The influence of different balloon materials on the medical outcome in the human thoracic aortas

Tomasz GAJEWSKI¹, Hannah WEISBECKER², Krzysztof SZAJEK¹, Tomasz ŁODYGOWSKI¹, Gerhard A. HOLZAPFEL²

¹ Institute of Structural Engineering, Poznan University of Technology, Piotrowo 5 street, 60-965, Poznan, Poland
² Institute of Biomechanics, Graz University of Technology, Kronegasse 5-I, 8010 Graz, Austria

1. Introduction

According to the World Health Organization cardiovascular diseases are the main causes of death in the world over the past decade [1]. One of the mechanically-based intervention relevant in clinics is the intra-aortic balloon occlusion. A balloon is delivered on the tip of a catheter to a blood vessel and later inflated to its nominal diameter. When the medical outcome is satisfying, the balloon is deflated and removed.

In that kind of catheter-based procedure the surgeons do not have a visual or haptic feedback from the inside of the artery wall. Therefore, numerical simulations with some essential assumptions of wall stresses and related damage can help to improve surgical techniques.

The Figure shows healthy artery with typical distinction on three structural layers: intima, media and adventitia. Intima, the thinnest and innermost layer, stiffens locally with atherosclerosis. Media, the middle layer with smooth muscle cells, elastin and bundles of fibrils has the ability to resist a circumferential loads. Adventitia with two families of fibers changes into a stiff tube at high strain level. [2,3]

2. Materials and Methods

A numerical investigation presents the influence of an inflated spherical balloon by contact on the ideal tube geometry of an artery. The initial diameter of the balloon and the inner radius of the aorta equals 25.6 mm. The nominal pressures of the balloon were set up to 6.5 atm. In a preliminary step, the artery is pressurized to a value of 120 mmHg and then the pressure is decreased to 80 mmHg to introduce a typical range of stress in the vessel. Then, the balloon is inflated up to 6.5 atm with a constant value of the diastolic blood pressure set to 80 mmHg.

The material model used in this research is based on the work of Holzapfel et al. [2]. Fiber dispersion is included according to Gasser et al. [3] and damage according to Weisbecker et al. [4]. The strain-energy function \( \Psi \) is decoupled into three parts, the penalty function \( \Psi_f \) to ensure quasi-incompressibility, the deviatoric part \( \Psi_d \) for the ground matrix exhibiting a neo-Hookean behaviour, and the anisotropic deviatoric contribution due to embedded \( i \)-th family of fibers \( \Psi_f \) multiplied by the damage variable \( \eta_i \). Thus, the strain-energy function is calculated from the expression

\[
\Psi(C, A_1, A_2) = \Psi_f(J) + \Psi_d(C) + \eta_i \sum_{i=1,2} \Psi_f(C, A_1, A_2)
\]

where \( C \) denotes the right Cauchy-Green tensor, \( J = \det C \) is the volume ratio, \( \overline{C} = \frac{1}{2}(C + C^T) \) is the related volume preserving tensor and \( A_1, A_2 \) are structural tensors. Constitutive parameters of intima, media and adventitia of the human thoracic aorta were taken from the median values as presented in the paper of Weisbecker et al. [4].

Furthemore, experimentally investigated in the axial and the circumferential direction by Ro et al. [5]. Due to the similar mechanical behavior in the two perpendicular directions, the material is considered to be isotropic.

In simulations, the Nylon-12 data [5] were used as the reference material. Based on its characteristics, modified versions of balloon material were created. The stress-stretch curves of the used balloons are presented on the lower-left figure. Each case is labeled by the initial balloon stiffness \( E_1 \) (in the reference case \( E_1 \) equals 1225 MPa). The balloon materials were created by multiplying the reference data with particular factor, e.g., the multiplication factor equals 1.082 (1325 over 1225) for \( E_1 \) with label 1325 MPa.

Results obtained by computations are presented in above figures. The investigation can be concluded by the following remarks:

- For small radial displacement of balloon, axial displacement between balloon materials is negligible (when 1.5 mm radial displacement is considered the difference is less then 2 %), when bigger radial displacements are considered the difference increases to several percentages (for radial displacement 3.5 mm difference equals 6 %).
- The bigger nominal radial displacement the more nonlinear behavior of balloon displacement ratio (radial over axial displacements) is observed for investigated balloon materials.
- The relation between selected balloon materials and pressure which should be applied to obtain particular radial displacement is linear.

3. Results and conclusions

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5. References