Remodeling of the collagen architecture in cardiovascular tissues

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Introduction

To optimize mechanical conditioning protocols of tissue-engineered (TE) load bearing cardiovascular constructs, a mathematical model is developed that relates changes in the collagen architecture (i.e., remodeling) to the local mechanical condition within the tissue. The model is applied to predict the typical collagen architecture present in arteries and aortic valves (Fig. 1).

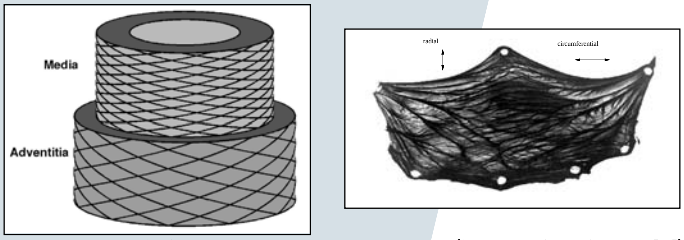

Fig. 1: *Typical fiber architecture in an artery (left, modified from [1]) and branching collagen architecture in a native leaflet (right, [2]).*

Materials and methods

The tissues are modeled as incompressible fiber reinforced materials and a structurally-based constitutive model is used that enables incorporation of the angular distribution of collagen fibers [3]. The in-plane distribution of fiber volume fractions (ϕ_f) is modeled by a periodic version of the normal probability distribution function:

$$\phi_f(\gamma) = A \exp\left[\frac{\cos\left[2(\gamma - \alpha)\right] + 1}{\beta}\right] \quad (1)$$

with γ the in-plane angle, α the main fiber angle and β the dispersity of the fiber distribution function. Stimulus functions (g_1 and g_2) in the principal directions (v_1 and v_2) are introduced to specify the value of the main fiber angle and the dispersity:

$$\alpha = \arctan(g_2/g_1) \quad (2)$$

$$\beta = \begin{cases} \frac{k}{(g_1/g_2)-1} & \text{for} \quad g_1 \geq g_2 \\ \frac{k}{(g_2/g_1)-1} & \text{for} \quad g_1 < g_2 \end{cases} \quad (3)$$

The stimulus functions are assumed to depend on the mechanical loading condition within the tissue, i.e., $g_i = g_i(\lambda_i, \sigma_i)$. The stimulus functions are specified such that: (1) for a uniaxial loading condition all fiber directions align with the major loading direction, (2) in case of a biaxial loading condition, the fiber families are situated in between the major directions with the main orientation and dispersity depending on the ratio of g_1 and g_2, and (3) for an equibiaxial loading condition, the fibers are distributed uniformly in the plane of the major directions $\vec{v}_1$ and $\vec{v}_2$.

The artery is modeled as a thick-walled cylinder, which is inflated by an internal pressure and stretched longitudinally. The aortic valve is modeled as a leaflet with uniform thickness and is loaded by a transvalvular pressure in the diastolic (i.e., closed) configuration.

Results

The predicted fiber directions in the arterial wall represent helical paths. The pitch of the helix and the dispersity of the fiber distribution increases from the inner wall towards the outer wall (Fig. 2), in accordance with observations from literature.

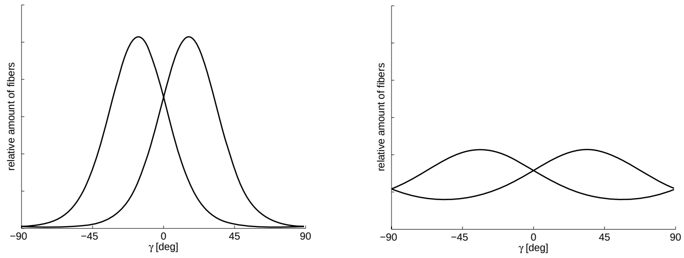

Fig. 2: *Angular fiber distribution at inner side (left) and outer side (right) of the arterial wall.*

For the aortic valve, the model predicts a branching diverging fiber architecture (Fig. 3) that resembles the hammock-type collagen network of native valve leaflets.

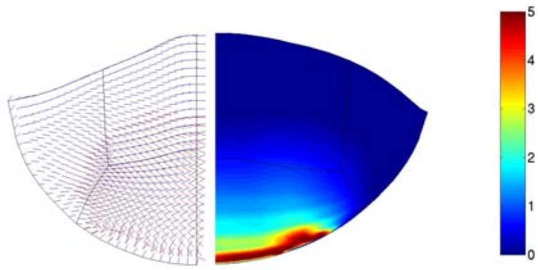

Fig. 3: *Predicted fiber directions (left) and dispersity of fiber distribution (right).*

Discussion

- ☐ The model considers the interaction between 1) the mechanical loading condition within the tissue and 2) changes in the collagen fiber architecture.
- ☐ The predicted collagen architecture is qualitatively consistent with experimental observations from literature.
- ☐ Experiments have to be performed to further validate the model quantitatively.

References:

[1] Holzapfel et al., J. Elasticity, 2000, 61, 1-48.

[2] Sauren, A.A.H.J., PhD thesis, Technische Hogeschool Eindhoven, 1981.

[3] Driessen et al., J. Biomech. Eng., 2005, 127, 494-503.

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