Linking microstructure with mechanical behavior on the thoracic aorta: a multiscale approach

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Abstract

Biomechanical analysis of soft tissues has emerged as a significant objective in recent years. This discipline seeks to improve our understanding of tissue behavior in both clinical and pathological conditions by studying the correlation between healthy and diseased tissues through mechanical tests, typically associated with the measurement of stiffness.

In terms of mechanical strength, collagen is the main protein that confers stiffness to the tissue. The vessel's collagen structure is composed of bundles of collagen fibers that are arranged in a helical pattern around the vessel. Even so, the mechanical contribution of collagen does not start immediately with deformation. Instead, the wavy collagen fibers are continuously recruited as the tissue undergoes deformation, resulting in a highly non-linear stiffening behavior. Hyperelastic and non-linear macroscopic responses of the tissue are significantly affected by the spatial and waviness distribution of this protein chain (1).

The fiber-reinforced-like constitutive models have been extensively used to study the mechanical response of arterial tissue. Those models describe the overall response of the material as a contribution of an isotropic energy term, representing the extracellular matrix of the tissue, and the contribution of an anisotropic term accounting for the collagen contribution. The collagen contribution is usually modeled with an exponential term.

Even though these models can describe the overall macroscopic mechanical response, the material parameters do not correlate directly with the microstructure of the material, and the mechanical parameters can be difficult to interpret in terms of the microscopic characteristics. Furthermore, modern techniques, such as confocal imaging or second harmonic generation, can be used to measure microstructural changes in tissue samples under many conditions. Therefore, the gap between mathematical formulations and the mechanical and geometrical composition of the material should be addressed, to better understand the complex mechanobiological relationships between microstructure alterations and mechanical loading.

Multiscale analysis is a tool that allows the understanding of the individual contribution of mechanically relevant components to the macroscopic response of different materials using a representative volume element (RVE) (2). This RVE is constructed using simple constitutive

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relations for each mechanical constituent, where the macroscopic response is obtained as a homogenized value of the microscopic stresses.

In the context of this investigation, an RVE is modeled as an isotropic hyperelastic ground material, representing the tissue extracellular matrix, and a set of unidimensional elements that account for the collagen fibers. The proposed constitutive model of each collagen fiber corresponds to a linear elastic model, with an offset to account for the recruitment stretch of each fiber. The exponential stiffening of the macroscopic stress is a result of the progressive recruitment of many fibers.

This research focuses on the mechanical behavior of the thoracic aorta in a wistar rat model. Through the use of confocal microscopy, the geometrical distribution of collagen orientation is measured, and the mechanical properties at a constituent level are obtained using other manuscript references. The implementation and verification of a multiscale analysis for aortic tissue is developed using the plugin framework of the FEBio software (3) and contrasted with planar biaxial data from experiments on this tissue.

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