13th conference of the European Society of Biomechanics, 1-4 Sept. 2002, Wroclaw, Poland

Soft Tissue Biomechanics: A necessity for future directions in engineering and medicine

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Introduction

The human body consists mainly of so-called soft tissues, which exhibit anisotropic material responses and form organs with irregular shapes. Therefore, the understanding of their mechanics at physiological and therapeutical loading conditions necessitates a sound continuum-mechanical basis and the use of nonlinear finite element methods.

Appropriate physical models of biological soft tissue organs and associated numerical algorithms are of great interest for clinicians and medical product suppliers, in particular, in the fields of orthopedics and cardiovascular medicine. However, numerous existing models of soft tissues suffer from a lack of experimental data, do not fulfil mathematical and mechanical requirements, and are not suitable for finite element implementations. In order to achieve clinically meaningful results an engineering approach requires, (i) a *comprehensive* experimental data base of the material to be modelled, (ii) a physical model that captures the essential mechanical characteristics and (iii) an efficient numerical model with the aim to study the effects of medical treatments subject to certain procedural parameters in a robust and reliable way. As in other fields of applied mechanics the computational approach offers an essential alternative in situations where experiments are either too costly or even impossible.

The great majority of diseases in the western world, such as atherosclerosis and degeneration of intervertebral discs are diseases of soft tissues. Hence, the multidisciplinary field of soft tissue research is of crucial scientific, medical and socio-economic importance. The fast progress in the developments of hard and software make it possible to thoroughly investigate biological soft tissues and their pathologies on a computational basis. Since soft tissues are biological materials, which fulfil mechanical purposes and adapt to their mechanical environment (growth, remodelling and morphogenesis), it is of fundamental importance to identify the complex interactions of mechanical and biological responses. This challenging field of *mechanobiology* bears the potential to be an important contributor to tissue engineering and clinical medicine.

Typical biological soft tissues are arteries, veins, intervertebral discs, cartilages, ligaments, tendons, muscles, skin, etc. In common, they are composites, which are reinforced by biological fibers such as collagen [1]. In general, soft tissues are strongly anisotropic materials undergoing large strains. Their stress-strain behavior is nonlinear with pronounced stiffening in the large strain domain due to the collagen fiber recruitment [2]. The strengths depend on the structural compositions, in particular, on the content of collagen fibers. For a certain range of load some tissues such as blood vessels are considered to be incompressible, whereas other types of tissues such as cartilages show significant compressible behavior and require to be modelled as biphasic (porous) materials.

Mechanical description and physical modeling of arteries

The following part of the presentation is focused on the mechanical description and the physical modeling of arteries. Depending on the histological composition, arteries behave *elastic* or *viscoelastic* in the physiological load range. However, for higher loads, which may occur during therapeutical procedures such as balloon angioplasty and stent deployment, experimental tests of vascular specimens suggest that *remaining strains* accumulate. A further increase of loads leads additionally to material damage, which ultimately results in tissue failure.

The hyperelastic responses of arterial tissues are described by a Helmholtz free-energy function [3], which depends on the deformation and the histostructure characterized by the preferred orientations of two families of fibers [4]. An extension of this constitutive model to the viscoelastic regime is based on the concept of internal variables [5]. By selecting suitable material parameters, **i** enables a cyclic response, which is frequency-independent (constant dissipation). This well-recognized mechanical response was found to be a general feature of arteries of the muscular type. The analytical expressions for the algorithmic stress and elasticity tensors are implemented in the FE analysis program FEAP. Detailed numerical aspects are given in [6]. For the high-pressure loading domain we assume that the collagen fibers embedded into the matrix material slip relatively to each other so that a permanent deformation remains after unloading. A plasticity model considers the slip of the two families of fibers.

Application: layer-specific finite element simulation of balloon angioplasty

The developed constitutive and numerical frameworks of arterial wall mechanics are used for the simulation of balloon angioplasty by means of high-resolution magnetic resonance imaging and mechanical testing [7].

We scanned a straight segment of a human external iliac artery (20.0 mm) with an eccentric stenosis by means of high-resolution magnetic resonance imaging (cross-sections with an in-plane resolution of 0.3 mm and an axial resolution of 1.0 mm). For each scanned cross-section, the borders of the arterial components were traced manually by a series of points. The traced cross-sections were combined along the arterial axis, which resulted in a set of 3D point clouds representing the boundary surfaces of the components. Finally, each of the boundary surfaces was represented as a NURBS spatial model (**N**on-**U**niform **R**ational **B**-**S**plines), which was fitted to the associated point cloud.

After scanning, the artery was cut through transversely into two halves. One half was used for corresponding histological analyses to allow material characterization, while the other half was dissected anatomically into its major components, which are non-diseased intima I-nos, collagenous cap I-fl (fibrotic part at the luminal border), fibrotic intima at the medial border I-fm, calcification I-c, lipid pool I-lp, non-diseased media M-

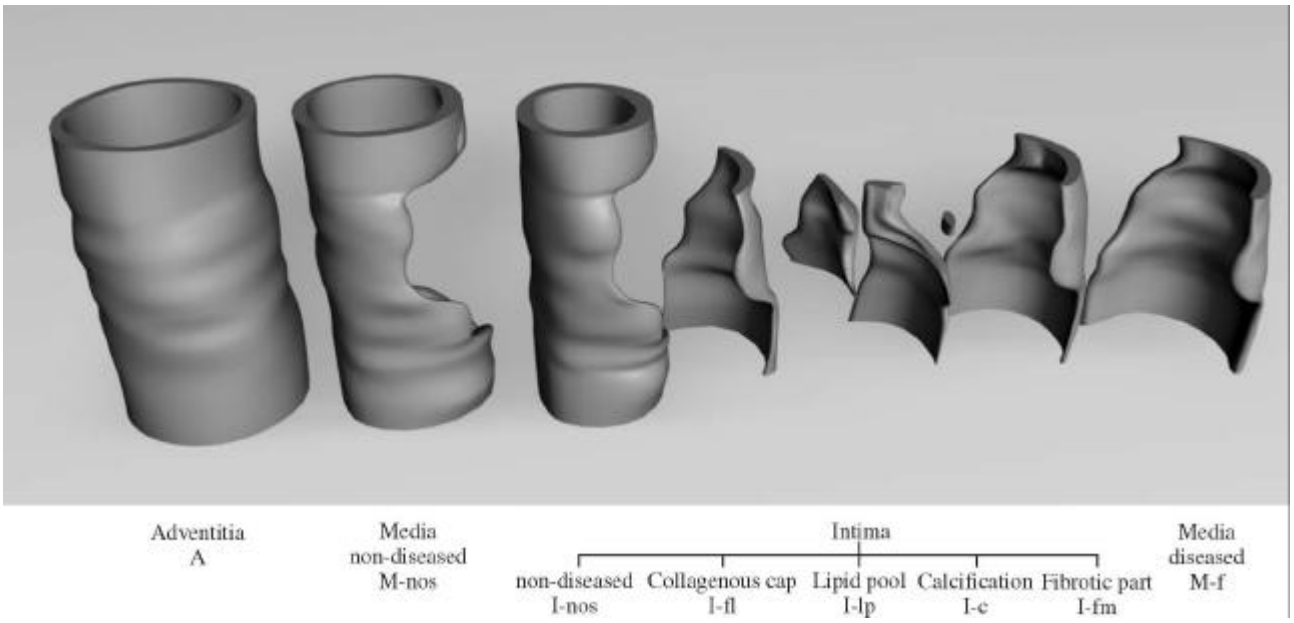

Figure. 3D reconstruction of eight distinct components of a human stenotic artery distinguished by two major regions: the *non-diseased wall* (consists of I-nos, M-nos and the associated part of A), and the *eccentric plaque region* (consists of I-fl, I-lp, I-c, I-fm, M-f and the associated part of A).

nos, diseased fibrotic media M-f and adventitia A [7,8]. From these components, stripes with axial and circumferential orientations were cut out and underwent cyclic uniaxial extension tests with continuous recording of tensile force, stripe width and gauge length at a constant crosshead speed of 1.0 mm/min. For most specimens preconditioning was achieved by executing five successive loading cycles. Typical specimen geometries can be estimated from the figure above. The calcification and the lipid pool were excluded from the tests and considered as rigid body and incompressible (very soft) solid, respectively.

Based on the classification scheme described above, a three-dimensional geometrical model of the considered stenosis was generated using interpolation between the 21 serial high-resolution magnetic resonance slices. The figure shows the three-dimensional reconstruction of the eight distinct tissues of the human artery.

The 3D finite element realization considers the balloon-artery interaction and accounts for vessel-specific axial *in situ* pre-stretches. 3D stress states of the investigated artery during balloon expansion and stent deployment were analyzed. Furthermore, we studied the changes of the 3D stress state due to model simplifications, which are characterized by neglecting axial *in situ* pre-stretch, assuming plane strain states and isotropic material responses, as commonly utilized in previous works. Since these simplifications lead to maximum stress deviations of up to 600% - where even the stress character may interchange - the associated models are in general inappropriate. The proposed approach provides a tool that has the potential (i) to improve procedural protocols and the design of interventional instruments on a lesion-specific basis, and (ii) to determine post-angioplasty mechanical environments, which may be correlated with restenosis responses.

Financial support for this research was provided by the *Austrian Science Foundation* under START-Award Y74-TEC. This support is gratefully acknowledged.

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