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Effects of the three-dimensional residual stresses on the mechanical properties of arterial walls

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HIGHLIGHTS

- Layer-specific three-dimensional residual stresses considering the bending and stretching both in the circumferential and axial directions of the three distinct layers of an arterial wall are discussed.
- Distributions of the three-dimensional residual stresses through the different layers of an arterial wall are given.
- The bending in the axial direction of the media significantly affects the global deformation and the stress distributions of arterial walls.

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ABSTRACT

Effects of the three-dimensional residual stresses on the mechanical properties of arterial walls are analyzed in this paper, based on the model which considered the bending and stretching both in the circumferential and axial directions of the three distinct arterial layers. Moreover, different constitutive models are proposed to quantify the nonlinear mechanics of the three distinct layers and the important constituents, i.e. elastin, collagen fibers and smooth muscle cells (SMCs), are all taken into account. The stress distributions and pressure–radius curves of the arterial wall are given in details. Results demonstrate that the maximum values of the circumferential stress and the corresponding stress gradient in the media under the mean arterial pressure are reduced significantly as a consequence of the SMCs. The bending in the axial direction of the media and the opening angle of the intima have an obvious impact on the mechanical behaviors of arterial walls. This study may not only develop the understanding of effects of the three-dimensional residual stresses on the arterial wall response, but also can increase the accuracy of the analyses for patient-specific studies used for the treatments of arterial diseases.

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1. Introduction

In the last decades, mechanical behaviors of soft biological tissues such as the arterial wall have got extensive attentions in the literatures. The reason may be that vascular diseases have become a leading cause of death worldwide. At the same time, the current treatments are not only very expensive but also high-risk (Humphrey, 2002a, 2002b; Vorp, 2007). It is generally believed that biomechanics mechanism may be important in the triggering of vascular diseases. Thus, in order to improve the treatments, the mechanical properties of vascular diseases need to be fully understood (Holzapfel et al., 2000; Taylor and Humphrey, 2009).

In a soft biological solid tissue, as its macroscopic mechanical properties are closely related to its internal micro-structure (Gasser et al., 2006), it is necessary to study the micro-structure of the arterial wall (Holzapfel et al., 2004; Gundiah et al., 2009; Watton et al., 2009; Schmid et al., 2013). Insight into its micro-structure, the arterial wall is a multi-layered structure composed of three distinct layers: the intima, media and adventitia. The load-carrying capability of the intima is contributed by the sub-endothelial layer consisting of the elastin and collagen fibers (Gasser et al., 2006). For the media and adventitia, the elastin and bundles of collagen fibers are both the main influence factors on the load-carrying capability, while the smooth muscle cells (SMCs), which are contained in the media, only affect the mechanical properties of the media.

Referring previous works (Holzapfel and Weizsäcker, 1998; Holzapfel, 2006; Watton et al., 2009; Schriefl et al., 2015), the elastin of arterial wall was usually treated as a neo-Hookean material and it is reasonable by the work of Gundiah et al.

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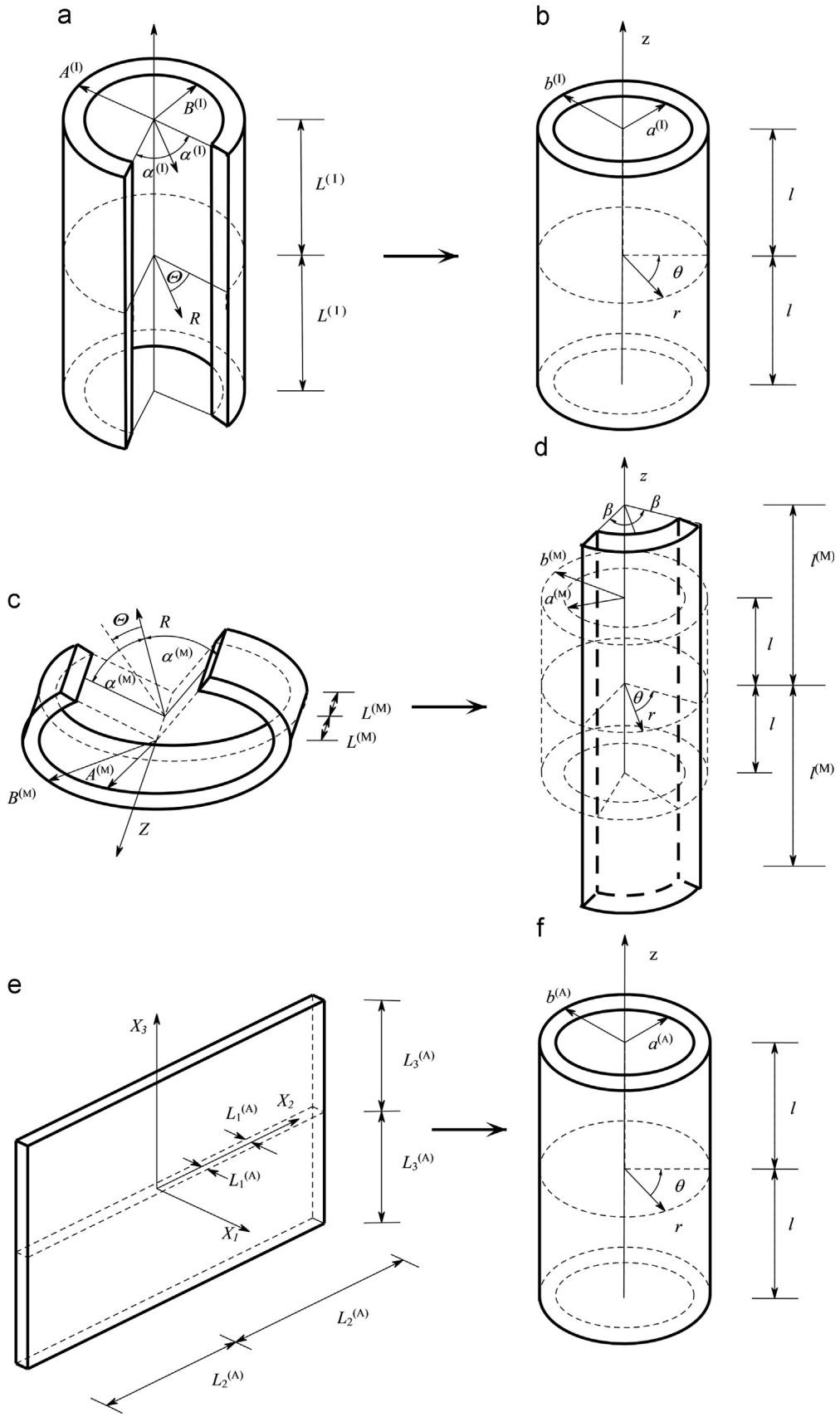

Fig. 1. Coordinate systems and related geometries of the intima, media and adventitia in their stress-free reference configurations (a, c, e), and load-free configurations (b, d, f), respectively. (It is based on the Fig. 4 of Holzapfel and Ogden (2010b)).

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