PATIENT-SPECIFIC 3D MODELING AND BIOMECHANICAL ANALYSIS OF ASCENDING THORACIC AORTIC ANEURYSMS

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INTRODUCTION

Bicuspid Aortic Valves (BAV) is the most common congenital cardiac abnormality, affecting 1% of the population (Nathan et al. 2011). It occurs when two of the three valve leaflets fuse into one. Many problems are associated with the BAV morphology, such as aneurysms. It has been shown that BAV morphology patients are more likely to develop Ascending Thoracic Aortic Aneurysms (ATAA) as compared to Tricuspid Aortic Valves (TAV) (Nathan et al. 2011). An ATAA is the dilation of the aortic wall. If left unchecked, the aneurysm may grow until the aortic wall ruptures and bleeds into the chest cavity.

There is so far no complete explanation as to why there is an association between BAV morphology and ATAA. One theory suggests that the BAV morphology has a weakened aortic wall. So it is believed that the weakened wall experiences a higher mechanical wall stress and the stress creates the ATAA.

Previous research has explored the effects of blood flow through the aorta when in combination with BAV morphology. These projects have failed to completely discover the cause of increased probability of ATAA formation. Therefore, more research into the problem must be done using other parameters. One such parameter, as previously mentioned, is mechanical wall stress.

Wall Stress is the amount of force experienced per unit area. In this case, it is the amount of force experienced per unit area of aortic wall. This stress comes in the form of normal stress and shear stress. Normal Stress occurs when the force is applied perpendicularly to the surface it is acting upon. Shear stress occurs when the force is applied parallel to the surface. However, to easily quantify these values using 3D models the use of Von Mises stress criterion is required. Von Mises stress criterion combines both normal and shear stress into a single scalar value. This allows for quick understanding of how much stress the wall is experiencing as well as simplifying the contour plots.

The way these models were test was through the use of Finite Element Analysis (FEA). FEA is a computerized numerical technique used to find the solutions to boundary value problems. It creates a mesh of small elements to create a grid of elements across the model in question. Each element has a set of material parameters applied that will interact with the underlying physical equations. The model is then run through the solving program which quickly solves the set of equations for each element based on the physics underlying the model.

OBJECTIVE

In order to try to develop a better understanding as to why BAV morphology patients exhibit a greater risk of ATAA development, the mechanical wall stresses of both BAV and TAV aneurysm patients were determined and compared to each other. The locations of the peak wall stress were observed and compared as well.

HYPOTHESIS

We believe that BAV associated aneurysms experience a higher peak wall stress as compared to TAV aneurysms. This higher stress is what contributes to increased ATAA risk. We also believe that the location of the peak wall stress will occur on the greater curvature of the ascending thoracic aorta.

METHOD

The overall process was completely computerized, using a multitude of programs. The CT scans of each de-identified patient generated a 3D model that was refined and meshed. Each meshed model was run through Abaqus CAE 6.13, which is a FEA program. The output of the program was contour plots of the Von Mises wall stresses as well as any maximums and minimums required for any parameter.

The CT scans for each patient were run through a program called Mimics. The program highlights the relevant region of each slice of the CT scan pixel by pixel. The program then compiles the highlighted regions one on top of the other, creating a solid 3D model of the aorta and the aneurysm. The model was then converted into a point cloud file. A point cloud file creates a surface of the solid model by picking up specific points on the surface. The point cloud is then imported into a program called Geomagic Studio® for smoothing and sectioning. The point cloud file generates a polygon mesh that can be smoothed and sectioned. The smoothed and sectioned surface model is then imported into Abaqus CAE 6.13.

Abaqus is the FEA program used to mesh and analyze the model. A mesh was generated over the whole aorta. The aspect ratio of each element was kept below 3:1. This allowed for a highly refined mesh while minimizing the chance of a failed analysis due to the mesh.

Each element had the same material properties per model. Prior research obtained the patient-specific material properties for each model (Pichamuthu et al. 2013). This was done using biaxial tensile testing of tissue removed from the specific patients after undergoing surgery to repair the aneurysm. Each opening to the aorta was given fixed boundary conditions, save the opening at the aortic root, which was given freedom of movement in the xy-plane. A static pressure of 120 mmHg was prescribed at each node in the lumen of the aorta to simulate the average systolic pressure. Each model was then run through
the analysis. The output generated was a Von Mises wall stress contour plot as well as the minimum and maximum wall stresses. The contour plot allowed the location of the peak wall stress as well as any other stress to be determined. The results from both BAV aneurysms and TAV aneurysms were then compared to each other.

RESULTS

So far only preliminary data was obtained in order to test the protocol. A model for each valve morphology was analyzed. When comparing the model, there is a small increase in peak wall stress.

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<th>BAV</th>
<th>TAV</th>
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<tr>
<td>Peak Von Mises Wall Stress (N/cm²)</td>
<td>42.5</td>
<td>42.2</td>
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Table 1. Preliminary peak stresses for 1 BAV model and 1 TAV model. Small increase in wall stress for BAV model.

The locations of the peak wall stresses were also found to be on the inner curvature of the aorta for both the BAV and TAV models.

As previously stated, this is preliminary data and more will come from the analysis of more models.

DISCUSSION

The results so far are inconclusive for both hypotheses. However, based on the preliminary data, the BAV model does have a small increase in wall stress but not enough to say any conclusive prediction. More data will provide a greater picture of the wall stress differences.

The locations of the peak wall stresses refute the hypothesis that it should be located on the greater or outer curvature of the aorta. However, it is even more interesting that the peak wall stress is located on the inner curvature for both the BAV and TAV models. This is contradictory to the literature found regarding the same type of research. More exploration into this aspect of the project must be done.

The results obtained did not come with problems. The meshing around tight and irregular geometries causes areas of false high stress. This was observed around the coronary arteries, the supra aortic branches and at the base of the aortic root. The irregularities were minimized as much as possible but some still remained, causing problems with the mesh and creating false stress regions. These regions may be worked with more to correct the problems or different boundary conditions may be used to more accurately model the mechanics of these regions.

FUTURE DIRECTION

The protocol will be used to continue the modeling and analysis of the BAV and TAV aneurysms. This will help to further the understanding of BAV morphology and pathology. The protocol will also be used to create a temporal study of aneurysms. This may allow the aneurysm to be studied as it changes rather than just one instance in time. The study of the formation of the aneurysm will give even more insight on the link between BAV morphology and ATAAs. Another potential use of the protocol is use in the clinic after a streamlining of the process. This could allow quick analysis of the aneurysm and faster determination of steps to be taken.

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REFERENCES
