COMPUTATIONAL MODELING OF WALL STRESS IN ASCENDING THORACIC AORTIC ANEURYSMS WITH DIFFERENT VALVE PHENOTYPES

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INTRODUCTION
Ascending thoracic aortic aneurysms (ATAA) affect about 15,000 people annually in the United States [1]. Aneurysm formation is associated with the stiffening and weakening of the aortic wall, leading to potential rupture [2]. Weakening of the wall occurs as a consequence of medial degeneration, deriving from apoptotic loss of smooth muscle cells and fragmentation of elastin and collagen fibers. The risk of rupture or dissection becomes 31% when the diameter of the aneurysm reaches 6.0 cm, therefore surgical intervention to repair the aneurysm is recommended once the aneurysm’s diameter reaches 5.5 cm [3]. The recommended intervention diameter has been shown to be an insufficient predictor of aneurysm failure, and therefore, a need exists for a more robust predictor of aneurysm failure as a clinical tool.

Bicuspid aortic valve (BAV) is the most common congenital heart defect, occurring in 1% to 2% of the population [4]. ATAAAs develop earlier in patients with a BAV than in those with a normal tricuspid aortic valve (TAV) [4]. Compared to the normal TAV, a BAV patient is more likely to have a larger aortic root diameter [4] and is at greater risk for aortic dissection [5]. Studies have shown that patients with different valve morphologies have different material properties within the ascending aorta [6].

OBJECTIVE
The objective of this research was to evaluate the relationship between ascending aortic stress, aortic geometry, and aortic valve morphology. Past that, this work will be used to develop a reliable prediction model of aortic rupture and dissection, to better inform doctors when to intervene to repair an ATAA.

HYPOTHESIS/SUCCESS CRITERIA
The BAV phenotype will have increased peak and average wall stress, and an increased rate of change of wall stress, as compared to the TAV phenotype, within the ascending aorta. To evaluate this hypothesis, the following goals were set: to develop a stress map over a patient-derived aortic model, to track changes in stress against time, and to compare stress values between TAV and BAV patients.

METHODS
Virtual 3D aortic geometries were reconstructed from pre-operative computed tomography (CT) scans of patients (n=19) undergoing elective surgery (after IRB approval) using computational tools including pixel thresholding (in Mimics), and smoothing (in Geomagic). For most subjects (n=16), there were additional preceding scans that were analyzed, allowing the tracking of the ATAA over time, for a total of 50 scans in the study. The reconstructed ATAA wall surface geometry was then meshed and discretized into finite elements (in Abaqus 6.13). The ATAA was modeled as a shell of homogenous material with a uniformly distributed thickness of 2.25 mm. The wall material was considered nonlinear, isotropic, hyper-elastic, and incompressible, and under a constant pressure of 120 mmHg. BAV and TAV patients were individually assigned wall material properties. The strain energy function (T) used was previously reported for BAV and TAV materials as:

\[ T = [2\alpha + 4\beta (\lambda^2 + 2\lambda^{-1} - 3) [\lambda^2 + \lambda^{-1}] \]

Where T is Cauchy stress, \( \lambda \) is stretch, and \( \alpha \) and \( \beta \) are model parameters. The values of \( \alpha, \beta \) were [0.0465, 0.152] for BAV subjects, and [0.065, 0.955] for TAV subjects [6]. The output of the computational modeling simulation was a stress map across the aortic wall surface.

DATA PROCESSING
The measure of transmural wall stress used is the “equivalent” or von Mises stress, which is frequently used to describe the stress field of materials under multi-axial loading conditions. Von Mises stress provides a scalar value to represent a vector-valued stress state. We define the peak wall stress (PWS) for a given model as the maximum von Mises stress acting anywhere on the ascending aorta. Also used was the mean wall stress (MWS), which is defined as the average value of von Mises stress acting within the ascending aorta. A two sample t-test was used to evaluate the difference between TAV and BAV stress states (both MWS and PWS).

RESULTS
From the data collected in our study, patients with a BAV had a MWS ranging from 14.2 N/cm² to 21.0 N/cm², and patients with a TAV had a MWS ranging from 10.2 N/cm² to 17.6 N/cm². Similarly, BAV patients had a PWS between 23.6 N/cm² 45.6 N/cm², while TAV patients had a PWS ranging from 19.0 N/cm² to 48.9 N/cm². At the time of elective surgery (the final time point in each case), the average MWS in BAV patients (17.27±2.00 N/cm²) was significantly higher than the MWS in TAV patients (15.04±2.16 N/cm²), with p=0.016, as seen in Figure 1. However, the difference in average PWS between BAV and TAV patients was not statistically significant. The location of peak stress within the ascending aorta was consistent between BAV and TAV groups, with the
maximum wall stress localized above the left coronary artery, as seen in Figure 2. The area of peak stress (shown in red) occurs in the lower half of the lesser curvature of the ascending aorta, above the left coronary artery (indicated with a white asterisk). The rate of change of stress per year was negligible for both TAV and BAV groups.

![Figure 1: Box and whisker plot of peak wall stress (PWS) and mean wall stress (MWS) for the final scan before surgical intervention for tricuspid aortic valve (TAV) and bicuspid aortic valve (BAV) subjects.](image)

### DISCUSSION

The results from the study indicate a difference in the average amount of stress (MWS) experienced in the ascending aorta between BAV and TAV phenotypes, while no difference in between the two valve types when looking at the location of peak stress, or value of peak stress (PWS) exists.

The finding that the location of peak stress is consistent between valve types indicates that, surgically, doctors can treat the repair of ATAAAs similarly regardless of valve type, and aligned with the clinical information provided by the Department of Cardiothoracic Surgery at the University of Pittsburgh Medical Center.

The finding that BAV patients experience a greater MWS than TAV patients was encouraging, but upon further analysis, comes with a significant caveat. Because BAV ATAA material is stronger than TAV ATAA material [6], a BAV can undergo a greater amount of stress before rupture. With respect to a future ATAA rupture prediction model, this finding must be further studied to examine the relationship between the scale of greater MWS between BAV and TAV patients to the scale of greater material strength between BAV and TAV patients. If the increase in BAV material strength (relative to TAV material strength) is greater than the increase in MWS in BAV subjects (when compared to TAV MWS), BAV patients may be at lower risk to rupture than TAV patients. The inverse (the increase in stress is greater than the increase in material strength for BAV subjects) could also be true, indicating, that BAV patients are more likely to rupture than TAV patients. As such, further analysis is required to fully understand this phenomenon.

The finding that the rate of change of stress against time was nearly zero was originally highly confusing, as the original hypothesis was that as the aneurysm grew older, it would experience more stress. However, it was realized that the model used for ATAA creation was purely geometry based, and the material properties were constant for all models. Aneurysm formation depends on the degradation of collagen and elastin fibers, and the death of smooth muscle cells [3], and as such, our model failed to account for changing material characteristics over time. Model improvements, that took into account differing material strength over time, would improve understanding of the rate of change of stress over time.

Improvements to the study are primarily driven by improvements to the computational model. Introducing a pulsatile flow (fluid dynamics), varying the applied stress (instead of assuming normal systolic blood pressure), and utilizing more complex material properties would all improve the accuracy of the simulation. Furthermore, stratifying analysis by a variety of factors (such as age or gender) could potentially tease out new differences between patient groups.

![Figure 2: Location of high stress locations (shown in red) for eight representative ATAA models. BAV subjects are shown on the left, TAV subjects on the right. The left coronary artery is marked with a white asterisk.](image)

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### REFERENCES