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Research Paper

Experimental and constitutive modeling approaches for a study of biomechanical properties of human coronary arteries

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ABSTRACT

The study concerns the determination of mechanical properties of human coronary arterial walls with both experimental and constitutive modeling approaches. The research material was harvested from 18 patients (range 50-84 years). On the basis of hospital records and visual observation, each tissue sample was classified according to the stage (0, I, II, III) of atherosclerosis development (SAD). Then, strip samples considered as a membrane with the shape of rectangular parallelepiped were preconditioned and subjected to uniaxial tensile tests in longitudinal (n=27) and circumferential (n=4) direction. With experimental data obtained, the stress-strain characteristics were prepared. Furthermore, tensile strengths and related strains, stiffness coefficients and tangent modules of elasticity were computed. For a constitutive model of passive mechanical behavior of coronary arteries, values of material parameters were computed. The studies led to the following conclusions. Most importantly, the atherosclerotic changes affect all the mechanical properties of arterial walls. A progress of arteriosclerosis contributes to an increase of vascular stiffness. The highest values of the stiffness coefficients are obtained for the tissues in the advanced stage of the disease. We were also able to observe that gradual calcification, progression of atherosclerosis and degradation of collagen in the tissue caused a decrease of tensile strengths and related strains. Finally, a comparison

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made for the tissues with the advanced SAD showed that the tensile strengths and strains were much higher in the case of the samples with the circumferential orientation rather than those with the longitudinal one.

1. Introduction

Most of the available studies concerning mechanical properties of arteries are focused on animal tissues, mainly obtained from pigs (Carmines et al., 1991; van Andel et al., 2003; Lally et al., 2004; Veerdhaval, 2005; Pandit et al., 2005; Bartkowiak-Jowsa et al., 2010), dogs or sheep (Patel and Janicki, 1970; Gow et al., 1974). It was found, however, that the properties of animal arteries are significantly different from those of human vessels (Carmines et al., 1991; van Andel et al., 2003). Hence, properties of animal tissues are not useful when calculating constitutive parameters of arteries, especially those to be used for the development of vascular implants. Despite rich literature on experimental studies of blood vessels, there are only a few reports describing the mechanical properties of human coronary arteries. Moreover, the available results based on in vitro experiments are characterized by very high (up to 80%) variance (Holzapfel et al., 2005; Gow and Hadfield, 1979; van Andel et al., 2003; Williams et al., 1999; Carmines et al., 1991). One of the reasons for such a discrepancy may be the fact that many authors average the results of experiments performed on arteries obtained from patients of different ages and at various stages of atherosclerosis. Analysis of the literature suggests that age and atherosclerotic changes affect the mechanical properties of the arterial walls, which is mainly caused by changes in their structure (Ozolanta et al., 1998). Based on in vivo studies, it was found that expansion coefficient of the healthy coronary arteries can be more than three times higher than that of tissue with atherosclerotic changes (Yamagishi et al., 1997; Reddy et al., 2004; Nakatani et al., 1995). Therefore, it seems to be essential to consider parameters such as the age of patients and the stage of atherosclerosis development when performing experimental studies of human arteries as well as creating their mathematical models.

In the present paper, structural and mechanical properties of the human coronary artery walls are investigated. The same research material was considered, e.g., in an interesting paper of Holzapfel et al. (2005). However, there are a few factors that distinguish their study from ours. One of them concerns a criterion of the selection of arterial walls for mechanical testing. Holzapfel et al. focused on segments from the midregion of the left anterior descending coronary artery. For some of the specimens, medium or high-grade atherosclerosis was observed. Nevertheless, the research was carried out only on straight segments (without palpable circumscribed wall hardening) such that an atherosclerotic plaque was not detected there and eccentric intimal thickening was not macroscopically visible. Then, the mechanical properties were determined for three individual layers (adventitia, media and intima) from uniaxial tensile tests in both longitudinal and circumferential directions. In our research, fragments of left and right coronary arteries were taken in account. All samples prepared for investigation (except for the one of patient XVIII) were characterized by varying (low, medium or high) degrees of atherosclerosis. As we know, the presence of large calcified atherosclerotic plaques usually cause significant changes in arterial structure and a layout of collagen fibers. In extreme cases the complete degradation of this structure in spots adjacent to a plaque can be observed. For these reasons, the separation of arterial walls into three layers and the determination of collagen fiber orientations were difficult or even impossible. As a consequence we decided to use a one-layer representation of the artery and study the mechanical properties of strip samples for three different stages of atherosclerosis. Such an approach resulted in different constitutive models applied for computation of material parameters. In our study we chose a combined polynomial–exponential model (with an exponential 'Fung-type' strain-energy function such that any structural parameters are not required) while in Holzapfel et al. (2005) a more advanced structurally-based model was used.

2. Materials and methods

Specimens: The research material consisted of 18 fragments of human coronary arteries. Coronary artery tissues were harvested from 5 women and 13 men [70.4 $\pm$ 9.8 (SD) year, range 50–84]. The use of biological material from human subjects was approved by the Bioethics Commission at the Regional Specialist Hospital in Wroclaw based on Decision KB/No 8/2011. Preparations were characterized by varying degrees of atherosclerosis (0, I, II, III). Different stages of atherosclerosis were categorized into two stages. First, by visual observation and classification to stage I (thickening of the artery), II (visible plaque) or III (artery is destroyed, layered, there is no structure due to large atherosclerotic plaque). Then, by histological observation done by a histologist (using H&E and Van Gieson's staining). Further information on the age and the sex of the patients and the severity of atherosclerotic changes are placed in Table 1. To prevent damage and changes of the mechanical properties and the structural characteristics of the arteries, the samples were stored not longer than 24 h in a saline solution. Fragments of left (LCA)/right (RCA) coronary arteries without side branches were selected and pruned from the surrounding connective and fat tissues. Using a scalpel and a punch with two parallel blades, two types of samples were prepared: (a) longitudinal rectangular specimens (with their longer sides parallel to the