Ascending Aortic Geometry and its Relationship to the Biomechanical Properties of Aortic Tissue

Daniella Eliathamby, B.Eng, Melanie Keshishi, BHSc MBDC, Maral Ouzounian, MD PhD, Thomas L. Forbes, MD, Kongteng Tan, MD, Craig A. Simmons, PhD Peng, Jennifer Chung, MD MSc

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Ascending Aortic Geometry and its Association with Aortic Biomechanics

Ex-vivo Biomechanics of Aneurysmal Aortic Tissue

- Biaxial Tensile Testing
- Delamination Testing

Excised non-dissected aortic tissue
N=68

OC = Outer Curvature
IC = Inner Curvature

Aortic Geometry from Pre-operative CT

Aortic Geometry poorly reflects material properties of aortic tissue
Alternate markers for dissection prediction are needed

Ascending Aortic Diameter
Ascending Aortic Length
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Central Picture

Central Picture Legend: Geometry and biomechanics of ascending aortic aneurysms.
Central Message

The geometry of the ascending aorta is not a reliable marker of material properties in aneurysmal aortic tissue. Additional research is needed before length-based thresholds can be considered.
Perspective Statement

Current diameter guidelines fail to identify most type A dissection patients, promoting the exploration of aortic length as a new marker for dissection risk stratification. However, when compared against material properties of aneurysmal tissue, use of aortic length was inferior to diameter in distinguishing at risk aneurysms. Additional research is needed before length thresholds can be considered.
Abstract

Objective: To evaluate the relationship between ascending aortic geometry and biomechanical properties. Methods: Pre-operative computed tomography scans from ascending aortic aneurysm patients were analyzed using centerline technique (n=68). Aortic length was measured from annulus to innominate artery, and maximal diameter from this segment was recorded. Biaxial tensile testing of excised tissue was performed to derive biomechanical parameters energy loss (efficiency in performing the Windkessel function) and modulus of elasticity (stiffness). Delamination testing (simulation of dissection) was performed to derive delamination strength (strength between tissue layers). Results: Aortic diameter weakly correlated with energy loss ($r^2=0.10$, $p<0.01$), but not with modulus of elasticity ($p=0.13$) or delamination strength ($p=0.36$). Aortic length was not associated with energy loss ($p=0.87$), modulus of elasticity ($p=0.13$) or delamination strength ($p=0.90$). Using current diameter guidelines, aortas >55mm (n=33) demonstrated higher energy loss than those <55mm (n=35) ($p=0.05$), but no difference in modulus of elasticity ($p=0.25$) or delamination strength ($p=0.89$). A length cut-off of 110 mm was proposed as an indication for repair. Aortas >110mm (n=37) did not exhibit a significant difference in energy loss ($p=0.40$), modulus of elasticity ($p=0.69$), or delamination strength ($p=0.68$) in comparison to aortas <110mm (n=31). Aortas above both diameter and length thresholds (n=21) showed no significant difference in energy loss ($p=0.35$), modulus of elasticity ($p=0.55$), or delamination strength (0.61) when compared to smaller aortas (n=47). Conclusions: Aortic geometry poorly reflects the mechanical properties of aortic tissue. Weak association between energy loss and diameter supports intervention at larger diameters. Further research into markers that better capture aortic biomechanics is needed.

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Keywords

Ascending aorta
Aneurysm
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Aortic Biomechanics
Graphical Abstract

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Ex-vivo Biomechanics of Aneurysmal Aortic Tissue

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Excised non-dissected aortic tissue
N=68

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Ascending Aortic Diameter  Ascending Aortic Length

Aortic Geometry poorly reflects material properties of aortic tissue
Alternate markers for dissection prediction are needed
Introduction

Patients with ascending thoracic aortic aneurysms (TAAs) are at increased risk of dissection or rupture. To prevent these events, current guidelines recommend elective repair of most ascending TAAs at diameters ≥ 55 mm (1–4). However, while enlarged aortas are undoubtedly at risk for dissection, data from the International Registry of Aortic Dissection (IRAD) and others report that this threshold fails to identify the majority of patients presenting with acute type A aortic dissection (ATAD) (5,6). As such, alternate markers capturing dissection risk in aneurysms with smaller diameters are urgently needed.

Recently, aortic length has become a marker of interest for prediction of ATAD. The use of aortic length was first introduced as part of the TAIPAN (Tübingen Aortic Pathoanatomy) project, in which the lengths of the ascending aorta in 150 patients who had aortic dissection were observed to be significantly longer than healthy aortic controls (7). Our group confirmed that after adjusting for demographic covariates and the conformational changes associated with the dissection event, the dissected aortas were longer than normal aortas and aneurysms that had not dissected (8). Furthermore, the Yale group identified a hinge point rise in the probability of adverse aortic events for ascending aortas longer than 11.5 cm, prompting the authors to suggest an 11 cm length cut off for offering elective repair (9). However, our group found only 45% of patients treated for ATAD presented with lengths > 11 cm at the time of dissection (8). It therefore remains unclear whether aortic elongation can reliably predict the risk of aortic dissection.
Examination of aortic biomechanics may help clarify the usefulness of aortic length. Aortic biomechanics provides information on the material properties of aortic tissue and its susceptibility to dissection. Several biomechanical parameters have been previously described and include: (1) energy loss, a measure of the efficiency in which the aorta performs the necessary Windkessel function (10,11); (2) modulus of elasticity, a measure of tissue stiffness (12–15); and (3) delamination strength, a measure of the adhesion strength between layers of tissue (11,16,17). Patients with aneurysmal ascending aortas exhibit increased energy loss (11) and modulus of elasticity (14), as well as decreased delamination strength (11,17) compared to healthy aortic controls.

Here we examine the relationship between aortic geometry of the ascending aorta, i.e., aortic diameter and length, and the mechanical properties of aneurysmal aortic tissue. We hypothesize that increased aortic length, and not just aortic diameter, is associated with increased risk of mechanical failure in the aorta, as defined by increased energy loss and modulus of elasticity, and decreased delamination strength. Current and proposed geometric based thresholds are also evaluated to determine whether they successfully segregate patients into high and low risk groups with respect to their biomechanical features.

2. Methods

2.1 Study Population

This study was approved by the Research Ethics Board of the University Health Network (UHN), Toronto, Canada (REB #16-6285, July 27, 2017). All participants provided written informed consent. Ascending aortic samples from 112 patients undergoing elective aortic surgery
were collected between March 2017 to August 2019. Patients without available pre-operative computed tomography scans (CTs) (n=38) and patients without aortic biomechanics data (n=6) were excluded, leaving a final cohort of 68 patients. All patient records were reviewed and relevant clinical data was collected.

All aneurysms were subdivided into a small or large aneurysm group using three definitions: 1) a diameter threshold of 55 mm (> 55 mm: N=33, < 55 mm: N=35), 2) a length threshold of 110 mm (> 110 mm: N=37, < 110 mm: N=31) and 3) a combined diameter threshold of 55 mm and length threshold of 110 mm (> 55 mm & 110 mm: N=24, < 55 mm & 110 mm: N=22).

2.2 Sample Preparation

Aneurysmal ascending aortic tissues from patients who underwent elective aortic surgery at Toronto General Hospital were collected from the operating room and immediately placed on ice. The tissues were then stored at 4 °C in Ringer’s lactate solution and tested within 24 h of collection. Aortic samples were received in the form of a complete ring, with orientation marked by the surgeon (Figure 1A). A custom-made 14 mm x 14 mm cutter was used to collect square samples from the outer (OC) and inner (IC) curvature for biaxial tensile tests. Up to three square samples were cut along the longitudinal axis of the OC, and one square sample was cut from the IC. Adjacent to biaxial squares, a 6 mm × 30 mm rectangular piece was cut for delamination testing (Figure 1B)

2.3 Mechanical Testing

2.3.1 Biaxial Tensile Testing
Aortic thickness for biaxial tensile testing was measured using a high magnification (12×) zoom lens (Navitar) prior to mechanical testing. Biaxial testing was performed as before (11). Briefly, each biaxial square sample was mounted onto a Biotester (CellScale) using tungsten rakes for displacement controlled biaxial tensile testing in 37°C Ringer’s lactate solution (Figure 1C). Samples were subjected to 10 preconditioning stretch cycles followed by 3 analyzed cycles under 25% equibiaxial strain. From the generated stress-strain curve, energy loss and the tangent modulus of elasticity at 10% strain were calculated in both the longitudinal (long) and circumferential (circ) directions of loading.

Energy loss is a measure of the efficiency with which the aorta performs the Windkessel function. Higher values of energy mean a higher proportion of energy absorbed by the aorta during loading is dissipated and less of it is returned to the circulation. Modulus of elasticity measures tissue stiffness, with higher values indicating greater stiffness. Less healthy tissue would therefore have higher levels of both energy loss and modulus of elasticity.

2.3.1 Delamination Testing

Delamination tests were performed on the rectangular tissue samples as before (11). Tissue width was confirmed using the built in Biotester camera and measured using ImageJ version 1.52p (National Institutes of Health). An initial incision was made in the media and the medial layer was manually peeled from the proximal to distal end of the aorta tissue section until 14 mm of unpeeled length remained. The samples were then mounted onto the Biotester for uniaxially peeling at a constant rate of 0.01 mm/s in 37°C Ringer lactate solution (Figure 1D). Force measurements were recorded, and delamination strength was found by dividing average force by sample width. Aortic tissue that is resistant to dissection has a higher delamination strength than aortas that are prone to dissection.
2.4 Aortic Dimension Measurements

All image analysis for this study was performed using Aquarius iNtuition (TeraRecon, Inc.). In the coronal view, digital markers were placed from the annulus to the most distal end of the visible aorta, ensuring accurate coverage up to the aortic arch (Figure 1A). A semiautomatic centerline was generated through the entire length of the aorta, with manual inspection for appropriate symmetry around the centerline. For aortic length measurements, manually placed markers at the annulus and proximal limit of the origin of the innominate artery were used to define the ascending aorta (Figure 1B) (Video S1). The maximal diameter measurements for this segment were then generated from built-in volume analysis tools, with manual inspections and adjustments to aortic boundaries made as needed.

2.5 Statistic Analysis

All continuous variables are presented as median and interquartile range [quartile 1 – quartile 3]. All categorical variables are presented as percentages. To compare between two continuous variables, Mann-Whitney tests were used. To compare between two categorical variables (e.g., sex across groups), chi-square tests were used. Linear regression models were used to quantify the association of aortic biomechanics with aortic diameter and length, separately, as evaluated by coefficient of determination. To compare aortic biomechanics between defined aortic subgroups, unpaired Mann-Whitney tests were used. All analyses were completed using Prism 5 (GraphPad) and assumed a significance level of 5%.

3. Results
The average age of this 68 patient cohort was 64.50 years (53.50–74.00 years) and 32% were female. Demographic data for the defined small and large diameter and length aneurysm groups are presented in Table 1. Patients with large lengthwise aneurysms (>110 mm) were significantly taller than smaller lengthwise aneurysms (<110 mm) (1.75 m (1.69-1.80 m) vs. 1.70 m (1.54-1.78 m), p=0.056) and patients with large diameter-wise aneurysms (>55 mm) presented with fewer cases of aortic stenosis than smaller diameter aneurysms (<55 mm) (n=12 vs. n=40, p=0.01). Otherwise, no other significant differences in patient demographics were observed between small and large aneurysms using either the diameter or length cut-offs (Table 1). When comparing aortic size in terms of both diameter and length, larger aneurysms (diam > 55 mm and length >110 mm) presented with more cases of aortic insufficiency than smaller aneurysms (diam <55 mm and length <110 mm) (n=54 vs. n=23, p=0.04) and fewer cases of aortic stenosis (n=8 vs. n=41, 0.01). No other significant differences in baseline characteristics between larger and smaller aneurysms when considering both diameter and length were observed (Supplemental Table 1).

### 3.1 Ascending Aortic Geometry vs. Aortic Biomechanics

#### 3.1.1 Ascending Aortic Diameter

Ascending aortic diameter (54.65 mm (48.15-58.53 mm)) was compared against the 3 biomechanical parameters: energy loss, modulus of elasticity, and delamination strength. In the outer curvature, increasing aortic diameter was associated with increasing energy loss only (p<0.01) (Figure 3D). No correlation between aortic diameter and modulus of elasticity (circ.: $r^2=0.04$ [p=0.13]; long: $r^2=0.02$ [p=0.22]) (Figure 3E) or delamination strength ($r^2=0.01$ [p=0.36])
(Figure 3F) was observed. In the inner curvature, there was no correlation between aortic diameter and any of the three mechanical parameters (Figure 3A, 3B, and 3C).

### 3.1.2 Ascending Aortic Length

Ascending aortic length (110.5 mm (103.0-119.0 mm)) was compared against the same three biomechanical parameters: energy loss, modulus of elasticity, and delamination strength to evaluate association between aortic elongation and the biomechanics of the aorta. No significant correlations were observed in the outer curvature between elongation of the aorta and energy loss (circ.: $r^2=0.01$ [$p=0.51$]; long: $r^2=0.00$ [$p=0.87$]), modulus of elasticity (circ.: $r^2=0.01$ [$p=0.36$]; long: $r^2=0.04$ [$p=0.13$]), or delamination strength ($r^2=0.00$ [$p=0.90$]) (Figure 4D, 4E, and 4F). Similarly, energy loss (circ.: $r^2=0.00$ [$p>0.90$]; long: $r^2=0.02$ [$p=0.40$]) (Figure 4A), modulus of elasticity (circ.: $r^2=0.01$ [$p=0.37$]; long: $r^2=0.02$ [$p=0.53$]) (Figure 4B), and delamination strength ($r^2=0.00$ [$p=0.70$]) in the inner curvature were not correlated with lengths of the ascending aorta (Figure 4A, 4B, and 4C). Similar findings were observed using length indexed to patient height (Supplementary Figure 1).

### 3.2 Geometric-Based Thresholds of the Ascending Aorta

#### 3.2.1 Diameter Threshold

Aortic biomechanics between small (<55 mm in diameter; 48.60 mm (45.60-53.30 mm)) and large (> 55 mm in diameter; 58.60 mm (57.05-61.05 mm)) diameter-wise aneurysms were compared. In the outer curvature, larger diameter aneurysms exhibited greater energy loss in the circumferential axis but not the longitudinal axis (circ: $p=0.05$; long: $p=0.16$) (Figure 5A). No significant differences were observed in modulus of elasticity (circ: $p=0.25$, long: $p=0.32$) or
delamination strength (p=0.89) (Figure 5B and 5C). In the inner curvature, no differences
between small and large diameter aneurysms were detected for energy loss (circ: p=0.68; long:
p=0.52) (Figure 5D) or delamination strength (p=0.37) (Figure 5C). Smaller diameter aneurysms
exhibited marginally increased, but not significant, modulus of elasticity in the circumferential
axis (p=0.06) compared to larger diameter aneurysms (Figure 5E). No difference in modulus of
elasticity in the longitudinal axis was observed (p=0.10).

3.2.2 Length threshold

Small (<110 mm in length; 103.0 mm (95.90-108.0 mm)) and large (> 110 mm in length; 119.0
mm (113.0-123.0 mm)) lengthwise aneurysms were compared using aortic biomechanics to
evaluate the newly proposed aortic length guidelines in dissection risk stratification. In the outer
curvature, no significant differences in energy loss (circ: p=0.63; long: p=0.40), modulus of
elasticity (circ: p=0.73; long: p=0.69), or delamination strength (p=0.68) were detected between
small and larger length aneurysms (Figure 6A-6C). Similarly, no significant differences were
observed in the inner curvature for energy loss (circ: p=0.94; long: p=0.33), modulus of elasticity
(circ: p=0.60; long: p=0.77), or delamination strength (p=0.22) between aortic subgroups (Figure
6D-6F).

3.2.3 Combined diameter and length threshold

A combined diameter and length threshold was used to divide aneurysmal patients into small
(diameter <55 mm and length <110 mm) and large (diameter >55 mm and length >110 mm)
aneurysms for comparison with aortic biomechanics. In the outer curvature, there was no
significant difference in energy loss (circ: p=0.35; long: p=0.65), modulus of elasticity (circ:
p=0.55; long: p=0.41), or delamination strength (p=0.61) between small and large aneurysms
(Supplemental Figure 2A-2C). Similarly, in the inner curvature, no difference in energy loss (circ: \(p=0.93\); long: \(p=0.61\)), modulus of elasticity (circ: \(p=0.23\); long: \(p=0.34\)), or delamination strength (\(p=0.30\)) was observed (Supplemental Figure 2D-2F).

Discussion

In this study of systematic comparisons between aortic geometry and the biomechanics of the ascending aorta, we found aortic geometry poorly predicted material properties of aneurysmal aortic tissue. While increasing aortic diameter weakly correlated with increasing energy loss in aneurysmal tissue, we observed no significant difference in delamination strength between small and large aneurysms using a diameter threshold. Furthermore, we found no significant differences in material properties of longer aortic aneurysms compared to shorter-length aneurysms. Finally, when comparing small and large aortic aneurysms as defined using a combined aortic diameter and length criteria, we found no significant differences in their aortic biomechanics. Therefore, our study provides further evidence that aortic diameter alone is insufficient for dissection risk prediction; and that from a biomechanics perspective, the use of aortic length may not provide any additive value. We suggest that more study in this area is needed (Figure 7).

Previous studies have found longer aortas in dissected populations compared to healthy aortic controls (7–9). However, the observed lengthening may not be related to any changes in material properties that would render the longer aorta at greater risk of dissection. An alternative explanation is the notable relationship between aortic geometry and other factors common within the dissected aneurysm cohort, in particular, the presence of hypertension. Dotter et al. compared
length from sinus of Valsalva to left subclavian artery between 26 hypertensive patients and 86 aortic controls and found presence of hypertension significantly added to the lengthening process of the ascending aorta (18). Similarly, Craiem et al., after correcting aortic length for the effects of age, found unfolding due to presence of hypertension was equivalent to approximately 5 years of aortic aging (19). In our previous study on aortic length, the group that suffered aortic dissection exhibited the highest rates of hypertension (73%), followed by non-dissected aneurysms (54%) (8). We must therefore consider that longer aortas may in fact reflect the important but common and non-specific risk factor of hypertension, rather than the more specific correlation with the susceptibility to dissect in terms of the material properties of the aortic tissue. The consequences of recommending elective surgery to replace longer aortas requires closer examination.

This current study adds significantly to the scant literature on the association between aortic geometry and the biomechanics of the aorta. Iliopoulos et al. previously evaluated ascending aortic diameter and its relation to failure stress, a measure of tissue strength, and found no evidence to support a relationship between increasing aortic diameter and decreasing tissue strength (20). In line with this study, here we have also demonstrated no decrease in delamination strength with increasing aortic diameter, and furthermore, our group has also evaluated the relationship of aortic lengthening with the biomechanics of the aorta, in which we found no difference in tissue strength between varying aortic lengths.

In previous studies, our group has found a weak association between increasing aortic diameter and decreased tissue strength within the ascending aorta (11). While this relationship was not reproduced within this study population, our group did discover a weak association between aortic diameter and energy loss within aneurysmal aortic tissue, which was consistent with our
previous findings (10,11). There is therefore evidence to support larger diameter aneurysms can be associated with unfavourable material properties (i.e., higher energy loss) and thus, should be resected at current diameter thresholds. However, given a majority of dissection patients present at diameters less than the 55 mm threshold (5,6), diameter alone is not a reliable predictor for changes in material properties for smaller diameter aneurysms. This mismatch between aortic geometry and material properties can be explained when considering the underlaying microstructural changes seen in aneurysms of the ascending aorta. Mennander et al. captured medial degeneration between diameter matched BAV and TAV patients, including medial fibrosis, elastic fiber loss/fragmentation, and mucoid extracellular matrix accumulation, and discovered only minimal medial degeneration within larger diameter BAV aortas compared to TAV (21). Chaudry et al. also analyzed this association between aortic size and medial degeneration in 100 resected thoracic aortas without separation for valve morphology and found an overall weak association between increasing aortic diameter and increasing degree of medial degeneration by univariate analysis, with 20% of aortas under 55 mm in diameter also presenting with similar medial degeneration to larger aortic aneurysms (22). Given changes in aortic wall material properties are a functional result of medial degeneration, the poor association between aortic size and material properties in this study is therefore explained by the equaly poor association between size and degree of medial degeneration.

**Study Limitations**

Our study is limited by the fact that delamination strength is a surrogate for aortic dissection. The ex vivo experimental protocol is necessarily controlled and reproducible. In contrast, a patient’s aorta tears at various angles and directions, and under various loading conditions. Nonetheless, delamination strength was previously demonstrated to be significantly higher in transplant donor
patients with normal aortas compared to patients who had aortic dissection, and patients with aortic aneurysms demonstrating delamination strengths between these two controls.

We also acknowledge that the significant differences in patient demographics and comorbidities between comparison groups (i.e., sex, height, and aortic valve function) can influence the material properties of the aorta as well as aortic geometry. In fact, our group and others have previously demonstrated differences in material properties and geometry of the aorta when dividing patient populations based on sex and aortic valve morphology (11,23,24). Furthermore, while in previous work our group did not demonstrate a change in aortic length following increasing patient height (8), the aortic cross-sectional area to height ratio is well published within the literature and is still accepted by our group. Future studies, with larger sample populations, will incorporate adjustments for confounding factors (25–27).

Conclusion

The geometry of the ascending aorta is not a reliable marker of material properties in aneurysmal aortic tissue. Current diameter-based thresholds and newly proposed length-based thresholds cannot confidently discriminate aneurysms with high susceptibility to dissect. Additional research is needed before length-based thresholds can be considered to evaluate TAA patients for elective repair.
References


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Table 1: Patient demographics for study population as divided by diameter and length thresholds.

All continuous variables are presented as median and interquartile range (quartile 1–quartile 3).

All categorical variables are presented as percentages. To compare between two continuous variables, Mann-Whitney tests were used. To compare between two categorical variables, chi-square tests were used. Significance level of 5% was assumed and are indicated in italics.
Legends

Table 1: Patient demographics for study population as divided by diameter and length thresholds. All continuous variables are presented as median and interquartile range (quartile 1–quartile 3). All categorical variables are presented as percentages. To compare between two continuous variables, Mann-Whitney tests were used. To compare between two categorical variables, chi-square tests were used. Significance level of 5% was assumed and are indicated in italics.

Supplemental Table 1: Patient demographics for study population as divided by a combined diameter and length threshold. All continuous variables are presented as median and interquartile range (quartile 1-quartile 3). All categorical variables are presented as percentages. To compare between two continuous variables, Mann-Whitney tests were used. To compare between two categorical variables, chi-square tests were used. Significance level of 5% was assumed.

Central Picture Legend: Geometry and biomechanics of ascending aortic aneurysms.

Figure 1: Sample preparation and mechanical testing of samples from intact ascending aortic rings excised from non-dissected aneurysmal patients. Intact rings are oriented to identify inner curvature (IC) and outer curvature (OC) (A). Square and rectangular samples are taken from each region (B). Biaxial tensile testing is completed on square samples to derive energy loss and
modulus of elasticity (C); delamination testing is completed on rectangular samples to derive delamination strength (D).

Figure 2: Measuring ascending aortic geometry from computed tomography (CT) scans using centerline analysis techniques. Markers are manually placed from bottom of aortic annulus to proximal innominate artery to define proximal and distal boundaries of the ascending aorta (A). A centerline is then generated between defined boundary points, and ascending aortic length and maximum aortic diameter within this region is measured (B).

Figure 3: Ascending aortic diameter and its association with the mechanical properties of aortic tissue. Energy loss in the outer curvature was the only mechanical property associated with ascending aortic diameter (A). No relationship between modulus of elasticity and aortic diameter (B) or delamination strength and aortic diameter (C) in the outer curvature was observed. Similarly, no relationship between energy loss and aortic diameter (D), modulus of elasticity and aortic diameter (E), or delamination strength and aortic diameter (F) in the inner curvature was observed.

Figure 4: Ascending aortic diameter and its association with the mechanical properties of aortic tissue. No significant relationship between energy loss and aortic length (A), modulus of elasticity and aortic length (B), or delamination strength and aortic length (C) was observed in the outer curvature. Similarly, no significant relationship between energy loss and length (D),
modulus of elasticity and length (E), or delamination strength and aortic length (F) was observed in the inner curvature.

**Figure 5**: Biomechanical comparison of large and small diameter-based aneurysms. Larger diameter-wise aneurysms exhibited significantly higher energy loss compared to smaller diameter aneurysms in the outer curvature (A). No difference in modulus of elasticity (B) or delamination strength (C) was observed between large and small diameter-wise aneurysms in the outer curvature. Similarly, no difference in energy loss (D), modulus of elasticity (E), or delamination strength (F) was observed between large and small diameter-wise aneurysms in the inner curvature.

**Figure 6**: Biomechanical comparison of large and small length-based aneurysms. No difference in energy loss (A), modulus of elasticity (B), or delamination strength (C) was observed between longer and shorter length aneurysms in the outer curvature. Similarly, no difference in energy loss (D), modulus of elasticity (E), or delamination strength (F) was observed in the inner curvature.

**Figure 7**: Graphical Abstract. Ex-vivo biomechanics from aneurysmal aortic tissue samples excised from sixty-eight (N=68) non-dissected aneurysm patients were compared against measured aortic geometry (i.e. diameter and length) from patients’ pre-operative CT scans. Over all comparisons, aortic geometry poorly predicted material properties of aortic tissue.
Supplementary Figure 1: Ascending aortic length indexed to patient height and its association with the mechanical properties of aortic tissue. No significant relationship between energy loss and aortic length (A), modulus of elasticity and aortic length (B), or delamination strength and aortic length (C) was observed in the outer curvature. Similarly, no significant relationship between energy loss and length (D), modulus of elasticity and length (E), or delamination strength and aortic length (F) was observed in the inner curvature.

Supplemental Figure 2: Biomechanical comparison of large and small geometric based aneurysms, based on a combined diameter and length threshold. No significant difference in energy loss (A), modulus of elasticity (B), or delamination strength (C) was observed between overall small and large geometric aneurysms in the outer curvature. Similarly, no difference in energy loss (D), modulus of elasticity (E), or delamination strength (F) was observed in the inner curvature.

Video S1: The video shows how to measure ascending aortic length using computed tomography and centerline methodology. Best viewed with Windows Media Player.
Figures

Figure 1: Sample preparation and mechanical testing of samples from intact ascending aortic rings excised from non-dissected aneurysmal patients. Intact rings are oriented to identify inner curvature (IC) and outer curvature (OC) (A). Square and rectangular samples are taken from each region (B). Biaxial tensile testing is completed on square samples to derive energy loss and modulus of elasticity (C); delamination testing is completed on rectangular samples to derive delamination strength (D).
Figure 2: Measuring ascending aortic geometry from computed tomography (CT) scans using centerline analysis techniques. Markers are manually placed from bottom of aortic annulus to proximal innominate artery to define proximal and distal boundaries of the ascending aorta (A). A centerline is then generated between defined boundary points, and ascending aortic length and maximum aortic diameter within this region is measured (B).
Figure 3: Ascending aortic diameter and its association with the mechanical properties of aortic tissue. Energy loss in the outer curvature was the only mechanical property associated with ascending aortic diameter (A). No relationship between modulus of elasticity and aortic diameter (B) or delamination strength and aortic diameter (C) in the outer curvature was observed. Similarly, no relationship between energy loss and aortic diameter (D), modulus of elasticity and aortic diameter (E), or delamination strength and aortic diameter (F) in the inner curvature was observed.

Figure 4: Ascending aortic diameter and its association with the mechanical properties of aortic tissue. No significant relationship between energy loss and aortic length (A), modulus of elasticity and aortic length (B), or delamination strength and aortic length (C) was observed in the outer curvature. Similarly, no significant relationship between energy loss and length (D), modulus of elasticity and length (E), or delamination strength and aortic length (F) was observed in the inner curvature.
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Figure 6: Biomechanical comparison of large and small length-based aneurysms. No difference in energy loss (A), modulus of elasticity (B), or delamination strength (C) was observed between longer and shorter length aneurysms in the outer curvature. Similarly, no difference in energy loss (D), modulus of elasticity (E), or delamination strength (F) was observed in the inner curvature.
Figure 7: Graphical Abstract. Ex-vivo biomechanics from aneurysmal aortic tissue samples excised from sixty-eight (N=68) non-dissected aneurysm patients were compared against measured aortic geometry (i.e. diameter and length) from patients’ pre-operative CT scans. Over all comparisons, aortic geometry poorly predicted material properties of aortic tissue.
Video

Video S1: The video shows how to measure ascending aortic length using computed tomography and centerline methodology. Best viewed with Windows Media Player.
Ascending Aortic Geometry and its Association with Aortic Biomechanics

Ex-vivo Biomechanics of Aneurysmal Aortic Tissue

- Biaxial Tensile Testing
- Delamination Testing

Excised non-dissected aortic tissue
N=68

Aortic Geometry from Pre-operative CT

- Ascending Aortic Diameter
- Ascending Aortic Length

Aortic Geometry poorly reflects material properties of aortic tissue
Alternate markers for dissection prediction are needed

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Ascending Aortic Geometry and its Association with the Biomechanics of the Aorta

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