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A planar biaxial constitutive relation for the luminal layer of intra-luminal thrombus in abdominal aortic aneurysms

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Abstract

The rupture risk of abdominal aortic aneurysms (AAAs) is thought to be associated with increased levels of wall stress. Finite element analysis (FEA) allows the prediction of wall stresses in a patient-specific, non-invasive manner. We have recently shown that it is important to include the intra-luminal thrombus (ILT), present in approximately 70% of AAA, into FEA simulations of AAA. All FEA simulations to date assume an isotropic, homogeneous material behavior for this material. The purpose of this work was to investigate the multi-axial biomechanical behavior of ILT and to derive an appropriate constitutive relation. We performed planar biaxial testing on the luminal layer of nine ILT specimens obtained fresh in the operating room (9 patients, mean age 71 ± 4.5 years, mean diameter 5.9 ± 0.4 cm), and a constitutive relation was derived from this data. Peak stretch and maximum tangential modulus (MTM) values were recorded for the equibiaxial protocol in both the circumferential (θ) and longitudinal (L) directions. Stress contour plots were used to investigate the presence of mechanical anisotropy, after which an appropriate strain energy function was fit to each of the specimen datasets. The peak stretch values for the luminal layer of the ILT were (mean ± SEM) 1.18 ± 0.02 and 1.13 ± 0.02 in the θ and L directions, respectively ($p = 0.14$). The MTM values were 20 ± 2 and $23 \pm 3\,\text{N/cm}^2$ in the θ and L directions, respectively ($p = 0.37$). From these results and our observation of the symmetry of the stress contour plots for each specimen, we concluded that the use of an isotropic strain energy function for ILT is appropriate. Each specimen data set was then fit to a second-order polynomial strain energy function of the first invariant of the left Cauchy–Green strain tensor, resulting in an accurate fit (average $R^2 = 0.92 \pm 0.02$; range 0.80–0.99). Comparison of our previously reported, uniaxially derived constitutive relation with the biaxially derived relation derived here shows large differences in the predicted mechanical response, underscoring the importance of the appropriate experimental methods used to derive constitutive relations. Further work is merited in an effort to produce more accurate predictions of wall stresses in patient-specific AAA, and viscoelastic behaviors of the ILT.
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1. Introduction

Abdominal aortic aneurysms (AAAs)—characterized by the local dilation of the infrarenal aorta—represent a significant disease in the western population. Rupture of AAAs currently ranks as the 13th leading cause of death in the US (Powell and Brady, 2004), and there are approximately 200,000 patients in the US and 500,000 patients worldwide diagnosed with AAAs every year (Bosch et al., 2001). In the past 30 years, the incidence of

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AAA has tripled in the Western world (Bosch et al., 2001), and will most likely increase in the coming years as the average age of the population continues to increase.

Finite element analysis (FEA) may play an important role in the diagnoses and treatment of AAA (Raghavan and Vorp 2000; Raghavan et al., 2000). Recent studies (Fillinger et al., 2002, 2003; Venkatasubramaniam et al., 2004) have demonstrated a correlation between the risk of rupture and peak wall stress predicted using FEA. These studies, however, did not include the presence of the intraluminal thrombus (ILT), which is common in approximately 75% of AAAs (Harter et al., 1982). Our laboratory and others have performed FEA of AAAs to demonstrate that inclusion of ILT into FEA models of AAA may be important. These previous simulations utilized isotropic constitutive models for ILT, either with assumed properties (Inzoli et al., 1993; Mower et al., 1997) or with properties derived from uniaxial tensile experiments (Di Martino et al., 1998, 2001; Wang et al., 2002; Di Martino and Vorp 2003). Such simulations may lead to incorrect stress predictions, as the ILT is under a 3D state of stress in vivo.

Planar biaxial mechanical testing allows the investigation of mechanical anisotropy of a material as well as the development of a constitutive model from a more physiologically appropriate mechanical dataset. The implementation of a biaxial constitutive relation for the ILT into FEA may improve the prediction of stresses in patients-specific AAAs. For these reasons, there exists a need to investigate the biomechanical response of the ILT to multiaxial loading. Therefore, the purpose of the current investigation was to perform biaxial testing on freshly excised ILT, and to derive a multiaxial constitutive relation from the resulting data.

2. Materials and methods

2.1. Specimen preparation

All ILT specimens were harvested from patients undergoing elective open AAA repair according to University of Pittsburgh Institutional Review Board guidelines. Samples were stored in 0.9% saline in a 4 °C refrigerator and tested within 48 h from harvest (Medynsky et al., 1998). A previous study by our laboratory detailed three distinct layers present in the ILT (luminal, medial, and abluminal), highlighting the strong heterogeneity of this material as a whole (Wang et al., 2001). It should be noted here that each ILT fully encircled the AAA wall and was procured in its entirety (including an intact lumen), so that the local longitudinal direction of the biaxial specimen was designated as that parallel to the luminal blood flow. The luminal layer of the ILT was isolated from the medial and abluminal layers by gentle peeling. Square specimens (approximately 2 cm × 2 cm) of the isolated luminal layer were cut such that the in-vivo longitudinal and circumferential orientations of the specimen remained parallel with the square edges. The measurement of thickness for each biaxial specimen was taken at six locations using a dial caliper as follows. The specimen was held at eye level and the dial was lowered until the edge first touches the specimen, after which the thickness measurement was recorded. These measurements were all performed by the same person, eliminating any inter-user variability. The unloaded dimensions of the specimen in the circumferential (X_θ) and longitudinal (X_L) directions were measured and recorded.

2.2. Biaxial tensile testing

Details of the methods for the biaxial tensile testing procedures and analyses used here have been reported previously (Sacks 1999, 2000; Vande Geest, 2004, 2005). Briefly, the square specimens were mounted in a biaxial tensile testing device using four nylon sutures hooked to each side of the square specimen with surgical staples. The nylon sutures were connected to specially designed carriages that allow for self-equilibrated loads for each suture line. The specimen was mounted so that it was stretched along the circumferential (θ) and longitudinal (L) directions. Four markers were placed in a square fashion in the center of the testing specimen, and a CCD camera was used to capture marker displacement during loading.

Tests were performed using a Lagrangian membrane tension **T** (force per unit original length) controlled protocol, where the ratio of axial tensions $T_{\theta\theta}$:T_{LL} were kept constant during loading. The following protocols were performed in the order listed: $T_{\theta\theta}$:T_{LL} = 1:1, 0.75:1, 1:0.75, 0.5:1, 1:1, 1:0.5, 1:0.1, 0.1:1 and 1:1. The multiple equibiaxial tension protocols (i.e., $T_{\theta\theta}$:T_{LL} = 1:1) were performed throughout the test to ensure that no structural damage occurred as a result of the mechanical testing. The maximum tension value used for each specimen was 40 N/m. This value was determined in preliminary experiments in our laboratory to be the maximum tension ILT can withstand in the biaxial tester without the surgical staples detaching from the tissue. It should also be noted here that each attempt to test the medial and abluminal layers of ILT resulted in the surgical staple pulling out from the biaxial specimen edges. This is consistent with our previous observation that these layers are significantly weaker than the luminal layer (Wang et al., 2001).

Prior to collecting data for subsequent analysis, each specimen was preconditioned through nine loading and unloading cycles (half-cycle time = 12.5 s) to the same tension ratio. Data from the tenth loading cycle of each tension ratio protocol is used for analysis as described

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