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MODELLING OF EXAMINATIONS OF ARTERY WALL THICKNESS CHANGES

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The developed solver of acoustic field was used for simulation of the artery wall thickness examination. It is capable of describing spatial and time-dependent distribution of an ultrasonic beam, that is emitted by a piezoelectric ring transducer and then backscattered on cylindrical surfaces of the walls in artery models. The electrical signal received corresponds closely with the actual RF signal that is obtained during measurements at the output of the ultrasonic VED apparatus. The theoretical model of the artery for creating the ultrasonic reflected echoes was used. The internal radius of the artery model was equal 3 mm for the diastolic pressure and 3.3 mm for the systolic pressure. The intima-media thickness (IMT) of the artery wall was changed from 0.48 mm to 0.44 mm respectively. The echoes-tracking solver based on the zero-crossing and correlation methods was used for detecting changes of the IMT.

Keywords: ultrasound, common carotid artery, elasticity, intima-media thickness, numerical solver.

1. Introduction

Considerable interest is observed in a contemporary ultrasonic medical diagnosis in examining the artery walls by means of invasive and non-invasive methods. The basis of assessment of structural changes taking place in the artery wall is the measurement of its thickness and stiffness [1, 2]. In case of non-invasive ultrasonic measurements, reproducibility of the obtained results is an extremely important parameter, since it is used to define sensitivity of the diagnostic tool [3]. The major objective of the thesis was to develop a numerical solver that would be capable of describing spatial and time-dependent distribution of an ultrasonic beam that is emitted by a piezoelectric ring transducer and then backscattered on cylindrical surfaces of the walls in artery models.

The numerical solver was then used for modeling the process of the artery wall thickness examinations[(1)] . The investigations were carried out using the VED equipment, designed and constructed in the Department of Ultrasound of the Institute of Fundamental Technological Research of the Polish Academy of Sciences, aimed at elasticity examination of arterial walls in human body [1, 2].

2. Physical model

Using the dimensionless variables, the equation that defines the propagation of sonic waves in a homogeneous (with undisturbed parameters of the material), nonlinear and absorbing medium, can be expressed by the following equation [4]:

$$\Delta P - \partial_{tt} P - 2\partial_t \mathbf{A} P + q\beta\partial_{tt}(P)^2 = 0, \tag{1}$$

where $\mathbf{A}P \equiv A(t) \otimes P(x,t)$, $A(t) = F^{-1}[a(n)]$ and $P(x,t)$ is the pressure in the 3D coordinate system x at the moment of time t; $\mathbf{A}$ is a convolution-type operator that defines the absorption; q is the Mach number (in our case the Mach number is calculated for velocities on the surface of the disturbance); $\beta \equiv (\gamma+1)/2$; $\gamma \equiv (B/A)+1$ or γ – adiabatic exponent, $n \equiv f/f_0$ – non-dimensional frequency; f, f_0 – respectively: frequency and characteristic frequency; $a(n)$ – the small signal coefficient of absorption, $\mathbf{A} = F^{-1}[a(n)]$, $F[\cdot]$ – Fourier transform.

For the medium with disturbed material parameters, the equation of the scattered field P^{sc} can be obtained from the formula (1) (a more details see [5]) and takes the form:

$$\Delta P^{\mathrm{sc}} - \partial_{tt} P^{\mathrm{sc}} - 2\partial_t \mathbf{A}\, P^{\mathrm{sc}} = -\mathit{\Pi}\,\partial_{tt}(P^{\mathrm{sc}} + P^{\mathrm{in}}), \tag{2}$$

where P^{in} – incident field which satisfies Eq. (1), $\mathit{\Pi}(\mathbf{x}) \equiv 1 - 1/c_r^2$ – scattering potential, c_r^2 – disturbed dimensionless sound velocity.

3. Solver

Construction of a solver for the backscattered fields is the fundamental issue for setting-up a numerical model of the experiment that is aimed at reflecting real situations that occur in ultrasonography practice. The solver that we have constructed consists of three parts:

1. Solver for the incident field. It is the solver that bases on codes JWNUT2D and JWNUT3D [6], which we have been using for many years. The first code solves the equation in the axially symmetrical cases; the second one is applicable to arbitrary, one-sided boundary conditions.
2. Solver for the backscattered field. It is the tool that is able to calculate the parameters of backscattered fields and their pressure on the detector surface, using the

(1) The first part of this paper was published in “Archives of Acoustics” in year 2006 [7].

numerically determined incident field and information on the geometrical and material parameters of the target as the basis for calculations.

3. Simulator of the electronic receiver channel that is used for calculation of pulse responds $h(t)$ of this unit. Distribution of pressure on the surface of the probe is averaged over the entire probe surface (the theory of piezoelectric phenomena says that electric signals at the probe output are proportional to the aforementioned average value):

$$P_E(t) = \frac{1}{S} \int\limits_{S(\mathbf{x})} P^{\mathrm{sc}}(S(\mathbf{x}), t)\ Ap(S(\mathbf{x}))\,\mathrm{d}S, \tag{3}$$

where $S(\mathbf{x})$ denotes a point on the transducer surface, S stands for the transducer surface area and $Ap(S(\mathbf{x}))$ is the apodization function for the transducer surface. In this study $P_E(t)$ is referred to as the echo. The RF signal $P_{\mathrm{RF}}(t)$ represents a single line of scanning and is calculated as follows:

$$P_{\mathrm{RF}}(t) = h(t) \otimes P_E(t), \qquad h = F^{-1}[H(n)], \tag{4}$$

where $H(n)$ is the system transmittance.

The developed solver was tested for results in experiments when an elastic pipe was immersed in water [7]. The investigations were carried out using the VED equipment. Comparison between the results, which were obtained from numerical calculations and from measurements [7], serves as the proof that the numerical model which was developed by us enables simulation of the experiments with a good accuracy.

4. Simulation of artery wall thickness examinations

The artery wall consists of three layers: the adventitia, the media and the intima. The basic difficulty in ultrasonic examination of the wall thickness is a limited longitudinal resolution of ultrasonic systems. For the applied transmission frequency between 5–10 MHz, the longitudinal resolution varies from 0.4 to 0.2 mm. Generally, it is not enough to measure the intima thickness which is less than 0.2 mm. In this situation, the intima-media thickness (IMT) was calculated on the basis of the distance between two successive echoes, which correspond to reflection from the intima and adventitia layers, respectively. Moreover, the wall thickness changed under the blood pressure changing during the cardiac cycle.

The examination of the change in the artery wall thickness was carried out on a theoretical model. The wall thickness and the artery model diameter were similar to the corresponding dimensions of a common carotid artery for people at the age of 30 [8]. The internal radius of the artery model was 3 mm for the diastolic pressure and 3.3 mm for the systolic pressure. For a diastolic pressure, the thickness of the intima, the media and the adventitia layer were equal to 0.12 mm, 0.36 mm and 0.12 mm, respectively. Taking into account incompressibility of the material from which the artery wall was made, the relative change in the artery model wall thickness ΔIMT/IMT was determined using the formula (5):

$$\frac{\Delta \mathrm{IMT}}{\mathrm{IMT}} = \frac{R_i}{\mathrm{IMT}}\left[\sqrt{\left(\frac{\Delta R_i}{R_i}+1\right)^2 + \frac{\mathrm{IMT}}{R_i}\left(\frac{\mathrm{IMT}}{R_i}+2\right)} - \left(\frac{\Delta R_i}{R_i}+1\right)\right] - 1, \qquad (5)$$

where $\Delta R_i/R_i$ – the relative change of the internal radius R_i of the artery model under the action of varying internal pressure in the artery model. For the assumed artery model, ΔIMT/IMT was equal to -8%.

The RF signal was calculated for the following conditions:
- the investigations were carried out using the VED equipment,
- the frequency of the transmitted ultrasound was equal to 6.75 MHz,
- the bandwidth of the receiver, determined for the level of -3 dB was 2.37 MHz,
- the ultrasonic beam was focused at the depth of 21 mm from the transducer surface (in water medium),
- the pulse of the ultrasonic wave in the focus is shown in Figs. 1 and 2,

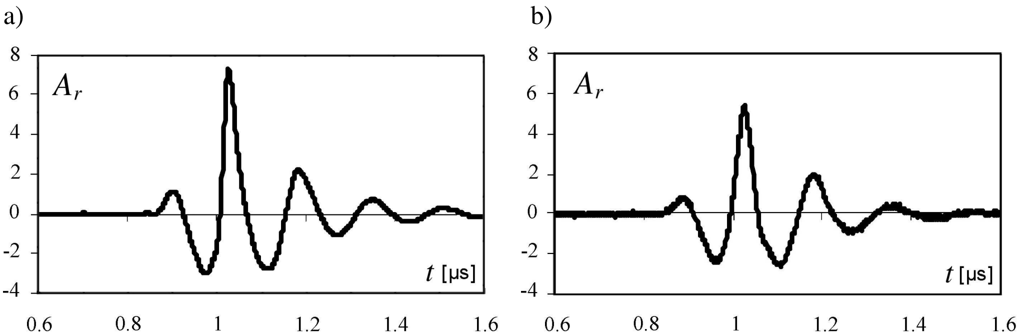

Fig. 1. The normalized scanning pulse in the focus in water medium: a) calculated from the numerical model, b) the normalized scanning pulse measured in the focus, $A_r = P/P_0$, where P – pressure, $P_0 = 0.25$ MPa [7].

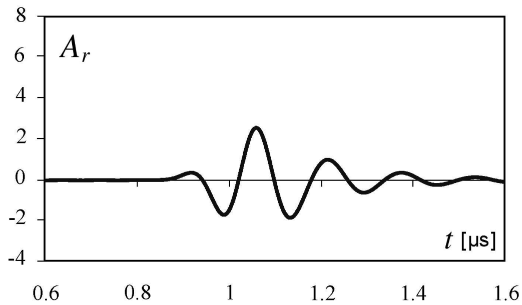

Fig. 2. The normalized scanning pulse in the focus calculated from the numerical model in the tissue outline of the artery, $A_r = P/P_0$, where P – pressure, $P_0 = 0.25$ MPa.

- the front surface of the artery wall was located in the focus of the ultrasonic probe,
- the density of the wall layer was as follows: 1.05 kg/m^3 for the adventitia and the intima layers, 1.1 kg/m^3 for the media layer,
- the attenuation of the ultrasonic wave in tissue was as follows: 9.2 Np/mMHz in the wall artery [1], 2.1 Np/mMHz in the blood [9], 5 Np/mMHz in the tissue outline of the artery.

5. Results

The RF signals calculated for the artery model are presented in Fig. 3. The RF signal (in VED equipment) was introduced by means of 2552 samples covering the distance of 36 mm and using 65 time sequences from the diastolic pressure to the systolic pressure. During the calculation of the IMT, the range gate (Fig. 3) was placed in the area of a group of echoes coming from the back surface of the artery wall, between the ultrasound echoes coming from the intima layer and the echoes from the adventitia layer.

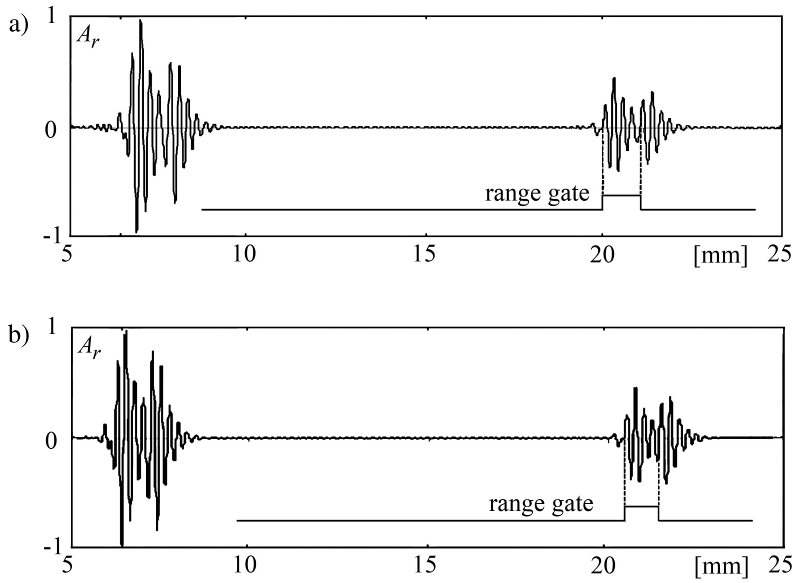

Fig. 3. The RF signal $P_{\mathrm{RF}}(t)$ from the artery model calculated by means of the developed solver for a diastolic pressure (a) and for a systolic pressure (b). Point 13.6 on the scale above corresponds to location of the artery centre at the distance of 25 mm from the ultrasonic probe, A_r – the relative amplitude (with respect to the maximum value of the RF signal amplitude).

Basing upon the calculated RF signal, the zero-crossing and the correlation methods were used to determine the relative IMT-changes of the artery model. The results obtained in the form of regression functions (b and c) are shown in Fig. 4. The results have been compared with the values obtained from Eq. (5).

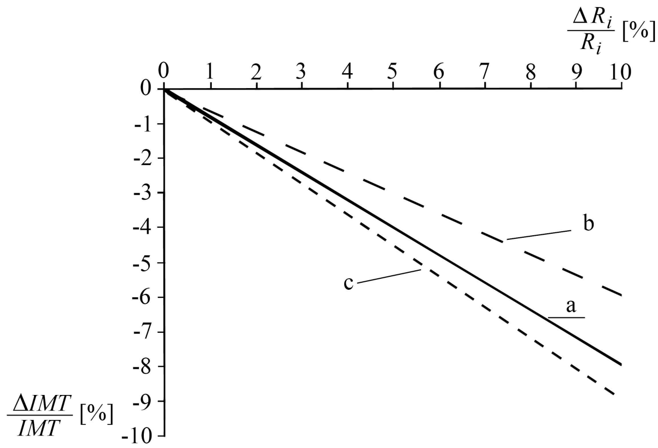

Fig. 4. Dependence between the relative change of the internal artery model radius $\Delta R_i/R_i$ and the relative change in the artery model wall thickness ΔIMT/IMT. a – value calculated from Eq. (5), b – value calculated on the basis of the RF signal by the zero-crossing method, c – value calculated on the basis of the RF signal by the correlation method.

The relative IMT-changes obtained by means of the zero-crossing method are smaller, and those due to the correlation method – greater than the IMT-changes on the basis of Eq. (5).

6. Conclusion

The IMT-variability is the basis for evaluation of elastic properties of the artery walls [10, 11]. The paper presents the results of modeling of IMT changes examinations. The developed solver of acoustic field was used for simulation of RF signal in the ultrasonic VED equipment. For the artery model in which the internal radius changed by 10%, the relative changes of IMT obtained on the basis of the RF signal analysis was equal to -9.1% due to the correlation method, and to -6.3% due to the zero-crossing method. Agreement of these results with the assumed value (Eq. (5)) is satisfactory in the case of the correlation method. On the basis of Eq. (5), the relative variation of IMT was equal to -8%.

The simulation of the artery wall thickness examinations on the basis of the RF signal proves that the numerical solver of the acoustic field can be useful in determining the IMT changes. The study will enable the creation of a numerical model of a measurement system for examination of the elastic properties of the arterial wall.

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