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Effects of pressure on arterial failure

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ABSTRACT

A three-dimensional multilayer model of mechanical response for analyzing the effect of pressure on arterial failure is presented in this work. The multilayer arterial wall is considered to be composed of five different layers. The three-dimensional effects are incorporated within the five-concentric axisymmetric layers while incorporating the nonlinear elastic characteristics under combined extension and inflation. Constitutive equations for fiber-reinforced material are employed for three of the major layers, i.e., intima, media and adventitia and an isotropic material model is employed for the other two layers, i.e., endothelium and internal elastic lamina. Our own developed three-dimensional five-layer model has been utilized to model propagated rupture area of the arterial wall. Required parameters for each layer are obtained by using a nonlinear least square method fitted to in vivo non-invasive experimental data of human artery and the effects of pressure on arterial failure are examined. The solutions from our computational model are compared with previous studies and good agreements are observed. Local stresses and strain distributions across the deformed arterial wall are illustrated and consequently the rupture area is predicted by varying luminal pressure in the physiological range and beyond. The effects of pressure on the arterial failure have been interpreted based on this comprehensive three-dimensional five-layer arterial wall model. This is the first study which employs two constitutive equations and incorporates a five-layer arterial wall model in three-dimensions based on in vivo non-invasive experimental data for a human artery.

1. Introduction

A cardiovascular system encompasses a pump (heart), a delivery network (arteries) and a return network (veins) to return the blood back to the pump to complete the cycle. The pressure resulting from the blood flow acts on the endothelium cells of an artery. The endothelium cells respond to stress and strain by inflation or contraction and extension. In this work, we analyze conditions under which arterial failure could occur. As such, the initiation and propagation of rupture area is predicted and an assessment of rupture area is qualitatively established. Mechanical properties of stress and strain of the arterial wall have received more attention in recent years. Several constitutive models have been proposed (Holzapfel et al., 2000; Delfino et al., 1997; Fung, 1990, 1997, 1993). Monolayer homogenous arterial wall is the simplest model to represent an artery. However, it is well known that the arterial wall is a non-homogeneous material. A better approach is to model heterogeneity of the arterial wall by considering it as a multi-layer structure while incorporating its architecture and its different layers, namely endothelium, intima, internal elastic lamina, media and adventitia. The pressure acting on the inside surface of arterial wall is caused by the lumen. While there are several definitions of stress and strain (Fung, 1969, 1994, 2001), in the present study, the Cauchy stress and the Green–Lagrange strain are used to refer to the force acting on the deformed area and the ratio of inflation and extension.

A biological tissue can be subjected to chemical changes, which can be effectively represented by changes in the stress and strain. By monitoring stress and strain during a cyclic load experiment, the response of an artery can be assessed during the loading and unloading processes (Holzapfel et al., 2004b). As such, stress and strain behavior of an arterial wall incorporating elastic deformation under a pressure load is investigated in this work. A three-dimensional five-layer model is established for studying the effect of pressure on the arterial failure. In particular, various pressure levels are studied and the rupture area is consequently predicted.

2. Analysis

2.1. Structure of an arterial wall

Typical histological and anatomical structure of an arterial wall is shown in Ai and Vafai (2006). The arterial wall is composed

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Nomenclature

$\boldsymbol{A}$	structure tensor of fiber direction
$\boldsymbol{a}$	acceleration vector
$\boldsymbol{a_o}$	fiber direction vector
$\boldsymbol{b}$	the left Cauchy Green tensor
$\boldsymbol{C}$	the right Cauchy Green tensor
c	stress-like parameter of isotropic term
DBP	diastolic blood pressure
$\boldsymbol{E}$	the Green-Lagrange strain tensor
$\boldsymbol{F}$	the deformation gradient tensor
$\boldsymbol{f}$	the body force tensor of blood
$\boldsymbol{G}$	the body force tensor of arterial wall
H	thickness of arterial layer
$\boldsymbol{I}$	identity tensor
I	principal invariant
k_1	stress-like parameter of anisotropic term
k_2	dimensionless parameter of anisotropic term
L	overall longitudinal length in reference configuration
MBP	mean blood pressure
MSE	mean square error
N	number of experimental data points
P	Lagrange multiplier
p	luminal pressure
R	radial position in reference configuration
r	radial position in deformed configuration
r_p	the Pearson product moment correlation coefficient
$\boldsymbol{S}$	the second Piola–Kirchhoff stress tensor
SBP	systolic blood pressure
T	period of cardiac time
t	time
U_o	reference bulk inflow velocity
u	velocity component
$\boldsymbol{v}$	velocity vector
$\boldsymbol{X}$	the position vector in reference configuration
$\boldsymbol{x}$	the position vector in deformed configuration
Z	longitudinal position in reference configuration
z	longitudinal position in deformed configuration

Greek symbols

β	angle of collagen fibers
δ	parameter for fluctuation of pulsatile flow
ζ	fold value of mean
Θ	angular position in reference configuration
θ	angular position in deformed configuration
λ	stretch ratio
μ	dynamic viscosity of blood
ξ	fold value of amplitude
ρ	density of arterial wall
$\boldsymbol{\sigma}$	the Cauchy stress tensor
Φ	opening angle
ψ	the strain energy function
Ω	the deformed configuration
Ω_o	the reference configuration

Superscript

$-$	deviator component
$*$	normalized value

Subscript

adv	adventitia
end	endothelium
i	inside
iel	internal elastic lamina
int	intima
j	arterial layer
med	media
o	outside
v	equivalent
vol	volumetric component
z	longitudinal direction

Other symbol

A_O	the average height above the abscissa
A_J	the height of the oscillation in terms of cosine
B_J	the height of the oscillation in terms of sine
$\boldsymbol{\nabla}$	gradient operator

of five layers. From the lumen side outward, the five layers of arterial wall are: endothelium, intima, internal elastic lamina (IEL), media and adventitia. The innermost layer, endothelium, is a single layer of endothelial cells lining the interior surface of the artery which are in direct contact with the lumen and could be elongated in the same direction as the blood flow (Yang and Vafai, 2006). Intima, the innermost major layer, consists of both connective tissue and smooth muscle. Intima grows with age or disease and consequently might become more significant in predicting the mechanical behavior of an arterial wall. The internal elastic lamina separates the intima from the media. The media, the thickest layer, consists of alternating layers of smooth muscle cells and elastic connective tissue which gives the media high strength and ability to resist the load. The media layer is surrounded by loose connective tissue, the adventitia. The adventitia is the outermost layer of the arterial wall, which is composed of fibrous tissue containing elastic fibers, lymphatic and occasional nutrient vessels. At high pressure levels, the adventitia behaves like a stiff tube to prevent the artery from rupture.

2.2. Stress and strain characteristics

Lets consider the body of an arterial wall in the reference configuration Ω_o. A material particle point in the cylindrical coordinate system is represented as $\boldsymbol{X}(R, \Theta, Z)$. After the arterial wall is deformed, the material point $\boldsymbol{X}(R, \Theta, Z)$ transforms to a new position designated as $\boldsymbol{x}(r, \theta, z)$. The transformation can be described by

$$\boldsymbol{F} = \frac{\partial \boldsymbol{x}}{\partial \boldsymbol{X}} \tag{1}$$

The deformation gradients can be used to describe the distance between two neighboring points in these two configurations and the Green–Lagrange strain tensor $\boldsymbol{E}$ can be introduced as

$$\boldsymbol{E} = \frac{1}{2}(\boldsymbol{C} - \boldsymbol{I}) \tag{2}$$