Effect of Residual Stress on Femoral Arterial Stress-Strain Behavior

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It is well established that arteries are subjected to residual stress. Due to the effect of residual stress, the arteries open to a horse-shoe shape when a longitudinal cut is made on an excised arterial segment. Previously, the residual stress has been quantified by the opening angle of the horse-shoe shape. We have employed a finite element analysis of the open arterial segment to restore the same to the original cylindrical shape and computed the circumferential strain as well as the stress distribution in the wall. In this study, the stress and strain distribution in the femoral arteries of miniswine was computed with and without the residual stress for a range of transmural pressures. Our analysis showed that the residual stress has the effect of redistribution of the circumferential stresses between the intima and the adventitia under physiological loading. The redistribution of the stress with the inclusion of residual stress may be important in the studies on effect of wall stresses on the endothelial and vascular smooth muscle cells.

Key Words : Residual Stress, Arterial Material Property, Pressure-Strain Behavior, Circumferential Stress Distribution in the Arterial Wall

1. Introduction

The existence of residual stress or pre-stress in blood vessels has been previously demonstrated (Chuong and Fung, 1986; Fung Liu, 1989; 1991; 1992; Fung, 1991). If a ring-shaped segment of an artery is excised from the body, and an additional cut on the segment is made in the longitudinal direction, the segment will open up into a horse-shoe shape even though there is no transmural pressure exerted on the intimal surface. This change in shape demonstrates that residual stress was present in the ring-shaped element at zero load, and when the additional cut was made, the segment opened up to a stress-free state. Fung (1991) has pointed out that the presence of residual stress may play a significant role in the remodeling of the artery. Fung and colleagues (Chuong and Fung, 1986; Fung and Liu, 1989; 1991; 1992; Fung, 1991; Liu and Fung, 1988; 1989) quantitatively described the amount of residual stress by the opening angle of the segment. They demonstrated that the opening angle varied with the region from where the specimens were obtained (carotid, femoral, etc.) and also on the position where the longitudinal cut was made in a specimen (anterior, posterior, etc.). Vaishnav

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and Vassoughi (1987) and Fung (1991) also demonstrated that at zero load, the pre-stress was compressive in the intima and tensile in the adventitia of the arterial specimen.

It has also been pointed out that the presence of residual stress will affect the pressure-strain behavior of the arterial segments under physiological loading in vivo. In order to quantitatively demonstrate the effect of residual stress on the pressure-strain behavior, a knowledge on the magnitude and distribution of the residual stress along the thickness of the arterial wall is necessary, rather than by the magnitude of the opening angle. In order to compute the magnitude and distribution of the residual stress, we had reported on a novel finite element analysis method from our laboratory (Mun et al., 1999; 2001) In this method, a large deformation finite element analysis was employed to restore the open segment back to the ring-shaped element and the analysis yielded the magnitude and distribution of the residual stress in the arterial wall. Subsequently, the ring-shaped arterial segment was subjected to transmural pressure loading in the physiological range in order to assess the effect of residual stress on the pressure-strain behavior. Our studies (Mun et al. 1999; 2001) showed that, in the ileo-femoral arterial segments, the residual stress was compressive in the intima and tensile in the adventitia with the magnitude to be about 10 to 20 percent of the elastic modulus for the artery. Our results also showed that, with the presence of the residual stresses, the arteries were stiffer under physiological loading particularly in vessels where the thickness to the radius ratio was less than 0.1. Our results also identified a redistribution of stresses in the presence of residual stresses in the arteries.

A more detailed study on the stress distribution within the artery and the redistribution of the same in the presence of residual stress may be important to analyze the effect of wall stresses on the endothelial and vascular smooth muscle cells. In this paper, we present the distribution of the stress in the arterial wall with and without the presence of residual stress in order to quantitatively describe the redistribution of stresses.

2. Methods

The experimental and finite element analysis technique to compute the residual stress distribution in the arterial segments used in our laboratory has been described in detail (Mun et al. 1999; 2001). A brief description of the method is included here in the interest of continuity. Femoral arterial specimens of interest (2 cm in length) were harvested immediately post-mortem from domestic pigs from studies being performed in other experimental protocols. Fascia adherent to the adventitial surface of each artery was carefully removed. Six femoral arterial samples, each 2-3 mm long segments, were sectioned from different portions of the arterial segments, placed in a Petri dish containing 0.9% saline solution, and the ring-shaped cross-sections were photographically recorded. An additional longitudinal cut was made in the segment, and the cut section was let stand in the saline solution for 15 minutes so that the segment opened to the stress-free state. Sections with diameters greater than 5 mm were imaged directly using a color camera (Chroma-Chip II, Javelin Electronics, Japan) with a NTSC video output, and sections with diameters less than 5 mm were imaged through a microscope (OptiPhot, Nikon Inc., Japan) using the same color camera. The video output from the camera was digitized using a frame-grabber (Snappy Video Snapshot, Play Inc., Rancho Cordova, CA) resulting in images with pixel resolution. The images were spatially calibrated (pixel coordinates to spatial coordinates in cm), and the intimal and adventitial borders of each arterial section traced using a commercially available image-processing software package (SigmaScan Pro, SPSS Inc., Chicago, IL). The traced intimal and adventitial contours for each arterial section in the uncut and cut states were then combined to form one data file for each section. Typical ring-shaped uncut specimens of a femoral arterial segment and the corresponding cut sector shaped specimens are illustrated in Fig. 1.

The cut arterial segment, in the open horse-shoe shape, is at the stress-free state. We em-

Fig. 1 Photographs of typical segments of femoral arteries in the ring-shape (uncut) and the stress free horse-shoe shape (after radial cut)

ployed a finite element analysis technique (ABAQUS) to restore the open segment to the original ring-shape and to compute the residual stress distribution in the arterial wall. The FE mesh consisted of approximately 400 quadratic four-node elements and 480 nodes with five layers across the thickness in this two-dimensional analysis. The wall material was assumed to be incompressible and hyperelastic with a constitutive relationship for a Rivlin-type strain energy density function. The initial Young's modulus for the relationship was prescribed from the data presented by Bergel (1961) at zero transmural pressure. A displacement constraint was used as the boundary condition in the analysis such that the two free edges of the cut segment were joined together to form the ring-shaped geometry. In the nonlinear analysis, one end of the open sector segment is fixed, and nodes on the other end are moved as a rigid surface incrementally along a prescribed path so that both ends will meet. This prescribed displacement path is chosen such that no severe mesh distortion or entanglement occurs in each incremental solution stage. The strain energy density function W employed is given by

$$W=\sum_{m+n=1}^{\infty} C_{mn}(I_1-3)^m(I_2-3)^n \qquad (1)$$

In Eq. (1), I_1 and I_2 are the first and second invariants of Green deformation tensor $\boldsymbol{G}$

$$G_{ij}=F_{ki}F_{kj} \qquad (2)$$

where $\boldsymbol{F}$ is the deformation gradient, and C_{mn} are material constants. With the strain energy density function defined in Eq. (1), the stress can be obtained by

$$S_{ij}=\frac{\partial W}{\partial E_{ij}} \qquad (3)$$

where $\boldsymbol{S}$ is the second Piola-Kirchhoff stress that can be related to the Cauchy stress, and E_{ij} is the Green Lagrangian strain. The material constants can be related to Young's modulus E, with consideration of incompressibility, by

$$E=6(C_{10}+C_{01}) \qquad (4)$$

In practice, Eq. (1) is reduced to finite terms. In this study, a neo-Hookean model which contains only one term in the strain energy density function is employed:

$$W=C_{10}(I_1-3) \qquad (5)$$

Finite element formulation in ABAQUS with consideration of geometric and material nonlinearity using strain energy density function given in Eq. (5) is employed for the analysis of arterial deformation. In the subsequent analysis, 4-nodal quadrilateral element with reduced integration and hourglass control was used in the analysis to avoid volumetric locking. Nonlinear analyses were performed using incremental analysis, and solution convergence was checked in the nonlinear iteration of every incremental step.

In order to compare the shape of the original ring-shaped segment to that of the cut and restored segment, a simple shape analysis was performed. The centroids of the two shapes were computed so that the radius and wall thickness can be obtained. The similarity between the two shapes was assessed by comparing the average intimal radius and wall thickness.

The stress distribution in the finite element mesh of the cut and restored segment of the arterial cross-section represents a quantitative assessment of the residual stress in the vessel wall at zero transmural pressure. The normalized maximum principal stress in the elements was compared among the six femoral segments whose data were analyzed in this study. It was observed that the wall thickness to intimal radius ratio of the arteries varied significantly. Hence normalized maximum principal stress is defined as

$$\bar{\sigma}_p = \frac{\sigma_p}{6C_{10} * h/R_0} \tag{6}$$

where $\bar{\sigma}_p$ is the non-dimensional maximum principal stress, σ_p is the maximum principal stress, C_{10} is the specified hyperelastic material constant, and h and R_0 are the average wall thickness and intimal radius at zero transmural pressure, respectively of the ring-shaped specimen (i. e., without residual stress).

Our aim was to assess the effect of the residual stress in the artery on the subsequent deformation characteristics of the vessel with a transmural pressure load. In order to assess the effect of residual stress, we applied transmural pressures of up to 160 mm Hg on the two segment models (without and with residual stress) in an incremental fashion. The average circumferential strain ($\Delta r/R_0$) was computed at each pressure increment and the pressure-strain behavior was plotted where is the average intimal radial displacement and R_0 is the average radius at zero pressure. In the case of cut and restored segment (i.e., with residual stress), the finite element analysis was restarted at the point where the two free edges met, so that the computed residual stress was incorporated in the elements when the transmural pressure was applied. A comparison of the pressure-strain behavior was made between the uncut and the cut and restored segments. The hoop stress distribution within the wall segments was also computed to assess the effect of residual stress with the applied transmural pressure.

3. Results

Opening angles of the employed horse-shoe shaped (i.e., without residual stress) femoral arterial segments ranged from 19 to 107 degrees. The difference of average intimal radius between the *Ring shaped* (i.e., with residual stress) and the *Cut & Restored* (i.e., without residual stress) segment was 9.2±2.5% (average±standard deviation). The ratios of the wall thickness and intimal radius ranged from 0.55 to 1.09 and from 0.24 to 0.61 for 0 mmHg and 100 mmHg transmural pressure, respectively, as shown in Table 1. The six femoral arterial segments were categorized into two groups based on the wall thickness and intimal radius: Group 1 (arteries 1-3) and Group 2 (arteries 4-6). It can be observed from Table 1 that the wall thickness to radius ratio was sub-

Table 1 Comparison of the average intimal radius, and wall thickness to intimal radius ratio for ring-shaped and cut and restored arterial segments. The opening angle in the stress free state of the arterial segment is also included

Artery	Average intimal radius (mm.)		Percentage difference	Opening angle for cut specimen	(wall thickness)/(intimal radius)			
					0 mmHg		100 mmHg	
	Ring shaped	Cut & Restored	(absolute)	(degree)	Ring shaped	Cut & Restored	Ring shaped	Cut & Restored
Group 1								
1	1.3	1.4	11	60.0	0.61	0.58	0.28	0.27
2	1.5	1.5	5	19.4	0.56	0.55	0.25	0.24
3	1.5	1.7	8	80.1	0.62	0.57	0.26	0.25
Group 1								
4	1.1	1.2	9	79.8	1.06	1.09	0.60	0.61
5	1.2	1.3	12	107.1	0.94	0.90	0.50	0.46
6	1.0	1.1	10	49.1	0.98	0.95	0.57	0.55

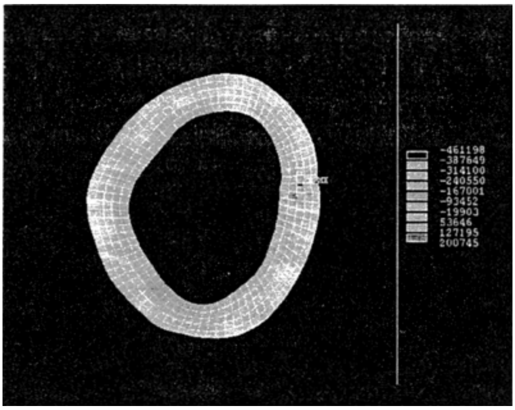


Fig. 2 Distribution of maximum principal residual stress (dynes/cm2) computed with the aid of the finite element analysis for a typical artery

Table 2 The maximum residual principal stress for the arterial specimens in each group. The residual stress was normalized with the assumed elastic modulus and the wall thickness to radius ratio and averaged in the circumferential direction

		Normalized residual stress (Intimal)	Normalized residual stress (Adventitial)
Group 1	1	−0.16	0.15
	2	−0.18	0.17
	3	−0.20	0.18
	Mean ± (S.D)	−0.18 ± (0.02)	0.17 ± (0.01)
Group 2	4	−0.15	0.14
	5	−0.19	0.16
	6	−0.18	0.16
	Mean ± (S.D)	−0.17 ± (0.02)	0.15 ± (0.01)

stantially larger in Group 2 arteries compared to that in Group 1. The distribution of the maximum principal residual stress, computed from the finite element technique to restore the open segment to the ring-shaped geometry for a typical artery is plotted in Fig. 2. The scale for the color-coded stress distribution is also shown in the figure. It can be observed that the residual stress at zero transmural load is compressive in the intimal region and tensile in the adventitial region as has been pointed out by Vaishnav and Vassoughi (1987) as well as Fung (1991). The computed

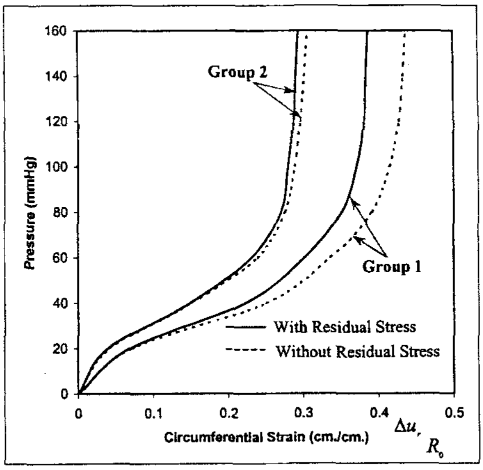


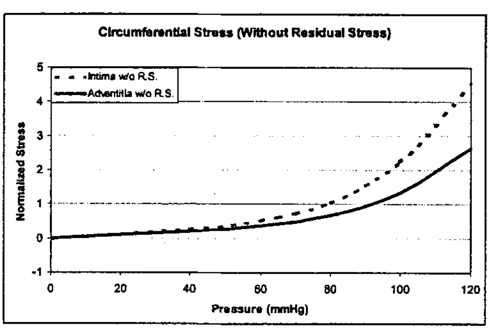
Fig. 3 Comparison of the pressure-strain plots for the two groups of arteries with and without the inclusion of the residual stress

residual stress was normalized with respect to the elastic modulus at the zero transmural pressure as well as the thickness-to-radius ratio as shown in Eq. 6. No significant difference for the normalized average residual maximum principal stress was observed between the two groups of arteries as shown in Table 2.

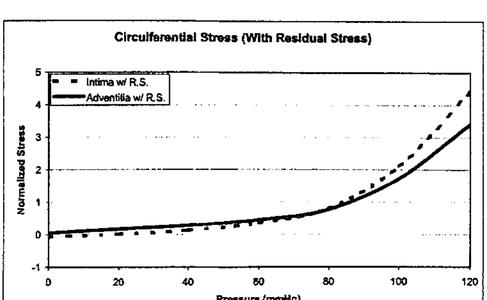
Figure 3 shows the pressure-strain relationship for the six arterial segments with and without the presence of the residual stress as the segments were subjected to transmural pressures of up to 160 mm Hg. As shown in the figure, the Group 1 segments with relatively smaller thickness to average radius ratio, the arteries were much stiffer when the effect of residual stress was included. In Group 2 arteries with relatively larger thickness-to-radius ratio, the effect of residual stress was not significant. A comparison of the averaged normalized circumferential stress in the intimal and adventitial regions for Ring Shaped (i.e., without residual stress) and Cut & Restored segments (i.e., with residual stress) subjected to an intimal transmural pressure load of 100 mmHg are given in Table 3. A significant difference of the average normalized circumferential stress between Group 1 and Group 2 is observed with and without the inclusion of the residual stress. Moreover, a redistribution of the stresses along the wall thickness is observed when the residual

Table 3 A comparison of the circumferential stress in the intimal and adventitial regions with (Cut & restored) and without (Ring shaped) the inclusion of residual stress with a transmural pressure load of 100 mm Hg. The circumferential stresses were normalized with the assumed elastic constant and the ratio of wall thickness to radius ratio and averaged in the circumferential direction

Artery	Average normalized circumferential stress		Average normalized circumferential stress	
	Ring shaped	Cut & Restored	Ring shaped	Cut & Restored
	Intimal		Adventitial	
Group 1				
1	1.14	1.09	0.72	0.86
2	1.32	1.17	0.85	0.94
3	1.26	1.12	0.81	0.84
Mean ± (S.D)	1.24 ± (0.09)	1.13 ± (0.04)	0.79 ± (0.07)	0.88 ± (0.05)
Group 2				
4	0.33	0.29	0.16	0.23
5	0.37	0.34	0.22	0.24
6	0.36	0.32	0.20	0.23
Mean ± (S.D)	0.35 ± (0.02)	0.32 ± (0.03)	0.19 ± (0.03)	0.23 ± (0.01)

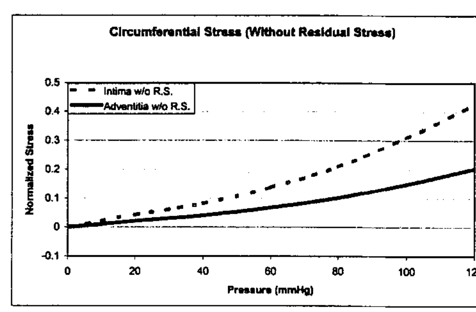


(a)



(b)

Fig. 4 Comparison of the average normalized circumferential stress distribution for a typical femoral artery in Group 1 as a function of transmural pressure



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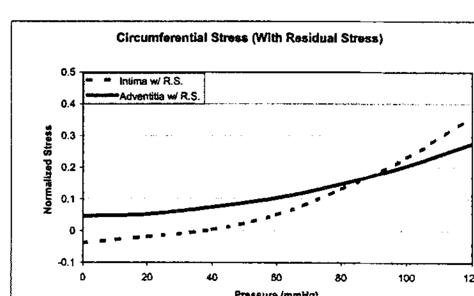


(b)

Fig. 5 Comparison of the average normalized circumferential stress distribution for a typical femoral artery in Group2 as a function of transmural pressure

Table 4 A comparison of the radial stress in the intimal and adventitial regions with (Cut & restored) and without (Ring shaped) the inclusion of residual stress with a transmural pressure of 100 mm Hg. The radial stresses were normalized with the assumed elastic constant and the ratio of wall thickness to radius ratio and averaged over the circumferential direction

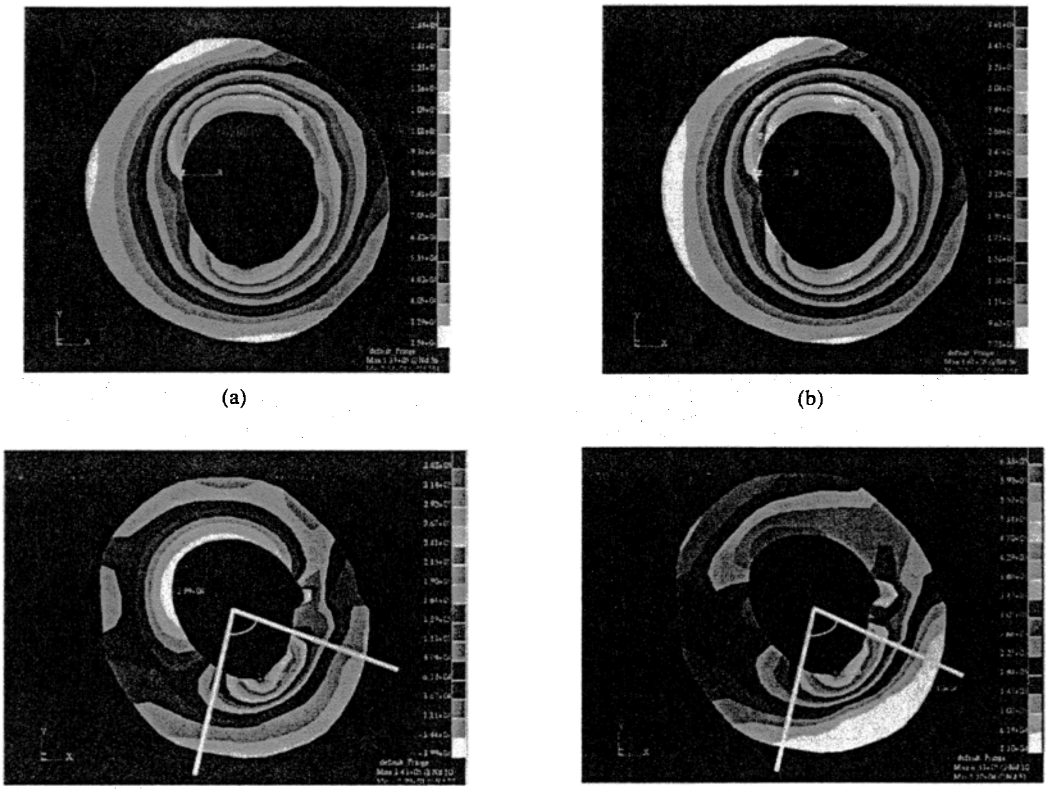
Artery	Average normalized radial stress		Average normalized radial stress	
	Ring shaped	Cut & Restored	Ring shaped	Cut & Restored
	Intimal		Adventitial	
Group 1				
1	0.31	0.25	0.21	0.23
2	0.36	0.34	0.24	0.26
3	0.32	0.29	0.24	0.25
Mean $\pm$ (S.D)	0.33 $\pm$ (0.03)	0.29 $\pm$ (0.05)	0.23 $\pm$ (0.02)	0.25 $\pm$ (0.02)
Group 2				
4	0.08	0.06	0.02	0.03
5	0.12	0.08	0.04	0.05
6	0.08	0.07	0.03	0.05
Mean $\pm$ (S.D)	0.09 $\pm$ (0.02)	0.07 $\pm$ (0.01)	0.03 $\pm$ (0.01)	0.04 $\pm$ (0.01)

stress is included as can be seen in Table 3. With the inclusion of the residual stress, the difference in magnitude of the circumferential stress between the intima and adventitia is reduced compared to that without the inclusion of the residual stress.

The redistribution of the stresses across the wall thickness with the inclusion of the residual stress is clearly observed in Fig. 4 and 5 for the two groups of arteries. In these figures, the average circumferential stress in the intima and adventitia for a transmural pressure range of 0 to 120 mm Hg are compared without and with the residual stress. Without the inclusion of the residual stress, the stresses in the intimal region were always larger than in the adventitial region (Figures 4(a) and 5(a)). On the other hand, with the inclusion of the residual stress (compressive in the intimal region and tensile in the adventitial region), the circumferential stresses in the adventitial region were larger only at the lower transmural pressures. In Group 1 arteries (with smaller thickness-to-radius ratio), the intimal and adventitial stresses were equal at a transmural pressure of 86 ± 3.8 mmHg (Average $\pm$ S.D.). In Group 2, the stresses were observed to be equal at a transmural pressure of 63 ± 8.5 mm Hg. A comparison of the average radial stresses in the two groups of arteries at a transmural pressure of 100 mm Hg is included in Table 4. The effect of pre-stress on redistributing the circumferential stresses within the arterial wall is clearly demonstrated in Fig. 6. In this figure, the color coded circumferential stress distribution with a transmural pressure of 40 mm Hg and 100 mm Hg have been plotted without and with the inclusion of the residual stress. In the figure, the region within the angle α demonstrates the stress concentration effect due to the displacement boundary condition in restoring the segment geometry from the horseshoe to the ring shape. Thus, this region is not included in the consideration of stress redistribution with the inclusion of the residual stress. It can be observed that the stresses are more uniform across the thickness of the vessel wall when the residual stress was included.

4. Discussion

Fung and colleagues (Chuong and Fung, 1986; Fung and Liu, 1989; 1991; 1992; Fung, 1991; Mun et al., 2001; Thurbrikar et al., 1990) as well as Vaishnav and Vassoughi (1987) had earlier



(a) (b) (c) (d)

Fig. 6 Comparison of circumferential stress (dynes/cm2) between Intact (without residual stress effect) and Cut & Restored (with residual stress) segments with transmural pressure load of 40 mmHg and 100 mmHg

demonstrated the presence of residual stress in blood vessels. The quantitative measure used to describe the magnitude of the residual stress in these studies was the opening angle of the segment in the stress-free state. By the measurement of the perimeter in the intimal and adventitial region before and after the longitudinal cut, these studies also demonstrated that the residual stress was compressive in the intima and tensile in the adventitia. The presence of residual stress in the arteries can be anticipated to have an effect on the pressure-deformation characteristics of the blood vessel under physiological transmural loading. In order to quantitatively study the effect of residual stress on the pressure-strain behavior, a knowledge of the magnitude and distribution of the residual stress in the arterial wall is necessary. We had reported earlier on a novel finite element analysis with large displacements in order to restore the open segment of the artery in the stress-free state to the ring-shaped element. We had reported on the magnitudes of the residual stresses in the intimal and adventitial region with the aid of such an analysis (Mun et al. 1999; 2001). Subsequent pressure-strain analysis with transmural pressures in the physiological range also demonstrated that the arteries became stiffer with the presence of residual stresses. The results also demonstrated that the effect of residual stress in the pressure-strain response is more significant for arteries with relatively small thickness-to-radius ratio.

Fung (1991) has pointed out that the residual stresses in the arteries may play a significant role on the remodeling of the arteries. In addition, the magnitude and distribution of stresses in the arterial wall has also been suggested as a causative factor in the development of atherosclerosis

(Lee and Tarbell, 1997; 1998; Thurbrikar 1990). However, in these studies, in defining the arterial wall material properties, the effect of residual stress was not taken into account. In the results reported in the present study, we employed a finite element analysis to analyze the pressure-strain behavior of the artery and also to compute the circumferential stress distribution across the arterial wall without and with the residual stress. We employed a hyperelastic, incompressible wall constitutive relationship in computing the stress distribution. Our analysis showed that the residual stresses were compressive in the intima and tensile in the adventitia. With the inclusion of the residual stresses, the stress distribution within the arterial wall was redistributed to become more uniform under the application of transmural pressures in the physiological range. In the analysis of on the effect of stresses on the endothelial and vascular smooth muscle cells in the development of atherosclerosis, the effect of such a redistribution of stresses due to the presence of residual stresses may be an important factor.

5. Acknowledgements

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