ON MODELLING THE MULTILAYER RESPONSE OF AORTA USING LAYER-SPECIFIC EXPERIMENTAL DATA

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Introduction

Healthy arteries are composed of three clearly defined layers; the intima consists of a single layer of endothelial cells, a thin basal membrane and a sub-endothelial layer; the media is composed of a 3D network of elastin, smooth muscle cells and collagen fibres; and the adventitia consists of fibroblasts, fibrocytes, ground matrix and thick bundles of collagen fibres.

To ideally describe the arterial wall from the mechanical point of view, three separate layers of this tissue are required for intima, media and adventitia layers. The reason for considering three separate layers also arose from histology of arteries because the composition of intima, media and adventitia layers (elastin, collagen and cell contents) is different. Since residual stresses have a strong influence in the final stress distribution within the arterial wall [1], including the residual stresses presented in a vessel is of paramount importance for the accurate modeling of their mechanical behavior under physiological conditions. It has been shown that the three individual aortic layers, undergo drastically different residual deformations upon separation.

Methods

To test the capability of the multilayer model, we used previously published layer-specific experimental data relating to the axial pre-stretch, the opening angle, the fiber distribution obtained by polarized light microscopy measurements, and the uniaxial and biaxial response of the porcine descending and abdominal aorta. We fitted the mechanical behavior of each arterial layer using a Gasser, Holzapfel and Ogden strain energy function using the dispersion parameter κ from the experimental fiber distribution. A multilayer finite element model of the whole aorta with the dimensions of the circumferential and longitudinal strips was then built. This model was used to capture the whole aorta response under uniaxial and biaxial stress states. After validation of the multilayer model, a model of idealized descending thoracic aorta was built using the whole sample dimensions and thickness ratio between intima-media-adventitia previously obtained. The effect of the layer specific residual stresses under internal physiological and supra-physiological pressures were studied. A diastolic 9.33 kPa (70 mmHg), physiological systolic 16 kPa (120 mmHg) and supra-physiological systolic pressures 20 kPa (150 mmHg) were considered.

Results

The multilayer model provides a good approximation of the uniaxial and biaxial experimental data only when the residual stresses are included. Results for internal pressure application are shown in Figure 1. It can be clearly observed how the inclusion of residual stresses in the model strongly modifies circumferential stress maps. Maximal circumferential stress values appear in the inner radius when no residual stresses are considered whereas they appear in the outermost radius when residual stresses are accounted.

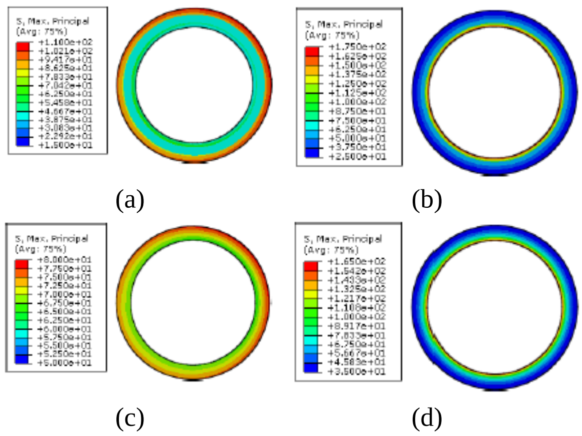

Figure 1. Circumferential stress under internal pressure and residual stress (kPa). (a) three-layer model with residual stresses;(b) three-layer model without residual stresses; (c) one-layer model with residual stresses; and

Discussion

Our results show that strong differences between multilayer models and experimental results can be observed, when residual stresses are neglected. The stress distribution obtained using the monolayer model evolve the discontinuous results obtained by the multilayer model. Accurate mechanical models of the artery are only obtained when a three-layer model with residual stresses are considered.

References

1. Peña, J. A., Martínez, M. A., Peña, E., 2015. Layer-specific residual deformations and uniaxial and biaxial mechanical properties of thoracic porcine aorta. J Mech Behav Biomed 50, 55-9.
2. Alastrué, V., Peñna, E., Martínez, M. A., Doblaré, M., 2007. Assessing the use of the \opening angle method" to enforce residual stresses in patient-specific arteries. Ann Biomed Eng 35, 1821-1837

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