BIAXIAL BIOMECHANICAL BEHAVIOR OF ABDOMINAL AORTIC ANEURYSM

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INTRODUCTION

The biomechanical response of human nonaneurysmal and aneurysmal abdominal aortic tissue to uniaxial loading conditions has been reported previously [1]. The information taken from uniaxial tensile testing is insufficient for the characterization of the multi-axial mechanical response of aortic tissue. In particular, the uniaxial response of a biological tissue in a given direction does not incorporate the effects of loading in an orthogonal direction. The biaxial testing of aneurysmal tissue allows for the appropriate modeling of such tissue as well as the investigation of any apparent anisotropy. The biaxial testing of AAA may also lead to a better understanding of the disease and its progression. For these reasons, there exists a need for an enhanced description of the mechanical response of AAA tissue to loading in multiple planar directions. For the current investigation, biaxial tensile testing was performed on both abdominal aortic aneurysm (AAA) and nonaneurysmal abdominal aortic (AA) tissue in order to gain insight into the differences in their biaxial biomechanical response.

MATERIALS AND METHODS

Abdominal aortic (AA) tissue samples were harvested from autopsy within 20 hours of death, following NIH and IRB guidelines. AAA samples were obtained from open resection surgery, taken primarily from the anterior portion of the aneurysm. Upon retrieval, the specimens were submerged in saline and kept in a 4°C refrigerator until testing. Biaxial tensile testing was performed using a well-validated biaxial testing device that has been described previously [2]. All testing was performed within 48 hours of retrieval.

A ~2cm square testing specimen was isolated and mounted in the biaxial device using a series of nylon loops. Care was taken to ensure that the circumferential (1) and longitudinal (2) orientation of the specimen was preserved throughout the testing. A tension-controlled protocol was utilized in which the ratio of the circumferential to longitudinal tension was kept constant. The circumferential: longitudinal tension ratios were varied using the following sequence: 1:1 (initial), 0.75:1.0, 1:0.75, 0.5:1, 1:1 (middle), 1:0.5, 0.1:1, 1:0.1, and 1:1 (final). 120 N/m maximum tension was used for all tension protocols. The three equi-biaxial tension runs were performed in order to inspect repeatability and for assurance that there was no structural damage done to the tissue throughout the testing protocol. For each tension ratio protocol, the specimen was taken through ten successive loading and unloading cycles to effectively precondition the tissue.

To determine the anisotropic mechanical behavior of abdominal aortic aneurysm wall tissue, the material was assumed to be incompressible and orthotropic, so that the 2nd Piola-Kirchhoff stresses (S_{ij}) can be related to the in-plane Green strains (E_{ij}) by

$$S_{ij} = \frac{\partial W}{\partial E_{ij}} \tag{1}$$

The two-dimensional strain energy function W was assumed to be of the form

$$W = \frac{c}{2} e^{Q} \tag{2}$$

where

$$Q = A_1 E_{11}^2 + A_2 E_{22}^2 + 2 A_3 E_{11} E_{22}. \tag{3}$$

Values for the material constants were determined using a Levenberg-Marquardt nonlinear curve fitting algorithm (SigmaStat v.2.03) in which experimental data from five biaxial test protocols (the initial and final 1:1 runs, as well as the 0.1:1 and 1:0.1 runs were excluded) were fit simultaneously to reduce the effects of multiple colinearities. A p-value taken from the regression portion of the ANOVA table was used to determine the significance of the model fit. The circumferential and longitudinal peak Green strains for equibiaxial protocols as well as the material parameters c, A_1, A_2, and A_3 were tabulated for all specimens. A paired t-test was used to investigate the differences between the A_i material parameters within each group. A

Student's t-test was used to compare the peak Green strains as well as a coupling parameter defined as

$$D = \frac{A_3}{0.5(A_1 + A_2)}$$

across groups.

AA PARAMETERS (n=6)

	C	A1	A2	A3	R^2	A1/A2	AGE
AVE	1.85	116.26	97.35	13.05	0.92	1.13	69.50
SE	0.83	29.81	24.39	3.70	0.03	0.11	2.22

AAA PARAMETERS (n=15)

	C	A1	A2	A3	R^2	A1/A2	AGE
AVE	1.24	591.50	568.63	186.93	0.83	1.88	73.27
SE	0.34	182.81	211.29	70.00	0.03	0.60	1.65

Table 1. Regression results

RESULTS

Six AA samples from six subjects and fifteen samples from fifteen AAA patients were successfully tested. A representative plot of the second Piola-Kirchhoff stress vs the Green strain can be seen in **Figure 1**. The Fung model fit all of the specimens well with an average R^2 of 0.92 ± .03 and 0.83 ± .03 (mean +/- SEM) for the AA and AAA groups respectively. The nonlinear regression fit of the constitutive model to the data for all of the specimens tested were found to be significant ($p<0.05$). The average and standard error for the model parameters along with the R^2 values for the nonlinear regression for both groups are listed in **Table 1**.

The average peak Green strains for the AA specimens were 0.11 ± 0.03 and 0.10 ± 0.02 in the circumferential and longitudinal directions, respectively. The average peak Green strains for the AAA specimens were 0.06 ± 0.01 and 0.10 ± 0.03 in the circumferential and longitudinal directions, respectively. There was found to be no significant difference between the longitudinal peak strain and the circumferential peak strain for both the AA ($p=0.39$) and AAA ($p=0.16$) groups. There was also found to be no significant difference between the mean of the material parameters A_1 and A_2 for both the AA ($p=0.08$) and AAA ($p=0.83$) groups. There was, however, a significant difference when comparing A_1 and A_3 as well as A_2 and A_3 for both the AA and AAA groups (all $p<0.05$). When comparing experimental values across groups, it was found that the only significantly different value was that for the peak strain in the circumferential direction ($p=0.03$). Although the coupling measure D was not found to be significantly different across groups, the value was consistently larger in the AAA group as compared to the AA group. The difference in the mean age of the two groups was also found to be not significant ($p=0.22$).

GREEN STRAIN AND COUPLING PARAMETER

AA

	Peak E11	Peak E22	D
AVE	0.11	0.10	0.15
SE	0.03	0.02	0.03

AAA

	Peak E11	Peak E22	D
AVE	0.06	0.10	0.23
SE	0.01	0.03	0.04

Table 2. Peak Green strains and the coupling parameter

DISCUSSION

The primary microstructure of the abdominal aortic media consists of layers of collagen and elastin arranged in a fiber network, with the fibers primarily running in the longitudinal and circumferential direction of the blood vessel. Because AAA is associated with the degradation of these fibers, one might expect to see differences in both the content and structure of these fibers in AAA as compared to AA. Indeed, the loss of elastin content in AAA has been reported previously [3]. The value of A_3 in the Fung model represents the coupling of stresses in one direction with strain in the other. One would expect this value to be much lower in a vessel with little or no fiber splay as opposed to one in which the fibers are randomly oriented. The results reported herein show a decreased value of A_3 with respect to both A_1 and A_2 for AAA, which suggests the fibers in this tissue may be more randomly oriented than that of the nonaneurysmal abdominal aorta. This phenomenon is further substantiated by a consistently larger value of D for AAA as compared to AA. The qualitative comparison of stress-strain plots displays a more abrupt change in slope for AAA, which is most likely due to the large decrease in elastin content.

The biaxial tensile testing results reported here demonstrate the presence of abdominal aortic aneurysm is associated with significant changes in the tissues biaxial biomechanical response. AAA tissue displays a stiffer response than does AA, as well as exhibiting a larger coupling term possibly due to a wider fiber splay.

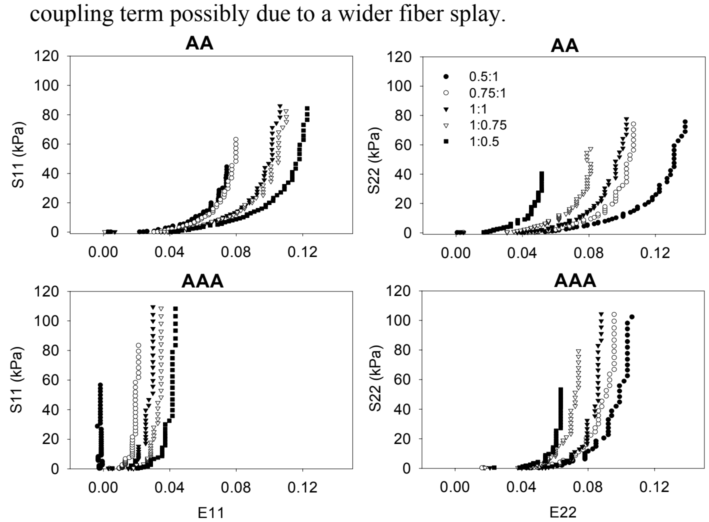

Figure 1. Stress-strain curves for representative AA and AAA samples. The circumferential direction is denoted as 1 and the longitudinal direction is denoted as 2.

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REFERENCES

1. Vorp, D.A., et al., 1996, Ann N Y Acad Sci. 800, pp.274-6.
2. Sacks, M.S., 2000, Journal of Elasticity, 61, pp. 199-246.
3. Carmo M., et al., 2002, Eur J Vasc Endovasc Surg, 23(6), pp. 543-9