MICROSTRUCTURE-INSPIRED MULTISCALE MODELING OF ARTERIAL TISSUE

M. Pétré[1,2,3], L. Maes[3], G. Hanon[1], M. Dalbosco[4,5], G.A. Holzapfel[4,6], L. Delannay[1], G. Kerckhofs[1,2,7,8], N. Famaey[3,9]

[1]Institute of Mechanics, Materials and Civil Engineering (iMMC), UCLouvain, Belgium; [2]Institut de recherche expérimentale et Clinique (IREC), UCLouvain, Belgium; [3]Department of Mechanical Engineering, KU Leuven, Belgium; [4]Institute of Biomechanics, Graz University of Technology, Austria; [5]GRANTE, Department of Mechanical Engineering, Federal University of Santa Catarina (UFSC), Brazil , [6]Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway; [7]Department of Materials Engineering, KU Leuven, Belgium; [8]Prometheus, Division of Skeletal Tissue Engineering, KU Leuven, Belgium, [9]FIBEr, KU Leuven Core Facility for Biomechanical Experimentation

Introduction

Atherosclerosis is one of the most common causes of mortality, characterized by the accumulation of plaque and fatty deposits in the blood vessels, leading to occlusion. Although treatment options such as balloon angioplasty are available, their success is frequently hampered by an insufficient understanding of the intricate relationship between the tissue microstructure and mechanical behaviour of the vessel. Representative volume element (RVE) models offer a microstructurally informed approach and provide insights into how changes in microstructure affect the mechanical behavior of blood vessels, enabling a better understanding in disease progression. There are several RVEs for arterial tissue available.

For example, in [1], a defined RVE incorporates two collagen fiber families that use embedded truss elements in a solid matrix to capture their orientation and dispersion. However, the elastin constituent is absent in this RVE as a separate phase, although it is abundant in the aorta. In this study, the model from [1] was expanded to include elastin constituents in the RVE model.

Methods

Microstructural parameters were derived from 3D contrast-enhancing computed tomography images of the medial porcine aortic layer [2] and relevant literature studies using scanning electron microscopy (SEM) [3,4]. It was shown that elastic lamellae are on average 15µm thick and spaced by 15µm [2]. Consequently, the 120 x 120 x 65 µm³ RVE consists of five 15µm thick elastic lamellae spaced by 15µm. Collagen fibers between elastic lamellae are periodic and follow a preferred orientation and dispersion determined by probability density functions [1]. In addition, elastin struts and interlamellar elastin fibers (IEFs) are introduced between the lamellae, connecting the lower plane to the upper, as depicted in SEM images [3,4]. The different constituents of the model are embedded in the ground matrix. Truss elements (T3D2) are selected for collagen fibers, elastin struts, and IEFs, shell elements (S4R) for the elastic lamellae, and solid elements (C3D8RH) for the ground matrix, as shown in Fig. 1.A. The same neo-Hookean material model was applied for the elastin constituents, while the ground matrix is also modeled with a neo-Hookean material. Finally, analogous to [1], a user-defined material model (UMAT) for the collagen fibers with periodic boundary conditions is implemented in Abaqus.

Results

A uniaxial tensile test up to 20% is carried out in Abaqus. A macroscopic response was obtained by homogenizing the microscopic fields (Fig. 1.B).

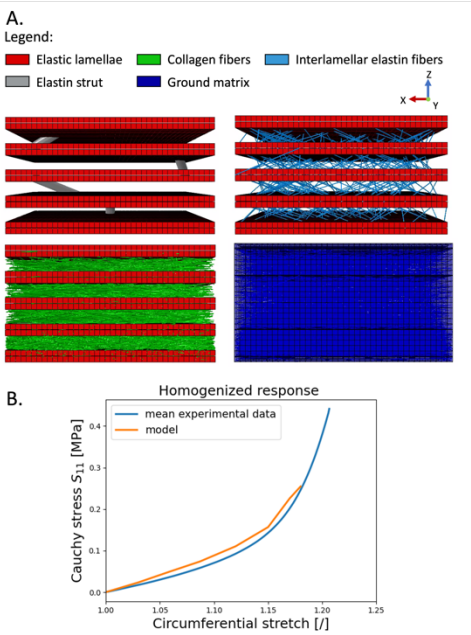

Figure 1: A. RVE model representing the medial layer of the porcine aortic wall. Elastic lamellae are shown in red. Elastin struts and interlamellar elastin fibers are shown in grey and light blue. Collagen fibers are shown in green and the ground matrix in which all other elements are embedded is shown in dark blue. B. Macroscopic response of the RVE model compared to experimental uniaxial tensile tests performed on the entire porcine aortic wall (n=8).

Discussions

The model response fits well with the experimental behavior, see Fig. 1.B. The elastin constituents contribute mainly at the beginning of the curve, while the exponential behavior is obtained by the contribution of collagen fibers and their recruitment stretch implementation [1]. Care must be taken when comparing the experimental and model curves because the model represents only the medial part of the wall, while the experimental test includes all three layers. Future refinements may include new experimental data only on the porcine medial layer.

References

1. M Dalbosco et al., Comput Meth Appl Mech Eng, 381:113844, 2021.
2. L Leyssens et al., Acta Biomater, 164:303-316, 2023.
3. MK O'Connell et al., Matrix Biol, 27:171-181, 2008.
4. A Giudici, et al., IEEE Rev Biomed Eng, 14:256-269, 2021