JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 60 (2016) 515–524

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www.elsevier.com/locate/jmbbm

Research Paper

Artery buckling analysis using a two-layered wall model with collagen dispersion

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ARTICLE INFO

Article history:
Received 28 October 2015
Received in revised form
24 February 2016
Accepted 9 March 2016
Available online 16 March 2016

Keywords:
Tortuosity
Mechanical instability
Critical buckling pressure
Two-layered artery wall
Collagen fiber dispersion

ABSTRACT

Artery buckling has been proposed as a possible cause for artery tortuosity associated with various vascular diseases. Since microstructure of arterial wall changes with aging and diseases, it is essential to establish the relationship between microscopic wall structure and artery buckling behavior. The objective of this study was to developed arterial buckling equations to incorporate the two-layered wall structure with dispersed collagen fiber distribution. Seven porcine carotid arteries were tested for buckling to determine their critical buckling pressures at different axial stretch ratios. The mechanical properties of these intact arteries and their intima-media layer were determined via pressurized inflation test. Collagen alignment was measured from histological sections and modeled by a modified von-Mises distribution. Buckling equations were developed accordingly using microstructure-motivated strain energy function. Our results demonstrated that collagen fibers disperse around two mean orientations symmetrically to the circumferential direction (39.02°±3.04°) in the adventitia layer; while aligning closely in the circumferential direction (2.06°±3.88°) in the media layer. The microstructure based two-layered model with collagen fiber dispersion described the buckling behavior of arteries well with the model predicted critical pressures match well with the experimental measurement. Parametric studies showed that with increasing fiber dispersion parameter, the predicted critical buckling pressure increases. These results validate the microstructure-based model equations for artery buckling and set a base for further studies to predict the stability of arteries due to microstructural changes associated with vascular diseases and aging.

1. Introduction

Tortuous arteries and veins, frequently seen in elderly, are associated with aging, hypertension, degenerative vascular disease and atherosclerosis (Del Corso et al., 1998; Han, 2012; Jackson et al., 2005; Nichols and O'Rourke, 1998; Pancera et al., 2000; Weibel and Fields, 1965). In recent studies, artery buckling (loss of mechanical stability) has been proposed as

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http://dx.doi.org/10.1016/j.jmbbm.2016.03.007

a possible mechanism for the development of vessel tortuosity (Han, 2012; Han et al., 2013; Zhang et al., 2014). Since microstructure of arterial wall changes with aging and diseases, it is essential to establish the relationship between microscopic wall structure and artery buckling behavior to better understand artery buckling and tortuosity in vascular disease.

Arterial walls are non-homogeneous with three-layered structure: intima, media, and adventitia. While initial mechanical analysis of arterial wall often simplified the arterial wall as a single layer of uniform wall, current studies often take into account the multi-layered structure of the arterial wall (Fung, 1993; Humphrey, 2002). Though intima with endothelium and base membrane has its distinct function, it is a very thin layer and mechanical often combined with the intima for mechanical analysis. Thus the arterial wall is often divided into two layers for mechanical analysis: Intima-media layer and the adventitia layer with distinct material properties (Bellini et al., 2014; Rachev, 1997; Ren, 2012; Wang et al., 2006; Yu et al., 1993). However, previous artery buckling analyses were limited to single-layered uniform arterial wall assumption (Han, 2009; Rachev, 2009).

The mechanical behavior of arteries depends upon their microstructure, including collagen fiber alignment in the arterial wall (Fung, 1993; Humphrey, 2002; Qi et al., 2015). Micro-structurally motivated constitutive equations have been established to model arterial wall behavior under various conditions (Baek et al., 2007; Holzapfel et al., 2000). We have recently demonstrated that collagen alignment affects artery critical buckling pressure using a four-fiber model (Liu et al., 2014). However, our previous models assumed perfectly aligned collagen fibers and homogeneous artery wall properties (Liu et al., 2014). Canham and colleagues showed that in contrast to media layer, collagen fiber orientation was dispersed in intima and adventitia layers (Canham et al., 1989). The idealized perfectly aligned two fiber family model, though well captures the feature of collagen alignment in the mdia, it is limited in capturing the dispersed distribution of collagen fibers in the adventitia (Gasser et al., 2006; Ren, 2012). An improved model with dispersed collagen fiber distribution is needed to better capture the actual wall structure. To this end, a hyperelastic strain energy function proposed by Gasser et al. (2006) based on generalized structured tensor to characterizes the dispersed collagen distribution could be employed for representing anisotropic behavior of the arterial wall.

The objective of this study was to develop and validate artery buckling equation using a two-layered microstructure based arterial wall model that incorporates collagen orientation dispersion obtained from experimental measurement. The developed artery buckling model can be used in future work to determine the effect of microstructural changes in arterial wall due to aging and disease.

2. Material and methods

Common carotid arteries were harvested from farm pigs (about 100 kg B.W.) post mortem at a local abattoir with the approval from the Texas Department of State Health Service. The arteries were transported to our laboratory in ice-cold phosphate buffer saline (PBS) and prepared for mechanical testing (Hayman et al., 2013; Lee et al., 2012).

2.1. Experimental measurements

2.1.1. Inflation test of intact arteries

To determine the stress–strain relationship of intact porcine arteries, the axial extension and radial inflation were measured in a group of seven porcine carotid arteries under internal lumen pressure (Lee et al., 2012). Our previous studies using similar sample sizes ($n=5$ to 7) were able to detect difference in vascular wall components and functions (Hayman et al., 2013; Lee et al., 2012; Zhang et al., 2014). Each artery was mounted horizontally onto a cannula at one end and tied to a luer stopper at the other end. The luer stopper closed the end but allowed for free axial movement. The cannula was connected to a pressure meter and syringe pump filled with PBS solution. The artery was preconditioned by slowly inflating the artery to a pressure of 300 mmHg and then deflating for 5–6 cycles to obtain reproducible mechanical data. After preconditioning, the artery was slowly inflated while the outer diameter and length were photographed. These vessel dimensions were then measured from digital images taken during the inflation test. The outer diameter was obtained by averaging several measurements along the vessel and vessel length were measured along the central line of the vessel. The initial lumen diameter and wall thickness were measured from the ring segments cutting from both ends of the vessel and averaged.

2.1.2. Buckling test

The arteries were stretched to the given levels of stretch ratios (1.0–1.7), with both ends tied to the fixed cannulae and pressurized with PBS solution under steady flow until large deflections were achieved. The steady flow was generated using a peristaltic pump and a pulse dampener dome (Cole-Parmer) in the flow loop (Liu and Han, 2012). The critical buckling pressure was determined as the pressure when the deflection at mid-point of the artery reached 0.5 mm which can be reliably measured and consistent with previous measurements (Lee et al., 2012).

2.1.3. Inflation test of intima-media layer

After completing the buckling test on each intact artery, the adventitia layer was carefully dissected. Then, the remaining intima-media (IM) layer was tested using the same pressurized inflation test protocol described above to obtain the mechanical properties of the intima-media layer.

2.1.4. No-load and zero-stress state

To obtain the no-load opening angle of the intact artery, rings were cut off from proximal and distal ends of the arteries and photographed under no-load condition. The rings were cut open radially and left in PBS solution for over 10 min to release the residual strain and photographed (Lee et al., 2012). The same process was repeated after removing the adventitia layer to measure the opening angle of the intima-media layer.