Investigation of the Relationship Between Abdominal Aortic Aneurysm Rupture and Mechanical Stress

by
Nicholas Agalzoff

A THESIS

submitted to
Oregon State University
University Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Bioengineering
(Honors Scholar)

Presented March 1, 2016
Commencement June 2016
AN ABSTRACT OF THE THESIS OF

Nicholas Agalzoff for the degree of Honors Baccalaureate of Science in Bioengineering presented on March 1, 2016. Title: Investigation of the Relationship Between Abdominal Aortic Aneurysm Rupture and Mechanical Stress.

Abstract approved:

______________________________________________________

Cindy Grimm

The factors that cause abdominal aortic aneurysm rupture were investigated. Included in this study were aneurysm volume, thrombus thickness, lumen area, thrombus area, the average stress acting on the aorta, and the maximum stress on the aorta. The geometric values were obtained by tracing a series of computerized axial tomography (CT) scans for each patient to obtain a series of cross sections of the lumen and the thrombus. The cross sections were then put through a program that found a best fit surface for both the lumen and the thrombus. These meshes were analyzed to obtain the geometric information. The stress data were calculated by using the meshes to make an ADINA file programmed with average human values for outlet pressure, flow rate of blood, and load pressure. This resulted in a model of each patient’s aorta with the stress values included. A binomial logistic regression analysis revealed that none of the parameters investigated here were able to predict a rupture with a high degree of confidence ($p<0.05$).

Key Words: Abdominal aortic aneurysms, mean max mechanical stress, mesh, model, Lumen, thrombus, area, volume

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Nicholas Agalzoff, Author
Investigation of the Relationship Between Abdominal Aortic Aneurysm Rupture and Mechanical Stress
Nick Agalzoff

Abstract

The factors that cause abdominal aortic aneurysm rupture were investigated. Included in this study were aneurysm volume, thrombus thickness, lumen area, thrombus area, the average stress acting on the aorta, and the maximum stress on the aorta. The geometric values were obtained by tracing a series of computerized axial tomography (CT) scans for each patient to obtain a series of cross sections of the lumen and the thrombus. The cross sections were then put through a program that found a best fit surface for both the lumen and the thrombus. These meshes were analyzed to obtain the geometric information. The stress data were calculated by using the meshes to make an ADINA file programmed with average human values for outlet pressure, flow rate of blood, and load pressure. This resulted in a model of each patient’s aorta with the stress values included. A binomial logistic regression analysis revealed that none of the parameters investigated here were able to predict a rupture with a high degree of confidence \( p<0.05 \).

Introduction

An abdominal aortic aneurysm (AAA) is defined as a segmental, full-thickness expansion of the abdominal aorta. The expansion qualifies as an aneurysm when it has a diameter greater than 3.0 cm, or exceeds the normal vessel diameter by 50%. The cause for the degenerative process remains unknown. Risk factors for having an AAA include: age, having ever smoked, and having a family history of AAA. AAAs are typically asymptomatic until rupture, which are often lethal; mortality is 85-90%. This has led to AAA causing a reported 13,000 deaths per year in the United States alone.

Surgical repair of an AAA is done when the risk of the rupture outweighs the risk of the surgery. AAA diameter is currently the primary factor that is used to assess the risk of AAA rupture. This is despite the fact that AAA rupture is known to be a complicated process with many potential factors. Of these factors, stress in particular may be of great significance in predicting a rupture.

In this work the stress mechanisms related to aneurysm rupture are investigated. The study of AAA wall stress can be accomplished using various computational methods, which include modeling the AAA geometry and applying boundary conditions and typical human blood pressures.
Materials and Methods

The project overview can be seen in Figure 1:

Figure 1: Flowchart of the series of tasks involved in the project. The contours traced on CT scans are used to generate point clouds. A best fit surface for the point cloud is calculated and then a water-tight mesh is obtained. The meshes for each patient’s lumen and thrombus, if they are clean and smooth, are used to generate and input file for ADINA. ADINA is used to solve the model so the stress values can be known. Ensight is then used to observe and calculate the wall stresses.

CT scan images were read into Matlab. A Matlab graphical user interface was used to trace the lumen and thrombus of patient aortas as shown in Figure 2. Traces were done on both aneurisms that did, and did not, rupture. The tracing was done prior to rupture for relevant cases. Traces were done on separate planes from the renal bifurcation to the iliac bifurcation until a viable point cloud like the one shown in Figure 3 was obtained.

Figure 2: This figure shows one plane of a CT scan. The full scan is contained as a dicom file that contained 50 to 600 planes depending on the patient. Here the lumen of the aorta is traced in red and the thrombus is traced in green. Each patient’s aorta is traced from the renal bifurcation to the iliac bifurcation.
Figure 3: Shown here is the result of the tracing of a thrombus. The thrombus and lumen for each patient are saved as separate files until the ADINA input file is created.

These point clouds were turned into watertight meshes as shown in Figure 4 by connecting the contours drawn at each level and applying local and global smoothing. The lumen and thrombus meshes for each patient were analyzed using code that determined average lumen and thrombus area versus normalized distance. Normalized distance is the percent of the total length of the model. The watertight meshes were checked at this stage for any issues. These issues could include folding or wrinkling of the mesh, sharp edges, or the mesh not converging. These were usually due to the code not being able to handle concavities in the aorta properly. The meshes were retraced from the very beginning if this occurred to fix any issues. If issues persisted after three retraces the patient file was omitted.

It was also during this stage that model parameters were input into the ADINA file. Each model used parameters based on the average human values. The relevant parameters were an outlet pressure of 120 mmHg, inlet flowrate of 110 mL/s, and a load pressure of 120 mmHg.
Finite element modeling was done in ADINA. The modeling program Ensight was used to discern the mean and max stress of the aneurism after the model was solved. The edges of the model were excluded from the calculation so the results were not skewed by the boundary conditions. An Ensight model can be seen in Figure 5.

Figure 4: This is a complete mesh obtained from the point cloud shown in Figure 2. This was obtained by applying local and global smoothing in order to find a best fit surface. This is the same thrombus as shown before and it will be combined with the corresponding lumen mesh in order to make an ADINA input file.

Figure 5: The full model of the aorta presented in Ensight. This figure shows the distribution of wall stress (WS) on the aorta. The 0-200 kPa range was a standard range chosen for uniform viewing of all patients. The actual max stress of the above image is 494 kPa.
Results and Discussion

The meshes were used to obtain the average thickness of the thrombus, the average lumen area, and the average thrombus area. This information was used to calculate the percent volume the aneurysm accounts for in the whole aorta. The ADINA models were used to obtain the mean and maximum stress data. This information is summarized in Table 1. Whether or not a patient’s aorta ruptured is indicated by a 1 if it did and a 0 if it did not.

Table 1: Abdominal Aortic Aneurysm Data

<table>
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<tr>
<th>Patient</th>
<th>Average thickness (mm)</th>
<th>Average lumen area (mm²)</th>
<th>Thrombus area (mm²)</th>
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A binomial logistic regression was performed on the above data. The regression method was not able to use the provided data to predict a rupture with reliable accuracy. No variable had a \( p \) value below 0.05. Average stress was the best predictor, however, with a \( p \) value of 0.13.

The receiver operating characteristic (ROC) curve, produced from the regression analysis, had an area of 0.78. This is considered a fair area for an ROC curve to have with 1 being a perfect curve. The curve can be seen below to in Figure 6.

The ruptured and non-ruptured aneurysms were considered to be two populations for this analysis. Ruptured patients were represented by 1 and non-ruptured by 0. The binomial logistic regression uses the input variables to find trends in the data and assigns each patient a decimal number between 0 and 1. This is called the predicted condition. Then a classification cut-off is applied to draw a distinction between predicted ruptures and non-ruptures. The predicted results are compared to the actual values and true positive and false positive rates are obtained. The ROC curve is a representation of how these rates vary as the classification cut-off changes. The true positive rate is also called sensitivity and the false positive rate is 1-specificity. The ROC curve shows that any increase in sensitivity is accompanied by a decrease in specificity.

![Figure 6: ROC curve obtained from performing binary logistic regression on the geometric and stress data obtained in this project. This curve shows how accurately the variables predict a rupture and is assessed by measuring the area beneath the curve. This curve has an area of 0.78 which suggests that variables used in this analysis are either factors that predict ruptures or are related to other factors that do.](image)

The mean maximum stress for ruptured aneurysms was \( 246.2 \pm 256.6 \) kPa. Using standard deviation and for the non-ruptured aneurysms it was \( 223.9 \pm 95.5 \) kPa. The average mean stress values for ruptured and non-ruptured were \( 30.4 \pm 18.2 \) and \( 28.3 \pm 9.9 \) kPa. The values of both mean and max stress for both groups are close and the standard deviations are very high. This suggests that the rupture process is complicated and cannot be described by a single measure of stress. This data is shown graphically in Figure 7. The confidence intervals for ruptured and non-ruptured max stresses were \( 246.2 \pm 122.0 \) and \( 223.9 \pm 56.7 \) respectively. Mean stresses were \( 30.4 \pm 8.7 \) and \( 28.6 \pm 5.9 \) respectively.
Figure 7: Comparison of mean and max stress between ruptured and non-ruptured aneurysms. The black bars here represent standard deviations. There were no significant differences observed between the two groups.

Conclusions

None of the parameters measured in this study were able to predict whether or not an aneurysm would rupture. This is not surprising due to it being known that aneurysm rupture is a complicated process with many factors. The high variability of the mean and max stress values for the ruptured aneurysms suggests that there is no threshold value that predicts a rupture. The ROC curve obtained from the regression analysis has a high enough value to suggest that there is a way to reliably predict a rupture. The parameters investigated here are likely either part of the factors that actually lead to a rupture or are related to them.

Acknowledgments

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References