Growth and remodeling of arterial tissue

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Growth and Remodeling of Arterial Tissue

I. Machyshyn¹, P. Bovendeerd¹, A. van de Ven², P. Rongen³, F. van de Vosse¹

¹ Biomechanics & Tissue Engineering (BMTE), Cardiovascular Biomechanics

² Mathematics and Computer Science, TU/e

³ X-ray Pre-development, Philips Medical Systems, Best

Introduction

Living tissues continuously undergo growth, i.e. reorganization or renovation, and remodeling, i.e. a change in mass. Modeling both growth and remodeling (G&R) of the vascular tissue is aimed to provide the insight into the adaptation of the tissue, in the healthy and diseased state, and upon surgical intervention.

Material and methods

We model the tissue as two component constrained mixture, composed of anisotropic collagen fibres, and an isotropic matrix. The remodeling of the tissue is attributed to the degradation and the deposition of collagen. To keep track of properties of collagen fibres deposited at different times, we consider a *collagen generation*, a bundle of collagen fibres, deposited at time interval $(t, t+\Delta t)$.

Collagen degradation. Generations degrade with time, gradually decreasing their mass, until complete disappearance.

Collagen deposition. To compensate for the loss of collagen, a new collagen generation is created (Fig. 1).

Fig.1 Scheme of collagen degradation and deposition. At $t=t_n$ a collagen generation, represented by the black lines is present in the tissue. At $t=t_{n+1}$ the black generation has degraded partially, whereas a new (blue) generation is created. Finally, at $t=t_{n+2}$ the blue generation starts degrading, the black one vanishes almost completely, and the red one is just deposited

Directions of collagen fibres belonging to the new generation form a distribution, which depends on the local principal stretch directions of the tissue v_1 and v_2 (Fig. 2).

Each individual deposited collagen fibre is supposed to attach to the tissue with a constant prestretch λ_a , which is the collagen stretch at the homeostatic state. The unstretched length of collagen fibres is governed by remodeling history, and may, therefore, differ over the generations (Fig. 3).

Fig. 2 Distribution of collagen fibre directions of collagen generation at the moment of its creation. The fibre directions are presented with respect to local principal stretch direction of largest stretch; μ is the main fibre angle

Fig.3 Stretch of collagen fibres, belonging to the black, the blue, and the red collagen generations, see Fig. 1

The rate of total mass of collagen is given by

$$\dot{M}_c(t) = \dot{M}_c^{(h)}(t) + \dot{M}_c^{(e)}(t),$$

where

$$\dot{M}_c^{(e)}(t) = K_g (\bar{\lambda}_c - \lambda_a),$$

$\dot{M}_c^{(h)}(t)$ the homeostatic production of collagen compensating for collagen degradation, $\dot{M}_c^{(e)}(t)$ the extra collagen production triggered by the violation of homeostatic stretch state, $\bar{\lambda}_c$ the collagen stretch averaged over generations and directions, and K_g is the coefficient of growth.

Tissue growth. The extra mass $\dot{M}_c^{(e)}(t)$ corresponds to a distribution of a relative volume change $J_g^{\text{des}}(t)$ throughout the tissue, that must be accommodated in a compatible way, maintaining tissue integrity. This is realized through a growth mechanics computation, using the following constitutive relation that drives the tissue to the desired volume change

$$\sigma^{\text{virt}} = \kappa (J_g - J_g^{\text{des}}) \mathbf{I} + \frac{c}{J_g^{\text{des}}} (\mathbf{F}_g \mathbf{F}_g^T - J_g^{2/3} \mathbf{I}), \quad (1)$$

with σ^{virt} the virtual tissue stress during growth, κ and c the bulk modulus and the shear modulus of the matrix respectively, $J_g = \det \mathbf{F}_g$ the actual volume change realized. The deformation gradient $\mathbf{F}_g$ is determined on satisfying an equilibrium condition $\text{div } \sigma^{\text{virt}} = 0$, and stress free boundary conditions in load free configuration using (1).

Results

The model was tested by determining a homeostatic state of cylindrical artery. At this state collagen stretch equals λ_a at each fibre direction, yielding no extra collagen production, and, consequently, no growth. Distribution of fibre directions is the same for all generations, changing in radial direction only. The results shown in Fig. 4 suggest that collagen fibres at the outer surface are more axially oriented and less uniform than the fibres at the inner surface, which is in agreement with histology.

Fig. 4 Distribution of collagen fibre angles with respect to the circumferential direction, at different radial positions of cylindrical artery at homeostatic state

Future work

Presented model of arterial G&R will be applied to cerebral arteries in order to predict aneurysm development.