ABSTRACT
The aim of this paper is to investigate the role of residual stresses in cerebral arteries, particularly in the Common Carotid Artery (CCA). Numerical simulations were based on experimental data described in the literature. Finite Element Method (FEM) was used, to calculate the stress response of the two-layer model of artery (intima-media and adventitia) to the transmural pressure. Strongly nonlinear stress-strain characteristics were applied. Conducted research showed the tendency and mechanisms connected with residual stress phenomenon. It was shown that residual stresses have strong impact on stress field for physiological and supraphysiological transmural pressures. Particularly, circumferential stress in the media layer was significantly reduced. We concluded that the presence of residual stress protects the intima-media layer against overstretching and rupture.

KEY WORDS
residual stress, arterial wall mechanics, biomechanics, common carotid artery.

1. Introduction
It has been known, for a long time, that the arterial wall is not homogeneous and its mechanical properties, at physiological and higher pressure, are determined mainly by its two layers: media and adventitia [1]. The remaining layer, intima, plays a secondary role due to a negligible mechanical strength, which offers endothelial cells and sub-endothelial connective tissue. Mutual quantitative relation of thicknesses of these three layers as well as the relation of the wall thickness to the internal radius of arteries are shaped differently in different vessels. The thickest layer is intima-media (M). It is mainly composed of smooth muscles, circularly arranged, with small share of elastic fibers and occupies about 2/3 of the total wall thickness. The rupture pressure of the intima-media is relatively low and equals about 60 kPa [2]. In turn, the adventitia (A), comprises a thin layer of loose connective tissue. It contains mainly fibroblasts and stroma enriched by helically arranged collagen fibers. Collagen fibers are characterized by a high coefficient of elasticity, which means that they are poorly distensible and in normal conditions they protect arterial wall against an excessive expansion. The rupture pressure of the adventitia is higher than intima-medias and lies above 250 kPa [2]. The ratio of total wall thickness to internal radius of large cerebral arteries is about 1 : 6. [3].

A great deal of arterial wall models of different degree of complexity have been proposed in the literature. These models start from the simplest, which treat the wall as a homogeneous [4], cylindrical membrane based on Laplace law [5], and end on sophisticated, multi-layer models taking into account the anisotropic, nonlinear, pseudoplastic mechanical behavior of each layer [2,6,7]. The former models, however, poorly adhere to reality. The main shortcoming of the latter models results from a large number of parameters, which are very difficult to identify and with a considerable mathematical complications.

The majority of biomechanical studies of arteries assume zero-pressure conditions as reference for the analysis, this means that for zero value of transmural pressure both the wall strain and the stress are also 0, which is not true. Already Vaishnaw and Vossoughi, 1983 [8] identified that the load free configuration does not mean a stress free state. According to many authors the residual stress should be involved in wall biomechanics [9, 10]. On the other hand, in literature, there is a lack of precise studies devoted to the role of residual stress on walls biomechanics, and the necessity of its involvement during calculation of stress-deformation of arterial wall. The main problem with determination of the residual strain in an arterial segment of a given length, external diameter and wall thickness lies in the complicated, indirect method of their evaluation. It requires:

a. separation of the adventitia from the intima-media by pulling off the adventitia from the underlying M tissue (to get rid of circumferential
residual stress) and precise measurement of their inside and outside radius: \(a_{ml}, b_{ml}, b_{al}, c_{al}\);

b. an axial cut of adventitia and intima-media rings in order to determine their curvatures and opening angles, \(a_a\) and \(a_{mv}\), respectively, in the stress-free state;

c. knowledge of experimentally identified nonlinear stress-strain characteristic of both arterial layers.

Detailed description of this method is given by [2,11]. Finally, the knowledge of enumerated parameters enables numerical calculation of residual stress in the load-free state. It should be added, however, that the reliability of all mentioned parameters is questionable: big experimental errors, likely damage of arterial tissue during dissection of layers or cutting the rings, dependence of the opening angle on the strip length, and above all, the fact that many tissue features are individually variable. Not to mention that the application of the procedure described in points a, b, c, to smaller cerebral arteries having a large number of perforating branches (e.g. from the region of the circle of Willis) is very difficult, if at all possible. Therefore, the question arises in what degree residual strains change the stress field and deformation of wall within the range of physiological pressure and in the range of large pressure, which is applied during balloon angioplasty. Answer to this question constitutes the main goal of this paper.

2. Material and Method

For reasons of simplicity and computational efficiency, the artery was treated as a two-layer and thick-walled, incompressible circular tube. Such simplification is justified as common carotid artery (CCA) over the long distance is straight and free of branches.

The numerical simulations were carried out using the commercial Ansys Structural software package which applies Finite Element Method. Geometry of layers was discretised using Ansys Meshing software. Hexagonal elements were generated. SOLID186 elements, contact elements: CONTA174 and TARGE170, and joint elements MPC184 were used. Large deformation effects were complied. Due to the axial symmetry of artery model the numerical mesh was restricted to a quarter of the cylinder. Layers were meshed using 20 elements/90° circumferentially and mesh independence check was performed to obtain optimal radial number of division (40 elements) (Fig. 1). The values of geometrical parameters necessary to compute residual stress, as well as, the nonlinear material characteristics of layers (shown in Fig. 2) were adapted from experimental results of Sommer et al [7].

To calculate residual stress coming due to inflexion and interference, the numerical simulations were divided into two steps (Fig. 3). In the first step, both strips of arterial layers in a stress-free state were bent, to create two cylinders. The inner cylinder has the outer radius larger than the inner radius of outer cylinder. In the second step, the adventitia was stretched onto the media layer. Thus, we obtained the state with residual stress in the load free configuration of arterial model. In this state, the internal and external radius of the artery is marked as \(a\) and \(c\), respectively. The radius of tube separating both layers is marked by \(b\). Once the residual stress was fixed, increasing pressure inside the model was applied.
Outside pressure was kept constant and equal to zero. The resultant fields of circumferential and normal stresses, as well as, the relationship between the inner pressure and the external tube radius were then calculated.

### 3. Results and discussion

In Fig. 4 the results of simulation of circumferential stress spread versus pressure with and without residual stress in the intima-media and the adventitia, is displayed. Only circumferential component of stress was shown as it is always higher than the normal stress component, and in artery rupture analysis plays the main role. As we can see, in the residual stress-free configuration both the intima-media and adventitia are subjected to pure stretching. The situation is more complicated when the residual stress is present. The intima-media layer is subjected to both compression and stretching depending on the value of internal pressure. It is interesting to note, that the circumferential stress - pressure relation is not monotonic. Initially, stress increases, as the increasing internal pressure produces stress that counteracts that coming from residual stress. When the pressure increases further, the adventitia becomes very stiff (a leather-like response of the collagen) and prevents intima-media, which is much more elastic and behave more or less like rubber, from further expansion. This mechanism (resulting directly from the strong nonlinearity of stress - strain characteristic) is responsible for diminishing of circumferential stress in the media layer. Difference in the adventitia response to increasing pressure with and without residual strain is less spectacular and is substantial only for the lower pressure range. For high pressures the maximum stress are of the same order in both situations, although, the spread between the maximal and the minimal value of circumferential stress is lower in the presence of residual stress.

![Fig. 3. Simulation procedure. Dimensions of typical CCA was presented in the table.](image)

![Fig. 4. Circumferential stress spread in the media and the adventitia layer. Red color represents layer with a residual stress, blue without.](image)
Another interesting observation is, that the residual stress in the intima-media influences circumferential stress distribution within the whole applied pressure range. Therefore, we can consider the presence of residual stress as the mechanism protecting the intima-media against overstretching.

Stress analysis is crucial in understanding of the mechanism of arteries ruptures. Another field of using arteries models is fluid-structure simulations (FSI) [12,13]. To obtain reliable wall shear stress field, the deformation of an artery wall has to be considered. In Fig. 5, the external radius versus pressure characteristic is presented. As we can see, the difference in the artery deformation is significant (up to 40 %) near physiological pressures (of about 10 - 20 kPa). Of course, including residual stress into FSI simulation would be troublesome due to technical limitations, but a suitable increase of material stiffness should be sufficient for analysis under physiological loadings.

4. Conclusion

It was shown that residual stress have strong impact on stress field for physiological and supraphysiological transmural pressures and provided strong evidence for the necessity of taking them into account in computer simulation. Our research confirmed the main role of adventitia in protecting the intima-media against overstretching and rupture. In addition, the residual stress particularly reduces circumferential stress in media layer for the whole range of applied pressures. The role of residual stress on external radius-pressure response was also highlighted. Relatively large (up to 40%) change in deformation, compared to the case without residual stress, was observed.

References