Remodelling in statistically oriented fibre-reinforced materials in the arterial wall and its surrounding tissue

Fabrizio Gaudenzi¹, Maria T. Missanelli² *, Alfio Grillo³, Alberto P. Avolio⁴

¹IUSS di Pavia
Piazza della Vittoria 15, I-27100, Pavia, Italy
fabrizio.gaudenzi@gmail.com

²AL.MEC S.R.L.
Via Torino 172, I-12063, Dogliani (CN), Italy
missanelli@almec.net

³DISMA “G L Lagrange”, Politecnico di Torino
Corso Duca degli Abruzzi 24, I-10129, Torino, Italy
alfio.grillo@polito.it

⁴The Australian School of Advanced Medicine
2 Technology Place, Macquarie University NSW 2109, Australia
alberto.avolio@mq.edu.au

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ABSTRACT

The artery has a multilayer structure in which three main strata can be distinguished. From the innermost to the outermost, these are named intima, media, and adventitia. The intima consists of endothelial cells.

The media is mainly made of muscle and collagen fibrils, and features several fiber-reinforced layers.

The adventitia is prevalently made of thick bundles of collagen fibers that are arranged helically. Several arterial models have been proposed in which different mechanical behaviors have been assumed [1, 2, 3]. In the last decades, this soft tissue has been studied by adopting symmetry assumptions about its geometry, which has been taken to be a circular cylindrical tube made of a fiber-reinforced hyperelastic material [4, 5, 6]. Moreover, the distribution of fibers has been often assumed to be deterministic. For a young and healthy artery, Holzapfel [5] considered an incompressible two-layer structure (media and adventitia) in which the preferred orientation of the collagen fibers for each layer was recovered from histological information [2, 3].

In the case of hyperelastic materials undergoing large deformations, the orientation of the fibers has been accounted for by introducing the relative structure tensor in the strain energy function [7, 8]. The mechanical response of the artery subjected to both static and dynamic boundary loading conditions has been retrieved by means of a three-field Hu-Washizu variational approach with an augmented Lagrangian optimization technique in a finite element implementation [5].

We modeled the radial artery at the wrist and the surrounding tissue as a two-layer cylinder with a reticular dermis jacket. Each layer of the resulting three-layer model is treated as a fiber-reinforced material. The model predicts the displacements of this biological structure under physiological pressure conditions, and it allows for the extrapolation of the general stretch behavior of the different layers [9]. Moreover, we drop the hypothesis that the biological structure exhibits axial-symmetry. We do this with the purpose of making our model more suitable for arteries of irregular shapes, as it may happen in the
case of damaged, or old, blood vessels. Moreover, we consider the remodeling process as the evolution of the internal structure, namely the reorientation of the fibers, under mechanical stimuli.

The radial artery is a distal, medium-sized artery. Its media is prevalently made of muscular fibers. At the wrist, the surrounding adipose layer is relatively thin, and can thus be assumed to have a negligible effect on the tissue’s overall mechanical response. In our model, the structure of the considered soft tissue sandwich consists of a common matrix, a circumferential muscular fiber in the media, double-helically coiled collagen fibers in the adventitia, and collagen fibers arranged along the circumferential and longitudinal directions in the dermis.

In [9], a one-dimensional finite element analysis has been performed in quasi-static conditions, under the hypothesis of cylindrical geometry, and by assuming only radial displacement across the sandwich thickness at internal systolic pressure. This study aimed to assess the relationship between the subtle motions of skin arising from blood flow in the artery at physiological pressures. The obtained one-dimensional displacement is consistent with those that may be inferred from previous studies and/or comparable with existing data, although in the numerical simulation we treat the tissue sandwich as a compressible material. The constitutive framework is easily adaptable to other types of arteries by suitably adjusting the biomechanical parameters.

We intend to perform the finite element analysis of the considered tissue by removing the hypothesis of axial-symmetry of the computational domain, and accounting for the inertial term previously neglected in the equilibrium equation. In addition, we will study the remodelling phenomena with a statistical distribution of fibers [10, 11]. In particular, we postulate that the strain energy function of a layer, \( l = 1, 2, 3 \), is obtained from the superposition of the contribution provided by the matrix (which is assumed to be isotropic), \( W_m \), and that supplied by a finite number of families of fibers. The strain energy of the \( f \)th family of fibers in the \( l \)th layer is denoted by \( W_{lf} \), and is taken to be a function of \( C \), and the material structure tensor \( A(M) = M \otimes M \). The fibers of the \( f \)th family are assumed to be oriented statistically according to the probability density distribution \( P \). Therefore, the strain energy of the \( l \)th layer, \( W^l \), reads

\[
W^l = W^l_m(C) + \sum_{f}^{N_f} \int_{S^2} P(\Theta_f, \lambda_f, M) W_{lf}(C, A(M)) \, dS, \quad l = 1, 2, 3,
\]

where \( \Theta_f \) is the mean angle, \( \lambda_f \) is the square root of the variance of \( P \), and \( S^2 \) is the set of all directions in space. This form of the overall strain energy has been suggested in [12, 13].

Under the assumption of almost incompressible material, we adopt a finite element implementation with the mean dilatation technique, based on the Uzawa algorithm for the Schur complement of the system arising from the mechanical balance equations.

The scope of the simulations is to evaluate the outer deformation of the tissue in response to the dynamic inflation of the arterial segment subjected to sinusoidal pressure loads, which reproduce a physiological pulse wave.

References


