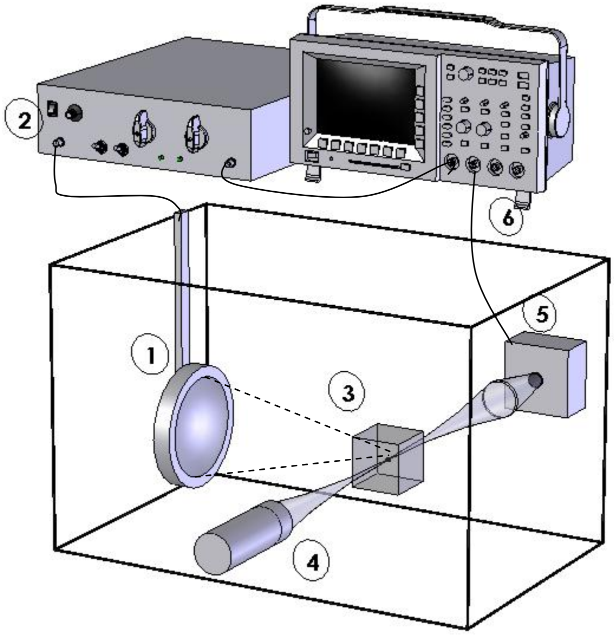
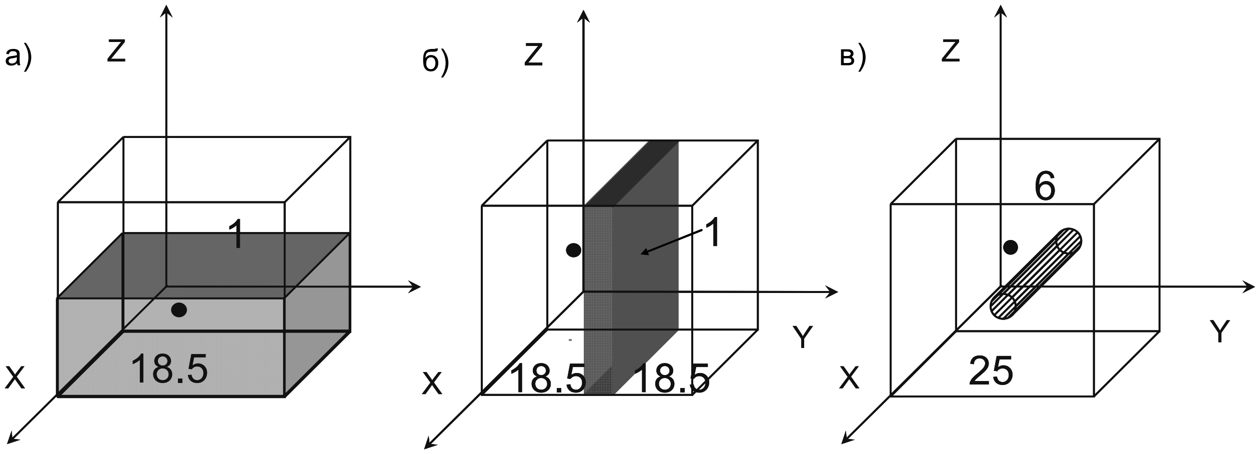


Figure 2.-Experimental setup for shear wave excitation and detection in polymer sample.

The samples were in cubic shape with 40 mm side. They were made of the rubber-like polymer (M-F Manufacturing Co., Fort Worth, USA) which shear modulus can be varied in wide range from 1 to 40 kPa. Optical transparency of the fabricated samples allowed us to employ optical registration of excited shear waves. Several kinds of phantoms were fabricated for studying of the shear wave propagation in nonhomogeneous media (Fig. 3). One of the samples was made of two identical layers with 1.0 kPa (soft layer) and 18.5 kPa (hard layer) shear moduli. In the second sample the thin soft layer with 1 kPa was embedded into the cube made of relatively hard (18.5 kPa) plastic. The third sample was made of plastic with 25 kPa shear modulus and it contained the soft cylindrical inclusion with 6 kPa shear modulus.



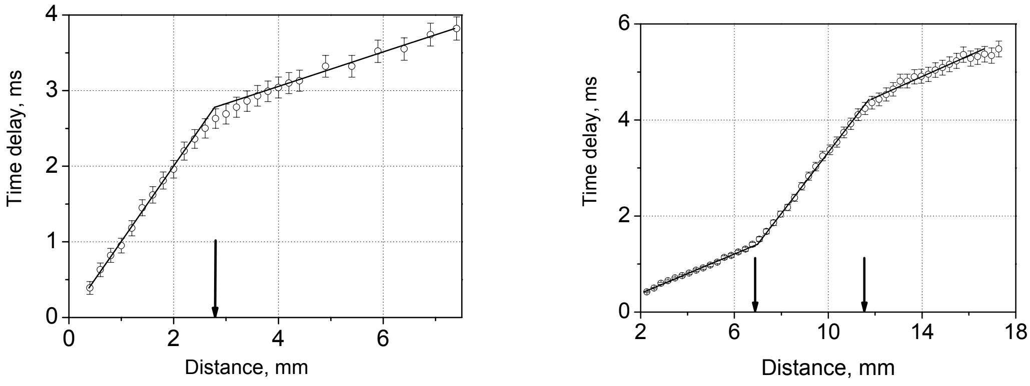
a *b* *c*

Figure 3.- The polymer samples used in experiments: with two layers (*a*), with inclusion in a form of rectangular layer (b) and the sample with cylindrical inclusion (c).The black point shows the position of opaque particle. Numbers correspond to shear modulus values in different parts of the samples.

RESULTS

Detection of shear inhomogeneities

Results of measurements are shown in Fig. 4. The opaque particle was placed in the median plane near the boundary of two layers marked by the solid line in Fig.3a.



a b

Figure 4. - Time delay of the shear wave propagated in the two-layered sample (a), in the sample with 5-mm thickness soft layer (b), and in the sample with the 5-mm cylindrical inclusion (c). Numbers on the graph (c) correspond to the shear wave velocities obtained from a linear regression of data at the particular parts of the curve. A zero at a horizontal axis corresponds to the position of opaque particle inside the sample which was used as a light shutter. The circle marks the relative position of the cylindrical inclusion.

Ultrasonic beam was directed parallel to axis Y into the hard layer. The shear wave excited with ultrasonic burst propagated in Z direction. When focus of the transducer moved from the particle the time delay of the peak shear displacement was increased. Three different parts can be distinguished in the graph depicted in Fig. 3a.

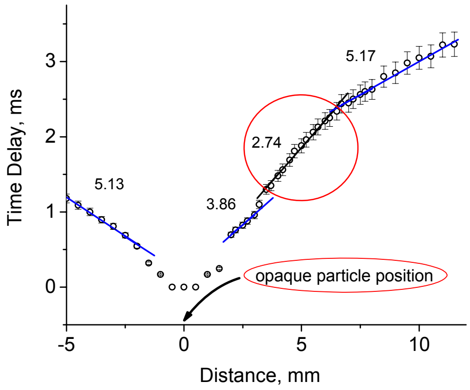


Figure 4c**.**

The first part corresponds to the shear wave propagation inside the hard layer, the second part (from 2.6 to 3.3 mm) represents the transient region with intermediate value of shear modulus, and the third part corresponds to the shear wave propagation inside the soft layer. The shear wave velocity in these particular regions can be calculated by approximating data at these particular parts by the straight lines. The calculated shear moduli were 18.5 kPa in the hard layer (18.0 kPa was obtained from static measurements), 1.0 kPa in the soft layer (1.1 kPa was obtained from static measurements), 10.5 kPa in the transient region. The transient layer was resulted due to specific technique of the sample fabrication. At the first step a hard layer was made. After that the warm liquid plastic was filled on the top of the hard layer and part of softener component diffused inside the hard layer making it softer. Detection of the transient layer demonstrates the accuracy of the proposed method for a measurement of the shear modulus spatial distribution inside rubber-like media.

In the third sample the 5-mm diameter cylindrical inclusion with 6 kPa modulus was embedded inside the plastic cube with 25 kPa modulus. The axis of inclusion was parallel to X axis and it passed through the cube middle section. The opaque particle was also located in the cube middle section at several millimeters aside the cylinder surface. The ultrasonic beam was directed along line parallel to X axis in the plane where the opaque particle and the cylinder axis were placed. The measurements of time delay of the shear wave arrival to the point of registration (position of opaque particle) were performed. We started measurements when the ultrasonic beam was above the registration point, then it passed through the particle (it corresponds to 0 at abscissa axis) and through the cylindrical inclusion which position is marked by the circle in Fig. 4b. As in previous experiments with the layered sample the segments with particular dependencies can be recognized on the graph. The shear moduli calculated from linear regressions of data at these segments are the following: 26.5 kPa inside the plastic cube (25 kPa was obtained from static measurements), 7.5 kPa inside the soft inclusion (6 kPa was obtained from static measurements), 14.9 kPa in the transient region 1-mm around the inclusion surface. The calculated value of shear modulus inside the inclusion was varied in the range of 30% in dependence on a track path where the ultrasonic beam passed through the inclusion. But the inclusion itself and its position were recognized in all experiments.

Shear waves in ultrasonically heated medium

Heat deposition in the focal zone of an ultrasonic transducer results in appropriate changing of the shear modulus in the heated volume. The ultrasonically induced inhomogeneity of the shear modulus can be detected by the proposed technique. Temperature dependence of the shear modulus of the polymer material we used for the experiments was measured. The measurements were performed by indenting of the probing sphere into the polymer heated up to specified temperature. The polymer sample for these measurements was produced in the shape of 60-mm disk with 25 mm thickness. The sample was placed inside volume filled with heated water which temperature was sustained constant within 1 ^{0}C accuracy. Temperature of the sample was monitored by means of the thermocouple embedded inside the sample. Water temperature was changed in the discrete steps. The sample was kept at least 1 hour at each temperature changing to allow temperature be distributed uniformly over entire sample volume. The temperature dependences of the shear modulus obtained during heating and cooling were identical with high accuracy. In the used sample the shear modulus was reduced with temperature growth; its magnitude at 80 ^{0}C was about 2 times less compared to one at room temperature. Polymer melting was observed at 120±5^{o}C when the shear modulus was vanished.

The peak value of shear displacement excited in the medium with the μ_1 modulus and detected inside medium with μ_2 modulus in a plane wave approximation can be calculated as:

$$u_2 = u_1 T_u = \frac{f(\alpha, I_0, \tau_i)}{\sqrt{\mu_1}} T_u \tag{1}$$

where $T_u = \frac{2}{1 + z_2/z_1}$ is the transmittance coefficient of an amplitude displacement, $z_n = \rho_n c_{tn}$ is the acoustic impedance for a shear wave. The ratio of the peak shear displacements excited in the medium with heating u_2 and with no heating u_0 can be expressed as:

$$\frac{u_2}{u_0} = \frac{2}{1 + \sqrt{\frac{\mu_1}{\mu_2}}} \tag{2}$$

In the medium where the shear modulus is decreased with temperature growth, as in plastic we employed the peak shear displacement will be increased.

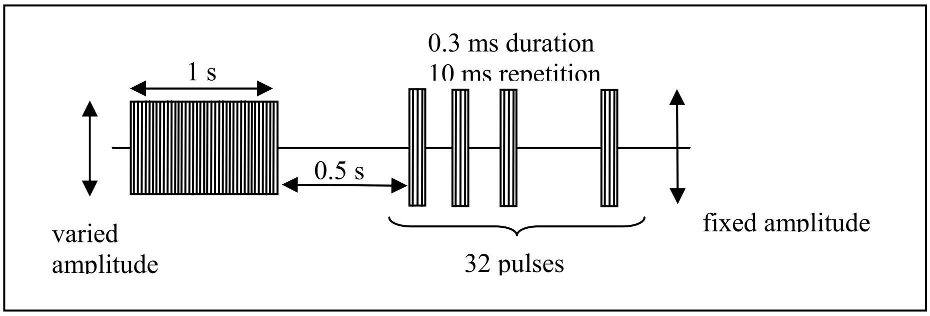


Figure 5. - Diagram illustrating the procedure of plastic heating by ultrasound and successive shear wave excitation in the heated focal zone.

The plastic in the focal zone of ultrasonic transducer was heated by the 1-s duration burst, which amplitude was varied to obtain heating up to different temperatures but not exceeding the melting point (Fig.5). The series of 0.3-ms bursts with the fixed amplitude excited the shear waves in the heated plastic. It was followed shortly by the heating burst. The 0.5-s gap between heating burst and the series of 0.3-ms bursts was enough for a complete absorption of all motions resulted due to the heating burst. On the other hand 0.5-s duration was small compared to heat diffusion from the heated zone and simple estimation for the temperature rise could be used. The shear waves were excited in the cube with 25 kPa modulus in 6-mm distance from the opaque particle. The peak shear displacement detected in the plastic heated up to 100 ^{0}C was 1.4 – 1.5 times larger then the displacement excited by the same bursts in the plastic at room temperature (Fig. 6). The same ratio provides formula (2), where $\mu_1 = 0.2\,\mu_2$. We had no experimental data for the plastic shear modulus at 100 ^{0}C as our measurements were limited by 80 ^{0}C. But we proposed that the temperature dependence in the 80 - 120 ^{0}C range was linear. In this assumption the experimental result corresponds to the predictable value for the peak displacement ratio. The 0.4 - 0.45 ms time shift between the peak amplitudes testified to the significant modulus reduction in the heated zone. No changes in the shear wave profile were detected when plastic was heated up to 42 ^{0}C.

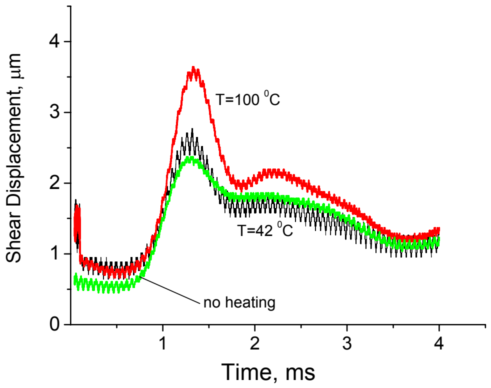


Figure 6. - Shear wave profiles excited in the focal zone where plastic was ultrasonically heated up to 100 ^{0}C and 42 ^{0}C.

To verify these results the similar measurements were performed in the sample with the cylindrical inclusion with the 4 times less modulus then in the cube. The peak displacement of the wave excited inside inclusion and detected at 6-mm distance outside the inclusion was 30% higher compared with the peak displacement of the shear wave excited and detected inside the same hard plastic.

ACKNOWLEDGMENTS

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