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THE MICROSTRUCTURE OF THE ADVENTITIA EXPLAINS ITS MACROSCOPIC MECHANICAL BEHAVIOR

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ABSTRACT

The arterial adventitia, like many other soft biological tissues, displays a highly anisotropic and nonlinearly elastic mechanical behavior, with a well-known J-shaped stress-stretch curve. The anisotropy of the tissue is due to the particular arrangement of the collagen fibers around two preferential orientations. The strong nonlinearity in the mechanical behavior is due to the progressive activation of fibers with deformation, in a process called recruitment.

Several constitutive models can be found in the literature that successfully describe this behavior at macroscopic (continuum) levels. Some of them explicitly include two anisotropy directions that take into account the effect of the collagen in the tissue [1].

At micro- and nanoscopic levels, however, the available models are unable to explain experimental data. Our investigations with small angle X-ray scattering (SAXS) techniques show that, under uniaxial stretch, the local fiber orientations are arranged around a single direction, which coincides with the loading direction [2]. Moreover, preconditioning alters the original isotropic distribution, so that the nanoscopic structure is anisotropic after only one preconditioning cycle. In addition, although the ultimate stress and stretch are sample-dependent, the distribution of the local fiber orientations is the same for every sample.

Under biaxial deformations, the distribution of the fiber orientations depends on the ratio of the circular and axial stretches, as shown in Fig. 1. Changing the ratio of stretches λ_y/λ_x alters the distribution of the orientations, so that values close to 1 show two different fiber families, while for values far from one only one peak is seen. After preconditioning, this process is reversible, so that returning to a given λ_y and λ_x gives the previous distribution.

Paradoxically, although the material is elastic and deformations are reversible, the above experimental results cannot be captured by affine transformations of the fiber orientations. In order to explain the data, we propose a model where the material architecture is described in more detail. The individual fibers, which are crimped but locally highly coherent, group into bundles. These can rotate with relative freedom, and form a three-dimensional, loosely coupled mesh where the nodes are created through interaction between bundles, and kept in place by friction as long as the bundles are in contact. When

two bundles touch, a new node in the mesh is created, which shortens the rotating length and locally restricts movement. Further deformation makes the bundles rotate around this node, while decreasing it makes the interaction disappear. The geometric characteristics of the mesh (e.g. average bundle diameter) limit the number of interactions that can happen.

The presentation will discuss these ideas and how they can simultaneously explain the experimental data at nanoscopic scale and the macroscopic mechanical behavior of collagen-rich soft biological tissues, especially the arterial adventitia.

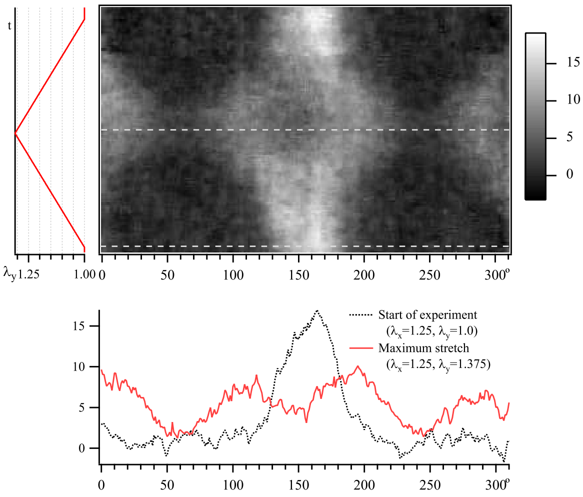

Figure 1: Change in the orientation distribution with biaxial stretch. The sample was stretched in the axial direction while held at a constant prestretched circumferential length (λ_x= 1.25). Top left: Stretch-time plot; Top right: Orientation-time contour. The X-axis represents fiber orientation in degrees (the circumferential direction lies at 150º); the Y-axis displays time in arbitrary units. Bottom: Profile curves at the positions marked in the top figure. The scale in both plots indicates peak height in arbitrary units.

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