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COMPARISON OF METHODS USED FOR ULTRASONIC EXAMINATIONS OF IMT IN THE WALL OF THE CAROTID ARTERY MODEL

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The aim of this paper is to compare the results of examinations of the intima-media thickness (IMT) in the wall of the carotid artery model by means of zero-crossing and correlation methods. The research was carried out on the elastic artery model (a pipe made of latex), with the internal diameter of 3, 5 and 8 mm and the wall thickness of 0.75, 1.25 and 2 mm. A numerical solver was created for the purpose of calculating the fields of ultrasonic beams and scattered fields under different boundary conditions, different angles and transversal displacements of ultrasonic beams in respect of the position of the arterial wall. A VED ultrasonic apparatus was used during the investigations. The frequency of the transmitted ultrasound was 6.75 MHz. The numerical solver was used for the creation of ultrasonic RF reference signals. A good conformity was obtained between changing the numerical reference of the IMT and the results of determining the IMT by both the zero-crossing method and the correlation method.

Keywords: ultrasound, carotid artery, intima-media thickness, numerical model.

1. Introduction

In the case of non-invasive investigations, the ultrasonic measurements for momentary diameters of arteries over the entire cardiac cycle serve as the basis of determining the elasticity of arterial walls. The maximum and the minimum values of the vessel diameter are associated with the respective systolic and diastolic blood pressures measured by a sphygmomanometer. Based on the above measurements, the elasticity factors of the arterial wall are determined [1]. In the case of non-invasive ultrasonic measurements, reproducibility of the obtained results is an extremely important parameter because it is used to de?ne sensitivity of the diagnostic tool [2]. The investigations were carried out with the use of the VED equipment.

2. Physical model

2.1. Basic equation

When applying non-dimensional variables, the equation, which defines the propagation of sonic waves in a homogenous (with undisturbed parameters of the material) non-linear and absorbing medium, can be expressed by the following equation [3]:

$$\begin{gathered}\Delta P - \partial_{tt} P - 2\partial_t \mathbf{A} P + q\beta\, \partial_{tt} (P)^2 = 0, \\ \mathbf{A}P \equiv A(t) \otimes P(\mathbf{x}, t), \qquad A(t) = F^{-1}[a(n)],\end{gathered} \tag{1}$$

where $P(\mathbf{x}, t)$ is the pressure in the 3D coordinate system $\mathbf{x}$at the moment of time t, $\mathbf{A}$ is a convolution-type operator which defines 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, $\mathbf{A} = \mathrm{F}^{-1}[a(n)]$, $\mathrm{F}[\cdot]$ – Fourier transform.

2.2. Equation for non-homogenous medium

The equation (1) can be expressed in the following manner:

$$\begin{gathered}\Delta P - \partial_{tt} P - 2\partial_t \mathbf{A} P + q\beta \partial_{tt} (P)^2 = -\Pi \partial_{tt} P + \Gamma q\beta \partial_{tt} (P)^2, \\ \Pi(\mathbf{x}) \equiv 1 - \frac{1}{c_r^2}, \qquad \Gamma(\mathbf{x}) \equiv 1 - \frac{\beta_r}{g_r c_r^4},\end{gathered} \tag{2}$$

where $c_r(\mathbf{x}) \equiv c_1(\mathbf{x})/c$, $g_r \equiv g_1/g$, $\beta_r \equiv \beta_1/\beta = (\gamma_1 + 1)/(\gamma + 1)$. Respectively, c_1, g_1 and γ_1 stand for sound velocity, density and "adiabatic exponent" within the disturbed area. In our case, $c = 1$ denotes the non-dimensional sound velocity in the surrounding reference medium, e.g. in water. The (2) omits perturbations $\delta\mathbf{A} \equiv \mathbf{A}_1 - \mathbf{A} = \mathrm{F}^{-1}[a_1(n) - a(n)]$ as the algorithms, which were developed by us, make it possible to achieve uniform solutions (in terms of absorption) of the model equations for all possible values of absorption and spatial configuration of absorbing constituents that have any importance for us. The Π and Γ factors may be defined as scattering potentials: linear Π and nonlinear Γ.

2.3. Derivation of model equations for the issues of backscattering

To establish the derivation of defining equations for our model, we made the following assumptions:

1) For the cases which are important for our considerations, the following relationship is fulfilled:

$$q\Gamma/\Pi \ll 1. \tag{3}$$

Therefore, the last term in (2) can be omitted. The attention should be paid to the fact that the coincidence of $c_r(\mathbf{x}) \cong 1$ and $g_r \cong 1$, i.e. practical absence of linear reflection cannot be excluded, especially for biological substances.

2) The following distribution of the acoustic field can be applied:

$$P = P^{\text{in}} + P^{\text{sc}}, \tag{4}$$

where P^{in} corresponds to the incident (scanning) field whilst P^{sc} stands for the backscattered field. The assumption is made that P^{in} fulfils the (1).

3) The substitution of (4) into (2) leads to the terms that depend on $P^{\text{in}} \cdot P^{\text{sc}}$. For all the cases, which are important in our deliberations, the assumption can be made:

$$P^{\text{in}} \cdot P^{\text{sc}} = 0. \tag{5}$$

The pressure in the backscattered field is much lower than the pressure of incident pulses $P^{\text{sc}} \ll P^{\text{in}}$. We can assume that in the (2)

$$q{P^{\text{sc}}}^2 = 0. \tag{6}$$

After having taken into account the foregoing assumptions from the (2), the following formula can be obtained to define backscattered fields:

$$\Delta P^{\text{sc}} - \partial_{tt} P^{\text{sc}} - 2\partial_t \mathbf{A} P^{\text{sc}} = -\Pi \partial_{tt}(P^{\text{sc}} + P^{\text{in}}), \tag{7}$$

where the incident field P^{in} fulfils the equation:

$$\Delta P^{\text{in}} - \partial_{tt} P^{\text{in}} - 2\partial_t \mathbf{A} P^{\text{in}} + q\beta \partial_{tt} \left(P^{\text{in}}\right)^2 = 0. \tag{8}$$

The equations (7) and (8) represent our mathematical model of the physical phenomena, which take place in the areas of propagation and scattering of ultrasonic signals.

3. Solver

The solver, which we constructed, is composed of three parts:

1. Solver for the incident field. It is the solver based on the codes JWNUT2D and JWNUT3D, which we have been using for many years.
2. Solver for the scattered field.
3. Simulator of electronic tracks, which is used for the calculation of pulse responses $h(t)$ to electronic tracks.

$$P_E(t) = \frac{1}{S} \int\limits_{S(\mathbf{x})} P^{\text{sc}}(S(\mathbf{x}), t) Ap(S(\mathbf{x}))\, \mathrm{d}S, \tag{9}$$

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

$$P_{RF}(t) = h(t) \otimes P_E(t), \qquad h = \mathrm{F}^1[H(n)], \tag{10}$$

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

4. Results

The research was carried out for a pipe made of latex, which acoustical parameters are very close to the material of the arterial wall, with the internal diameter of 5 mm and the wall thickness of 1.25 mm. The Vascular Echo Doppler (VED) ultrasonic apparatus developed in IFTR-PAS was used in the investigations [2]. The frequency of the transmitted ultrasound was 6.75 MHz. The comparison of the angle and transversal displacement shift characteristics of the ultrasonic probe are presenter in Fig. 1 and Fig. 2.

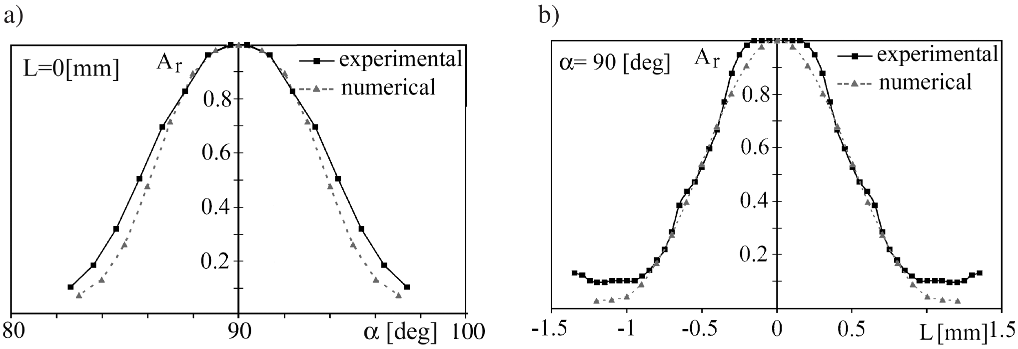

Fig. 1. a) Changes of the maximal RF – signal amplitude as a function of angle α and b) the transversal displacement L of the ultrasonic beam for phantom diameter 5 mm. A_r – maximal RF – signal amplitude in respect of the maximal RF – signal amplitude for the angle $\alpha = 90$ deg and transversal displacement $L = 0$ mm.

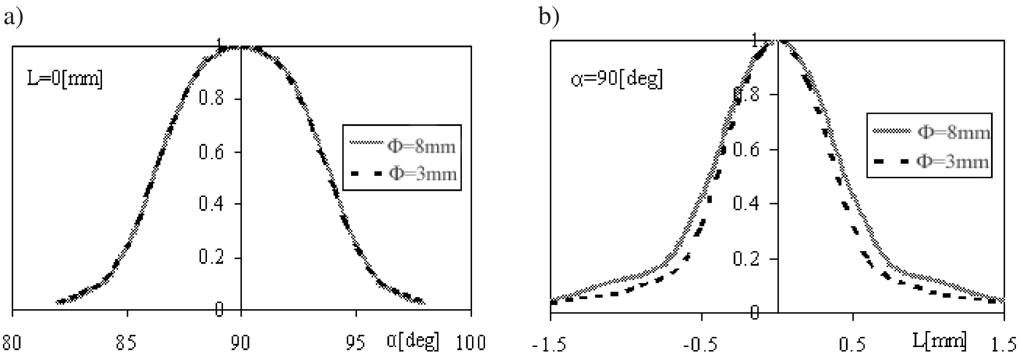

Fig. 2. Results of calculations for phantom diameter 8 mm and 3 mm: a) for the transversal displacement $L = 0$ mm, b) for $\alpha = 90$ deg. A_r – max. RF – signal amplitude in respect of the max. RF – signal amplitude.

5. Solver application

The internal radius of the examined pipe was 3 mm for the diastolic pressure and 3.3 mm for the systolic pressure. For the diastolic pressure, the thickness of the intima, the media and the adventitia layer was equal to 0.12 mm, 0.36 mm and 0.12 mm respectively. The density of pipe wall was 1.05 kg/m^3 for the adventitia and the intima layers and 1.1 kg/m^3 for the media layer. The numerical model of the artery consisted all of the above parameters also the absorption coefficients of the ultrasonic wave in outline of pipe, in all layers in the artery wall, and into the core of pipe where the blood like fluid was flowed. As the reference, the intima-media thickness (IMT1) was changed from 0.48 mm to 0.44 mm respectively. Zero-crossing and correlation methods were used to determine IMT_{ZC} and IMT_{COR}.

5.1. Comparison of methods

For the ideal method of the IMT determination, the relation between the true and the estimated value is as follows:

$$\text{IMT}(\text{IMT1}) = a \cdot \text{MT1} + b, \tag{11}$$

where $a = 1, b = 0$.

In our numerical experiment we obtained:

$$\text{IMT}_{\text{ZC}} = 0.8306 \cdot \text{MT1} + 0.1254, \tag{12}$$

$$\text{IMT}_{\text{COR}} = 1.2469 \cdot \text{MT1} - 0.0712. \tag{13}$$

That means, that the zero-crossing method is under- ($a < 1$) whilst the correlation method is over-estimated ($a > 1$) (see Fig. 3).

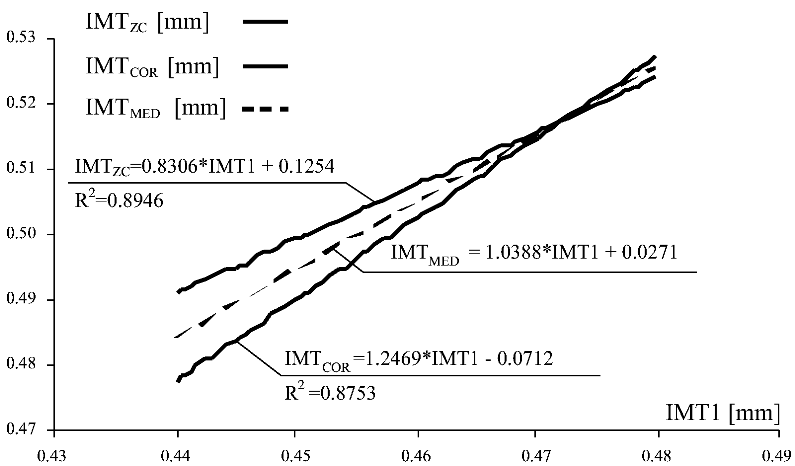

Fig. 3. Numerical experiment. Comparison of the methods used for IMT examination. IMT1 – true values. IMT_{ZC} – results obtained on the basis of the zero-crossing method IMT_{COR} – results obtained on the basis of the correlation method. IMT_{MED} – mean values – dashed line.

The $\text{IMT}_{\text{MED}} \equiv (\text{IMT}_{\text{ZC}} + \text{IMT}_{\text{COR}})/2$ denotes averaging results obtained from both methods. As we see for IMT_{MED} $a = 1.0388 \approx 1$; $b = 0.0271$.

6. Conclusions

The comparison between the results obtained from numerical calculations and from measurements serves as the proof that the numerical model, which was developed by us, enables simulation of the experiments with a good coherence. It is the matter of significant importance when optimizing the design process of measurement equipment. The results obtained on the basis of numerical calculations in the controlled environment (IMT1) allowed us to determine that the zero-crossing method and the correlated method are respectively under-estimated and over-estimated methods. Therefore, the results obtained, after averaging results from both methods, involve a very small error in their estimation, relatively the lowest compared with each of the methods.

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