MicroCT-inspired multiscale modeling of arterial tissue

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Arteries undergo continuous growth and remodeling processes driven by complex interactions between microstructural constituents and pulsatile blood flow. To gain a deeper understanding of these intricate microstructural interactions and their effect on the tissue scale, a representative volume element (RVE) approach can be used. Several RVEs for arterial tissue are available. In, e.g., [1] a RVE was defined that has two collagen fiber families incorporating their characteristic orientation and dispersion through the use of embedded truss elements in a solid matrix. However, the elastin constituent was not represented in the RVE, although it is very present in the aorta.

In the current study, the model in [1] was extended by incorporating elastin constituents into the RVE model, where the microstructural parameters are derived from 3D contrast-enhancing computed tomography images of the medial layer of the porcine aortic wall [2], and from relevant literature studies using scanning electron microscopy [3,4]. The RVE has a physical size of 140 x 140 x 120µm^3 and includes five elastic lamellae, each 15µm thick, arranged at 10µm intervals. Between the elastic lamellae there are collagen fibers, whose preferred orientation and dispersion is determined by probability density functions [1]. Additionally, elastin struts and interlamellar elastin fibers (IEFs) are introduced between the elastic lamellae, acting to bind the lower plane to the upper one. The different constituents in the model are embedded within the ground matrix. Truss elements (T3D2) are selected for collagen fibers, elastin struts and IEFs, shell elements (S4R) for the five elastic lamellae, and solid elements (C3D8RH) for the ground matrix, as shown in Fig. 1A. For the elastin constituents the same neo-Hookean material model was applied, while the ground matrix is also modeled with a neo-Hookean material. Finally, a user-defined material model (UMAT) for the collagen fibers is implemented, similarly to [1], with periodic boundary conditions. A uniaxial tensile test up to 15% is carried out in Abaqus. The macroscopic response is obtained by homogenizing the microscopic fields. The model response is almost linear and differs from the exponential behavior observed in the experimental data, see Fig. 1B. However, caution is required when comparing, as the model represents only the medial part of the wall, while the experimental test includes all three layers, with the adventitia being particularly rich in collagen.

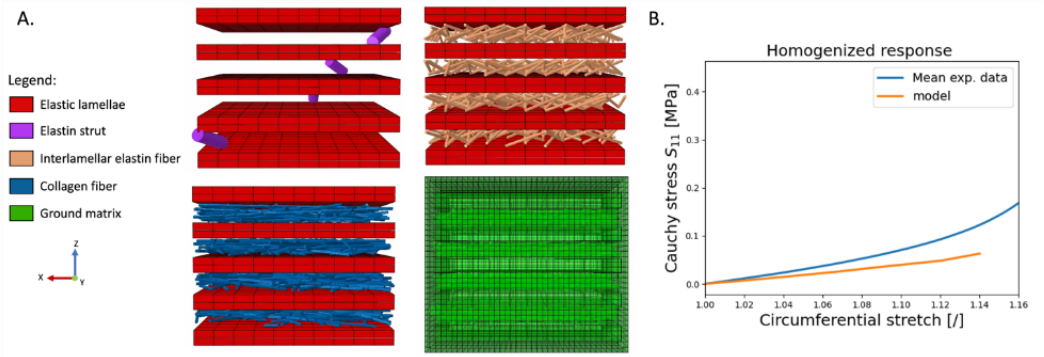

Figure 1: A. RVE model representing the medial layer of the porcine aortic wall. Elastic lamellae are shown as shell elements in red. Elastin struts and interlamellar elastin fibers are shown in white and blue with truss elements. Collagen fibers are shown in purple with truss elements and the ground matrix in which all other elements are embedded is shown in green with C3D8RH elements. B. Macroscopic response of the RVE model compared to experimental uniaxial tensile tests performed on the entire porcine aortic wall (n=8).

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.