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MODELING AND ULTRASONIC EXAMINATION OF COMMON CAROTID ARTERY WALL THICKNESS CHANGES

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The paper describes the initial results of numeric analysis of plane-strain of a model of the human common carotid artery. The results of computer modeling were compared with the experimental data obtained by means of ultrasonic measurements of the changes in the thickness of the common carotid artery wall. The ultrasonic examination was carried out on a 34 years old healthy male using the VED apparatus designed by the authors to measure the elasticity of arteries. The numeric analysis was made by means of the finite element method (FEM) using the MARC K7 programming of the Analysis Research Corporation based on the operating system UNIX. As a model of the common carotid artery the authors used a hollow cylinder made of the isotropic, homogeneous, almost incompressible material (Poisson's constant $\nu = 0.4999$) having the Young's module $E = 159.2$ kPa and the combined thickness of the internal and middle layer $\mathrm{IMT} = 0.52$ mm. The modeling of plane-strain concerned the effect of the change in the internal radius and the change in the cylinder wall thickness as a result of the static change of pressure inside the cylinder within the values of 0–45 mmHg. The study obtained satisfactory results in the computer simulation of the changes in the artery walls thickness.

Key words: ultrasound, elasticity of the common carotid artery wall, wall thickness.

1. Introduction

Considerable interest is observed in a contemporary ultrasound medical diagnosis in examining 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. It is assumed that the artery wall consists of three joint axis layers: the adventitia, the media and the intima (Fig. 1). The elasticity of the artery wall is determined by elastin and collagen fibers and by smooth muscles. Mutual proportions of elastin and collagen fibers and smooth muscles together with their connective tissue depend on the position of an artery in the vascular system.

There is a lack of quantitative description in literature of the reactions of individual layers of the artery wall to changes in blood pressure. The study of ARMENTANO *et al.* [1] describe the dependencies between selected strained and deformed elastin and collagen fibers and smooth muscles together with the corresponding values of their Young modules $E_e = 489$ kPa and $E_c = 130.6$ MPa. Similar values are presented by DOBRIN [4] $E_e = 0.4$ MPa and $E_c = 100{-}1000$ MPa. The deformation of elastin fibers has a linear character of approx. 300% of extended length in comparison with their initial length. However, collagen fibers break when they are subjected to the deformation of 3–4% in respect to their initial length.

HASEGAWA *et al.* [2] proposed a method of measurement of the changes in the artery wall thickness determining the mean elasticity module of the artery wall based on non-invasive ultrasound measurements. The Doppler technique was used for the purpose of assessing the crosswise speed of the two artery wall layers and then the time integrating method to obtain information concerning the displacement of the layers. The studies of KANAI *et al.* [5, 6] developed the above mentioned method.

Another approach to assessing the stiffness of the artery wall involves the use of an ultrasonic elastography (IVUS), which allows to obtain a sufficiently good longitudinal resolution in order to reflect the structure of the artery wall from inside. Based on the elastographic studies DE KORTE *et al.* [3] determined diversified values of the Young's module for different types of atherosclerotic plaque components in the artery wall containing a dominating fibrous build-up $E = 493$ kPa, fiber and fat $E = 296$ kPa and fat on its own $E = 222$ kPa.

The aim of this study is to compare the results of the computer analysis using the finite element method (FEM) to establish flat deformities of the model of the human common carotid artery and to compare them with the experimental data obtained by means of ultrasound measurements of the changes in the human common carotid artery thickness.

2. Method and equipment

The changes in the common carotid artery thickness were determined by the VED ultrasound apparatus designed by the authors in the Department of Ultrasounds having the frequency of transmitted ultrasound of 6.75 MHz. The VED apparatus [8] allows the examination of a instantaneous artery diameter or a instantaneous thickness of the artery wall (Fig. 1). Displacements of the artery wall layers are measured with the precision of 7 μm and the thickness of the artery wall layers with the precision up to 88 μm. The longitudinal resolution of the VED apparatus determined on the basis of the examinations of the model was < 0.33 mm in water (Fig. 2).

The numeric analysis of displacements in the artery wall model was made by means of the finite element method (FEM) using the MARC K7 programming of the Analysis Research Corporation based on the operating system UNIX. A hollow, axially symmetrical cylinder made of isotropic, homogenous, almost incompressible material (Poisson constant $\nu = 0.4999$) was used as a model of the common carotid artery. Geometrical measurements were assumed on the basis of ultrasound examinations of the total artery thickness and the combined thickness of the intima and the media IMT. The modeling of axially symmetrical deformations concerned the effect of the change in the internal

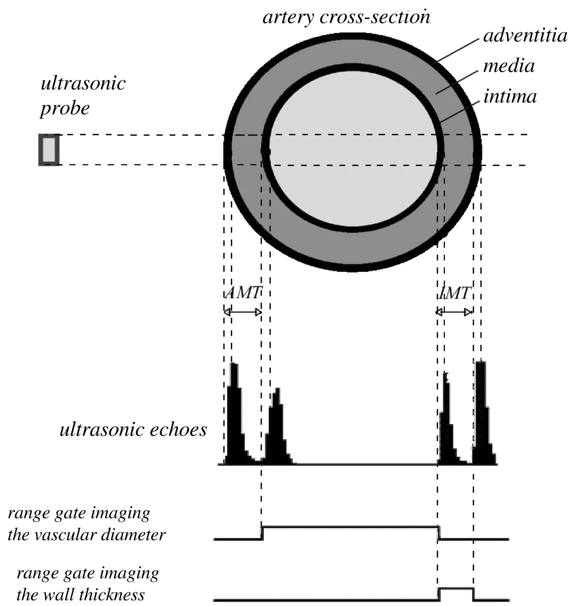

Fig. 1. Imaging of ultrasound echoes from the artery wall with the use of the VED apparatus. AMT – thickness of the adventitia + the media layers of the artery wall; IMT – thickness of the intima + the media layers of the artery wall.

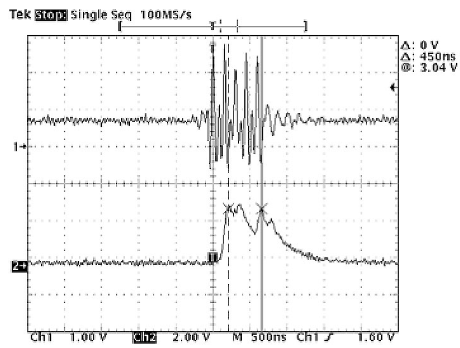

Fig. 2. An example of the longitudinal resolution examination by the VED apparatus. RF pulses and their envelope obtained from the surface of two thin (0.105 mm) PVC foil sheets immersed in water. The length between the surfaces reflecting the ultrasound wave impulse was 0.450 mm. The length measured on the basis of impulses' envelope was 0.454 mm.

radius R_i and the change in the wall thickness Δh of the cylinder as a result of the static change of pressure inside the cylinder within the values P: 0–45 mmHg resulting from the increase in blood pressure between the systolic and diastolic heart cycles. A linear dependency between strain and stress was assumed as the basis for modeling. The modeling process included an unknown value of the Young's model and the convergence criterion was a minimal error in reproducing the changes in the internal and external radius of the model.

3. Results and discussion

The ultrasound examination of the change in the internal radius and the change in the common carotid artery wall thickness was carried out on a 34 years old healthy male. During the examination the range gate (Fig. 1) 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 end of the echoes from the adventitia layer. The artery wall thickness h for diastolic blood pressure was 1.333 mm. The combined thickness of the IMT layer for the same blood pressure equaled 0.52 mm. Figure 3 depicts absolute and relative changes in the internal radius R_i and the external radius R_e of the artery, the changes in the artery wall thickness based on the calculations – Δh_1 and on the ultrasound measurement Δh_2 for one heart cycle.

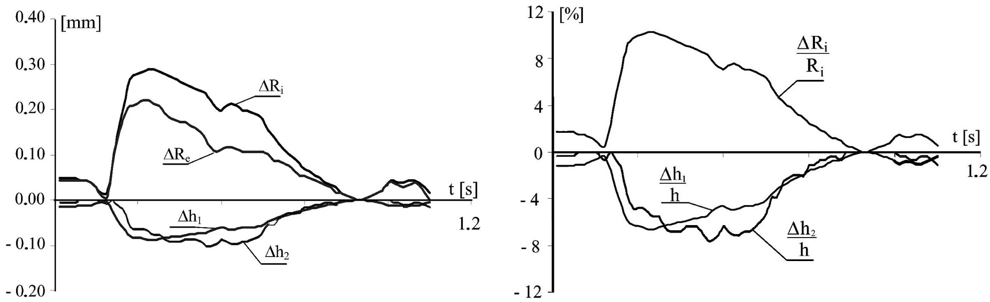

Fig. 3. Absolute and relative changes in the internal radius R_i and the external radius R_e of the artery, changes in the artery wall thickness based on calculations $-\Delta h_1$ and on the ultrasound measurement Δh_2 for one heart cycle.

Figure 4 depicts the modeling results established by means of the finite element method of the changes in the internal radius R_i and the external radius R_e of the artery and the changes in the radius R_m corresponding to the IMT layer. Figure 4 presents also the modeling results in the changes of the artery wall thickness Δh_1 and the layer IMT – $\Delta\mathrm{IMT}$. The biggest conformity between the results of measurements and calculations was established for the Young's module $= 159.2$ kPa.

The scope of the changes predicted in the layer thickness IMT of 40 μm obtained on the basis of computer modeling by means of the finite element method (FEM) conforms to the results of the experimental studies involving groups of people below the age of 50 presented by MEINDERS *et al.* [7].

The calculations' results obtained by means of the finite element method (FEM) were applied to the calculations' results established on the basis of dependency (1) expressing the relation between the relative change in the internal artery radius R_i and the relative change in the artery wall thickness h taking into account the incompressibility of the material, from which the artery wall was made.

$$\frac{\Delta h}{h} = \frac{R_i}{h}\left[\sqrt{\left(\frac{\Delta R_i}{R_i}+1\right)^2 + \frac{h}{R_i}\left(\frac{h}{R_i}+2\right)} - \left(\frac{\Delta R_i}{R_i}+1\right)\right] - 1. \tag{1}$$

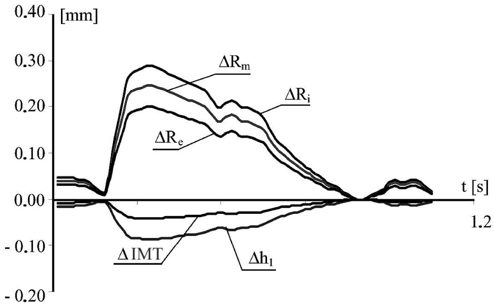

Fig. 4. Calculation results obtained by means of the finite element method (FEM): changes ΔR_i in internal radius, changes ΔR_m in the radius connected with the position of IMT layer, changes ΔR_e in the external radius, changes $\Delta \mathrm{IMT}$ in thickness of IMT layer and changes Δh_1 in the artery wall thickness of the artery model for one heart cycle. Calculation results obtained by means of the FEM method conform with the results obtained using the formula (1) to an accuracy of line thickness.

Described in the formula (1) dependency between the relative change in the internal radius $\Delta R_i/R_i$ and the relative change in the artery wall thickness $\Delta h/h$ is depicted in Fig. 5.

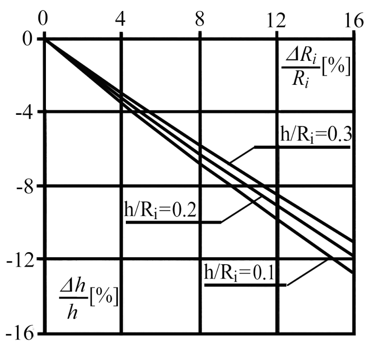

Fig. 5. Calculated on the basis of the formula (1) dependency between the relative change of the internal artery radius and the relative change in the artery wall thickness $\Delta R_i/R_i$ – relative artery diameter change, h – artery wall thickness, $\Delta h/h$ – relative change in the artery wall thickness.

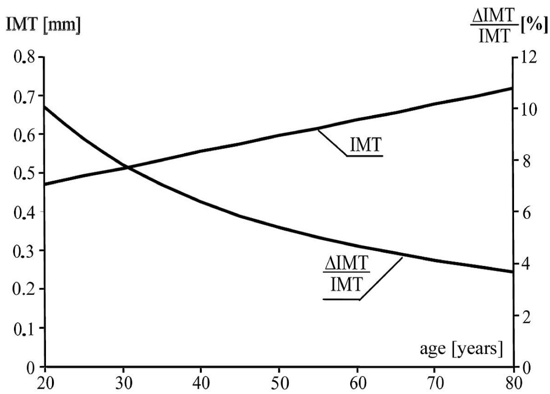

Fig. 6. The IMT layer thickness and its hypothetical relative changes in the age function.

The results obtained by means of the finite element method (FEM) showed considerable conformity with the calculations' results obtained by means of the formula (1).

The factor which limited the precision of the examination of the artery wall thickness is the longitudinal resolution applied in the measurements of the ultrasound apparatus. In non-invasive examinations this resolution does not exceed 0.3 mm and for this reason as the basis for assessing the artery wall thickness the combined thickness of the IMT layer is assumed (Figs. 1 and 6).

Assuming as the basis the IMT examination results and the internal radius of the common carotid artery [8], the hypothetical value of the relative changes in the IMT layer for healthy persons in the age function was determined using the formula (1). It is expressed by the following formula:

$$\frac{\Delta\mathrm{IMT}}{\mathrm{IMT}} = 0.0016x^2 - 0.2611x + 14.372, \tag{2}$$

where x – age of the examined persons.

The value of IMT and its hypothetical relative changes are depicted in Fig. 6. The figure shows that the change in the IMT layer thickness increases and the relative change in the IMT layer thickness decreases with age as a result of structural changes taking place in the artery wall during the ageing process. The above results were confirmed by the experimental studies of a group of people below the age of 50 determined by MEINDERS *et al.* [7].

4. Conclusions

The results obtained in the study indicate that the use of the finite element method (FEM) allows modeling of the radius changes and the changes in the artery wall thickness during static changes in blood pressure. The differences observed between the measured and calculated values of the changes in the artery wall thickness concern mainly the shape of their course and can originate from the limited precision of the measurement apparatus or may also result from the interference of ultrasound echoes in the area of the back surface of the common carotid artery wall. The highly precise reproductions of the calculations' results obtained on the basis of dependency (1) and on the basis of the finite element method (FEM) prove that that the use of the linear model for reproducing the above changes was fully justified.

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