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ASCENDING THORACIC AORTA EXHIBITS ANISOTROPIC FAILURE BEHAVIOR IN SHEAR LAP TESTING

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INTRODUCTION

Aneurysm dissection and rupture, resulting in imminent death, is the primary risk associated with thoracic aortic aneurysms (TAA). Nearly 60% of TAA involves the ascending aorta [1]. Dissection and rupture occur when the remodeled tissue is no longer able to withstand the stresses generated by the arterial pressure. As the ascending TAA grows, however, changes in its mechanical behavior, particularly wall strength, are unknown.

The stress near an advancing dissection includes a combination of radial tension (σ_{rr}) and shear ($\sigma_{r\theta}$, σ_{rz}). In-plane uniaxial tension tests [2, 3] provide information on tensile failure along the medial lamella, but the dominant stresses ($\sigma_{\theta\theta}$, σ_{zz}) are not those driving dissection. Peel tests on pieces of artery [4, 5] or aneurysm [6] provide insight into the failure behavior of the tissue in tensile loading perpendicular to the medial lamella (σ_{rr}). In this study, we supplement existing tensile data with a shear lap test (σ_{rz}, $\sigma_{r\theta}$), which characterizes failure under a shear force along the medial lamella, to provide a fuller picture of aneurysm failure mechanics. To our knowledge, we are the first to generate data on the shear strength of aortic tissue.

METHODS

Sample Preparation

Ascending aortic tissue was removed from adolescent male swine (~6 months; 82kg ± 6.2kg, mean ± SD) for testing. Tissue was obtained following an *in vivo* study on right atrial radio frequency ablation.

A ring of tissue was dissected from the ascending aorta. From this ring, 5mm x 10mm rectangular samples were cut in both the axial and circumferential directions. Samples were specially shaped to test the lap shear strength, Fig 1a and b. Samples were situated so the overlap area was within the medial layer of the aorta.

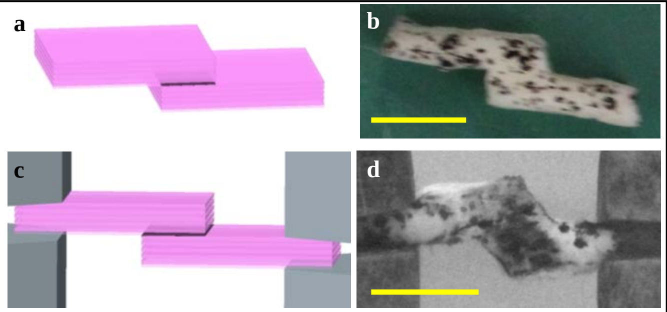

Fig 1 (a) Sketch showing the idealized sample geometry with overlap area, the area designed to undergo failure, highlighted black. (b) Representative sample post-cutting; scale bar is 4mm. (c) Sketch showing the shear lap loading configuration. (d) Representative sample prior to applying shear lap loading; scale bar is 4mm.

Mechanical Testing

Each sample was extended to failure as shown in Fig 1c and d, generating shear forces in the overlap region. Tissue dye was used to speckle the side of the sample in order to calculate local deformation. The sample was attached to a Microbionix tester (MTS, Eden Prarie, MN) via a custom rig and immersed in 1% PBS at room temperature for the duration of testing. Tissue was stored in 1% phosphate buffered saline at 4˚C whenever not undergoing mechanical testing. During testing, the force was recorded and deformation was captured by digital video. Displacement fields showing the movement of the sample surface were generated using an image correlation method described previously [7]. Green strains were computed from the displacement fields.

RESULTS

Fig 2 shows results for the axial sample from Fig 1b and d. The failure curve for the shear lap test shows a catastrophic event similar to a uniaxial test. This behavior is in sharp contrast to the steady loading behavior of a peel test [4, 5, 6].

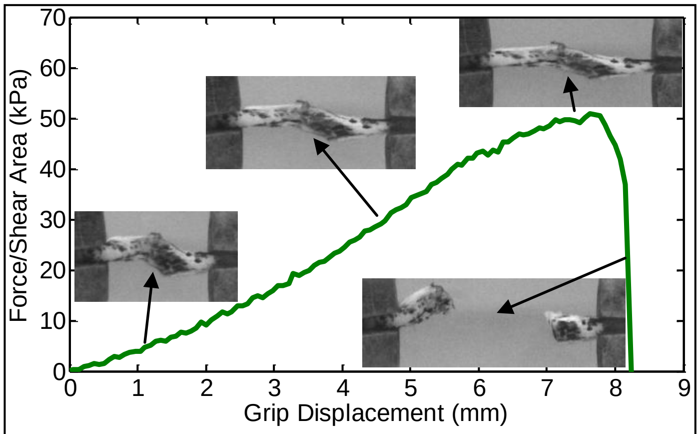

Fig 2 Loading behavior of representative sample.

The displacement field in the same sample at 7mm grip displacement, shown in Fig 3a, was primarily in the pull direction, as expected. The shear strain (Exy, Fig 3b) was, as expected, largest in the overlap region.

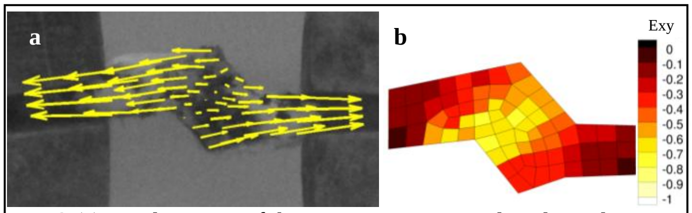

Fig 3 (a) Displacement of the representative sample, adjusted to zero displacement at the center. (b) Strain in the xy-direction.

In order to investigate the strain behavior of the tissue more fully, we drew a line at the overlap surface edge, Fig 4a. Strains tangential and normal to this line are plotted in Fig 4b along with the tangential and normal strains for a circumferentially aligned sample. For both the axially and circumferentially aligned samples, the shear strain, E_{nt}, was large in the overlap region, as desired. For the axial case, the tangential strain, E_{tt}, was also quite large, as expected since the tissue is relatively compliant in the axial direction. The normal strain, E_{nn}, was small. For the circumferential case, E_{nn} was largest, indicating some rotation of the overlap region. E_{tt} was low, the result of lower tissue compliance in the circumferential direction.

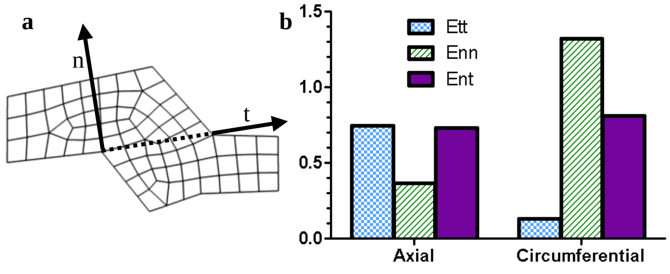

Fig 4 (a) Dotted line showing overlap surface edge and vectors with normal and tangential directions. (b) Graph showing strain averaged over the overlap surface edge for both the representative axial and circumferential samples.

The maximum force per overlap area, the nominal shear strength S_S, was used to characterize sample failure (S_{SCirc}=62.0 ± 11.4 kPa, S_{SAxial} = 45.2 ± 6.2 kPa, n_{Circ} = 22, n_{Axial} = 14, mean ± 95% CI), Fig 5a. Uniaxial failure requires maximum stresses more than ~29 times higher than the stresses we calculated for shear lap failure [2, 3]. Unlike the peel test, which exhibits higher force per width [4, 6] and dissection energy [5] in the axial direction, the shear lap test showed higher strength in the circumferential direction (p = 0.03).

The grip displacement at failure, d_f was used to quantify further the compliance of the tissue (d_{fCirc}=6.0 ± 0.8 mm, d_{fAxial} = 9.0 ± 1.3 mm). Greater deformation was necessary to fail samples aligned in the axial direction. The grip displacement at failure was significantly greater in the axial direction, (p < 0.01).

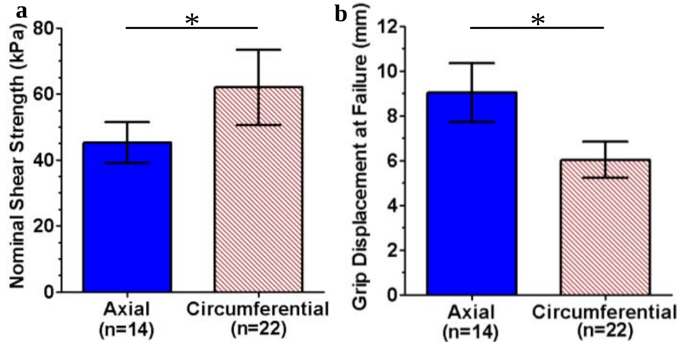

Fig 5 (a) The nominal shear strength was significantly higher for samples aligned in the circumferential direction. (b) Grip displacement at failure was significantly higher for samples aligned in the axial direction. (mean ± 95% CI, $* = p < 0.05$)

DISCUSSION

Both shear and normal stresses exist near the crack front of a dissection, therefore a range of *in vitro* loading conditions is required to characterize tissue behavior. Since shear is not captured by uniaxial or peel tests the data provided by the lap test is an invaluable addition to any model evaluation of either diseased or healthy aorta.

Shear lap tests reveal that failure occurs at much lower stresses (~29 fold [2, 3]), compared uniaxial extension, which is consistent with the laminate nature of the media. The typical anisotropic behavior observed in a peel test [4, 5], higher strength in the axial direction vs. the circumferential direction, is reversed for a shear lap test. We hypothesize this difference is due to the anisotropy of the tissue combined with the sample geometry (i.e. axial or circumferential). In axially aligned samples, collagen fibers are aligned predominately orthogonal to the direction of stretch and the maximum strain is largely a combination of tangential and shear. In circumferentially aligned samples, collagen fibers are aligned in the direction of stretch and the maximum strain is largely a combination of normal and shear.

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