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Spatial orientation of collagen fibers in the abdominal aortic aneurysm's wall and its relation to wall mechanics

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ABSTRACT

Collagen is the most abundant protein in mammals and provides the abdominal aortic aneurysm (AAA) wall with mechanical strength, stiffness and toughness. Specifically, the spatial orientation of collagen fibers in the wall has a major impact on its mechanical properties. Apart from valuable microhistological information, this data can be integrated by histomechanical constitutive models thought to improve biomechanical simulations, i.e. to improve the biomechanical rupture risk assessment of AAAs. Tissue samples ($n = 24$) from the AAA wall were harvested during elective AAA repair, fixated, embedded, sectioned and investigated by polarized light microscopy. The birefringent properties of collagen were reinforced by picrosirius red staining and the three-dimensional collagen fiber orientations were identified with a universal rotary stage. Two constitutive models for collagen fibers were used to integrate the identified structural information in a macroscopic AAA wall model. The collagen fiber orientation in the AAA wall was widely dispersed and could be captured by a Bingham distribution function ($\kappa_1 = 11.6, \kappa_2 = 9.7$). The dispersion was much larger in the tangential plane than in the cross-sectional plane, and no significant difference between the medial and adventitial layers could be identified. The layered directional organization of collagen in normal aortas was not evident in the AAA. The collagen organization identified, combined with constitutive descriptions of collagen fibers that depend on its orientation, explain the anisotropic (orthotropic) mechanical properties of the AAA wall. The mechanical properties of collagen fibers depend largely on their undulation, which is an important structural parameter that requires further experimental investigation.

1. Introduction

Ruptures of abdominal aortic aneurysms (AAAs) account for a large number of deaths, particularly in older men [20,36], and elective repair is indicated if the risk of aneurysm rupture exceeds the interventional risks. The clinically most frequently used indicator of the need for elective repair is the maximum diameter [1]. An AAA ruptures if the mechanical stress exceeds the local wall strength, hence alternative parameters to assess AAA rupture risk such as peak wall stress (PWS) [18,24,40,55] and peak wall rupture risk (PWRR) [24,40] are valuable. The computation of PWS and PWRR requires detailed knowledge of the constitutions of aneurysm tissues. Similar to other biological tissues, the mechanical properties of the aneurysm wall, such as strength, stiffness and toughness, depend to a large extent on the amount and spatial orientation of collagen [14,21].

Collagen is one of the most dominant structural proteins, and is critically involved in the gradual remodeling and weakening of the aneurysm wall [8]. Specifically, collagen fibrils are the basic building blocks of fibrous collagenous tissues [21], and their organization into suprafibrillar structures strongly influences the tissue's macroscopic mechanical properties. Consequently, biomechanical [29,39] studies invariably show that the mechanics of the arterial wall has a strong dependence on fibrillar collagens in media and adventitia. Collagen types I and III form about 90% of all collagen in the aortic wall, where the type I:type III ratio of about 74:26 remains unchanged between normal and aneurysmic walls [45,33]. While elastin almost disappears in large AAAs, the collagen content increases by about 50% compared to in the normal aorta [45]. Information of the collagen organization in the AAA wall permits a qualitative biomechanical understanding. However, the challenge is to relate it to engineering concepts and constitutive models, i.e. mathematical descriptions of biomechanical properties. Numerous constitutive models have been reported for soft biological tissues [16,17,25,30,37,41,44,52,53], some of which, denoted as

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