Effects of Arterial Tissue Storage and Burst Failure on Residual Stress Relaxation

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Abstract—This study examines how the relaxation of circumferential residual stress in the aortic tissue is altered with degradation of the tissue with in-vitro storage or circumferential expansion until failure. Results show that both treatments attenuate the effects of residual stress relaxation as assessed by opening angle. Possible reasons for such alteration are discussed considering the mechanical and structural factors.

I. INTRODUCTION

It has been known for a long time that the zero-load and zero-stress states of the artery are not identical [1,2]. This difference invalidates many early mechanical analysis works in arteries and has been attributed to the existence of residual stress within the tissue. Presence of residual stress was initially recognized by the unfurling of the aorta when a radial cut is made along the long axis of the tissue [1]. This procedure later became a benchmark test to correlate residual stress of aortic ring segments with measured opening angles of ring sectors over time [3,4].

Incorporating the tissue’s residual stress into stress calculations has yielded some interesting analytical observations. For example, more uniform stress distribution over the wall thickness, lower stress concentration factor, and lower shear stress have been found, suggesting that residual stress may have physiologic advantages [2,5]. However, the factors causing the residual stress, the regulatory mechanisms and the contributions of structural components and their interactions are controversial. Based on the opening of the ring segment into a sector, it has been assumed that the wall’s inner layers are under compressive residual stress whereas the outer layers are under tension [4]. However, studies show that the elastin fibers, which are mainly responsible for regulating the deformation of the tissue, could be under tension even when undulated in shortened configuration [6]. This observation opens the possibility that the wall might be entirely under tension or compression, with different magnitudes throughout the thickness.

These ambiguities arise from a general lack of knowledge about how morphology of the tissue and its components are related to stress state. This work examines the relaxation of arterial ring segments under different loading conditions to shed more light on this relationship.

II. METHOD

Long segments of bovine aorta were obtained from local abattoir. All animal were male, from Angus breed and with average age of 20.00 ± 3.27 months old. The tissue was carefully cleaned of large remnants of fat and attached connective tissues. Parts with branching holes or abnormalities were discarded. One piece of aorta was kept refrigerated in 4°C protease inhibitor solution for two weeks before being studied and another was examined within 48 hours postmortem. Collectively, 9 ring segments with average width of 11.57 ± 1.02mm were extracted: 6 from the fresh tissue and 3 from the stored tissue. In first set of experiments, the residual stress relaxation of 3 stored rings and 3 of the fresh rings was examined by placing them in a Petri dish filled with PBS and making a radial cut on the ring segments. For the other 3 fresh ring specimens, the rings were placed around a rubber tube surrounded by a bath of PBS in room temperature. By subjecting the rubber tube to high internal pressure, the ring segments were expanded circumferentially until they were torn apart. The ruptured ring sectors were quickly, but delicately, collected from the PBS bath and gently delivered into Petri dish for relaxation. The opening angles of cut and ruptured ring sectors were measured from digital images taken over the relaxation period.

III. RESULTS

A. Relaxation of Fresh Tissue

The three ring segments from fresh tissue subjected to radial cuts resulted in transient changes in opening angle as illustrated in Fig.1(a). From the figure, it is clear that there is a rapid change in the opening angle within first 30sec followed by more gradual increases that plateau to a presumably stress-free configuration over approximately the next 30min. After testing, tissues were then fixed in Clorox® and stained using a modified Masson’s Trichrome procedure, that included Verhoeff’s Hematoxylin, to examine tissue microstructure. These histological images of a representative intact ring and the tested specimen after relaxation are shown in Figs. 2 & 3, respectively. Elastin fibers, which are believed to be mainly responsible for viscoelasticity of the arteries, are stained as dark strands. The figures show that during relaxation, the...
elastin fibers near the inner regions change from undulated form to a more straightened configuration, Figs. 2(a) & 3(a), however, toward the outer regions, the changes in elastin were reversed, Figs. 2(b) & 3(b).

B. Relaxation of In-Vitro Stored Tissue

The time-dependent changes in opening angle of three ring segments from stored aortic tissue are shown in Fig. 1(b). It is found that the rings from the in-vitro stored tissue do not open as much as those from the fresh tissue do. Also, opening angle reaches steady-state much more abruptly with little time-variation.

![Fig.1- Residual stress relaxation in cut aortic ring segments from: (a)Tissue within 48 hours postmortem, (b) Tissue within 2 weeks postmortem](image1)

![Fig.2- Histological image of the ring’s cross section BEFORE relaxation: (a) Intima region, (b) Media/Adventitia regions](image2)

![Fig.3- Histological image of the ring’s cross section AFTER relaxation: (a) Intima region, (b) Media/Adventitia regions](image3)

![Fig.4(a)- Residual stress relaxation in ruptured aortic ring segments Fig.4(b)- Average opening angle for three different sets of rings Fig.4(c)- Percentage of increase in opening angle over relaxation period for three different sets of rings](image4)

C. Relaxation of Burst Tissue

Figure 4(a) shows the change in the opening angle of 3 ring segments that are loaded until rupture, which occurred at stretch of about \( \lambda = 3.25 \). The figure illustrates that the average opening angle of ruptured rings is lower than both fresh and stored rings that were cut. In addition, the ruptured ring segments show very small change in opening angle over time which means that there is little relaxation in the tissue after rupture.

IV. DISCUSSION

The average opening angle of ring segments was about 128.33 ± 9.05° and 78.59 ± 2.84° for the fresh and in-vitro stored tissues, respectively, while the opening angle changes about 23.60% and 11.30% over 30 min relaxation period, Figs. 4(b) & 4(c), respectively. This indicates existence of smaller residual stress in the stored tissue. The reason for this could be partial relaxation of the tissue over the postmortem period, even without cutting the tissue. This becomes more plausible when measurements show that the outer diameter of the aortic vessel increase about 4% during 2 weeks postmortem period. This enlargement might allow some relaxation within the tissue. On the other hand, it is known that vascular smooth muscle also play a significant role in regulating local residual stress distribution within the tissue [6,7] and progressively increasing death of these cells during in-vitro storage could be another cause of losing the viscoelastic relaxation of the tissue.

On the other hand, the rings, which are relaxed after being ruptured by high internal pressure, show an average opening angle of 62.09 ± 11.27° with 2.39% change in opening angle during the relaxation period which indicates very small relaxation in the tissue, Figs. 4(b) & (c), respectively. The elastin fibers typically undergo maximum stretch level of about \( \lambda = 2.5 \) before failure [8]. Therefore, one possible reason for the change in relaxation pattern of ruptured ring segments could be losing the contribution of elastin fibers in tissue viscoelastic deformation due to disintegration or breaking of the elastin network from the rest of the extracellular matrix. Beyond this point until rupture, the collagen would primarily preserve the integrity of the tissue.

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REFERENCES