UT-BATTELLE

Parametric Study of Mechanical Stress in Abdominal Aortic Aneurysms (AAA)

Presented to

George Seweryniak
Mathematical, Information, and Computational Sciences

Erin A. Lennartz
Virginia Polytechnic Institute and State University
Computational Sciences and Engineering Division

Oak Ridge, Tennessee
August 8, 2006

Outline

- Introduction to Abdominal Aortic Aneurysm (AAA)
- Project goals
- Software and model
  - Abaqus, Rhino3D
  - Why not linear-elastic
- What was found
- Future endeavors

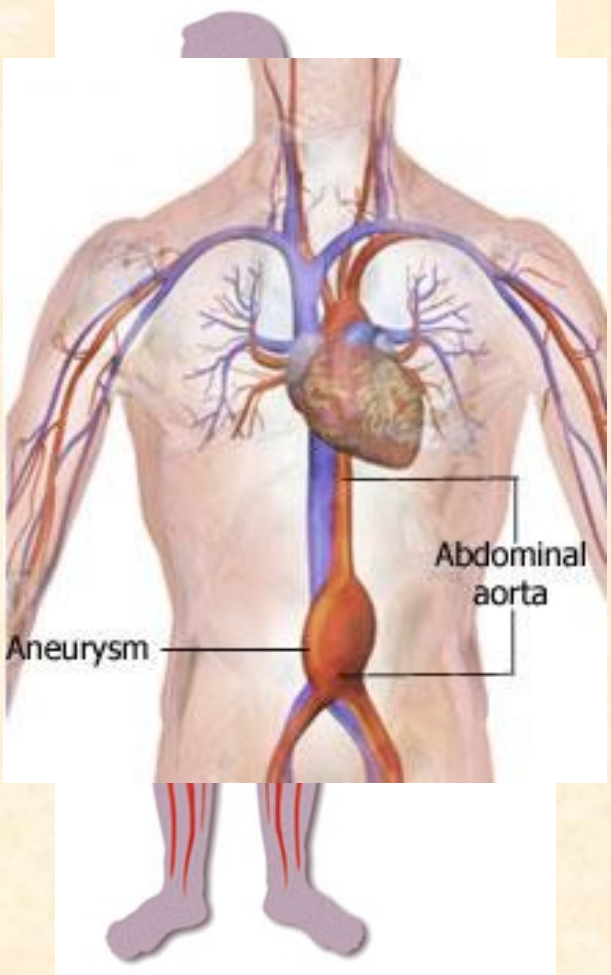
Introduction:

Abdominal Aortic Aneurysm (AAA)

- The Aorta is largest human artery originating from left ventricle of the heart
- An (AAA) is a disease where the abdominal aorta loses its structural integrity and dilates in a balloon-like manner
- Aneurysms in the aorta typically occur in abdomen due to two factors:

  - Decrease in elastin

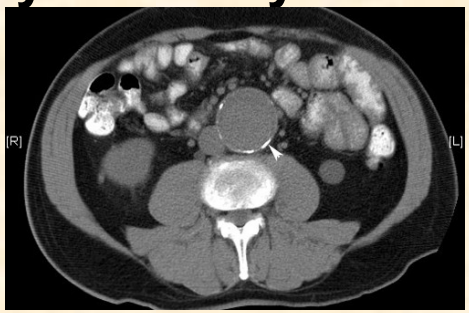
  - Lack of repairing structure vaso vasorum



Introduction

What is AAA Rupture?

- Rupture of a AAA occurs when the stress in the wall exceeds its strength
- Wall strength decreases due to a decrease in collagen due to increased MMP activity
- About 90% of AAA's that rupture lead to death
- Rupture of AAA's is a leading cause of death in the United States
- Currently aneurysms are not treated with intravascular or open surgery until they reach a maximum diameter of 5 to 5.5cm



AAA Rupture

Invasive surgery

Introduction

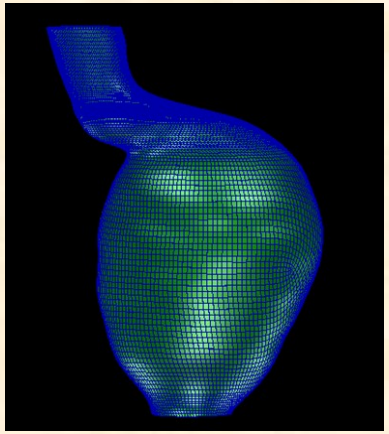
So Why the Concern?

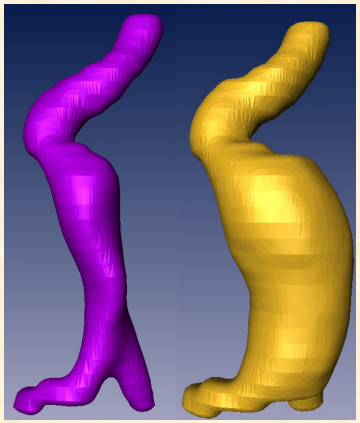
- Size criterion does not take into account unique properties of individual patient's arterial wall
- Aneurysms much smaller than 5 cm have ruptured, while others much larger have not
- Rupture depends on mechanical stress in the wall
- Mechanical stress depends not only on the maximum diameter, but the overall geometry, wall thickness, elastic properties, and pressure load of the aneurysm
- No effective, noninvasive way to measure these stresses to date

Introduction

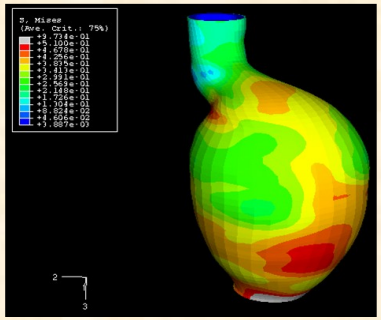
Project Start Point

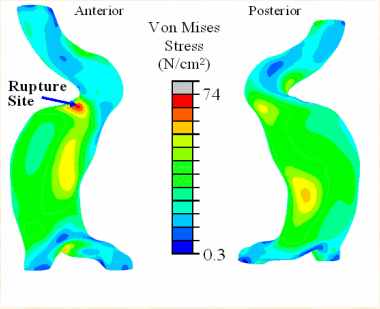
- Two previously created geometries were used for parametric study
- Each geometry was created from CT scans of patients shortly before rupture of the AAA occurred
- One geometry includes bifurcation into iliac arteries, while the other does not
- In both cases rupture location was known and accurately determined through use of patient averaged parameters





Geometries were created from CT images using Patran and Abaqus





The von Mises stress was computed using Abaqus and a linear elastic model

Project Goals

- Develop a noninvasive and more realistic model for predicting AAA rupture by:

  - Developing a hyper-elastic model for the bifurcated geometry

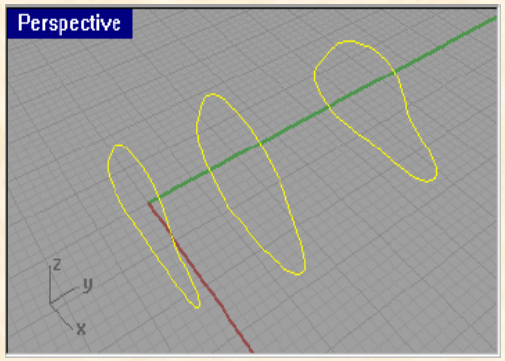
  - Determining sensitivity of mechanical stress calculations to changes in:
    (1) wall thickness
    (2) elastic properties of both the wall and thrombus
    (3) blood pressure.

  - Determining which parameters affect the stress calculations the greatest

Software Used

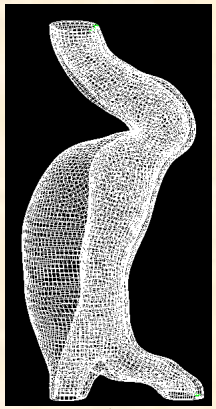
- Amira
- Rhino3D
- Patran
- Abaqus 6.5-1

CT Scan of AAA



Rhino3D segmentation

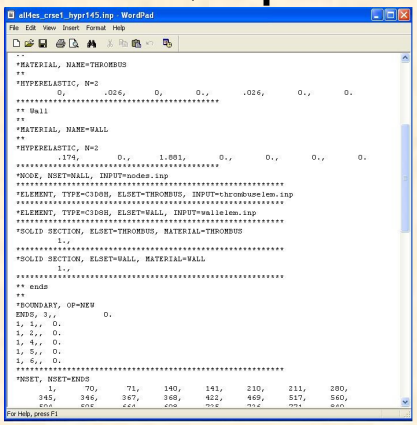
Patran Mesh

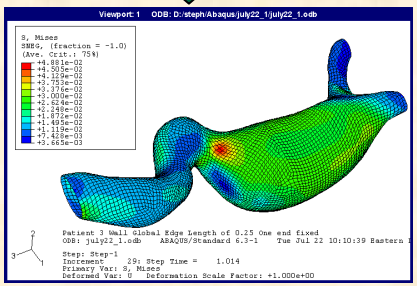


Hyper-elastic model

$$W = C1(I1 - 3) + C2(I2 - 3),$$

Input file





Abaqus CAE

Software Used

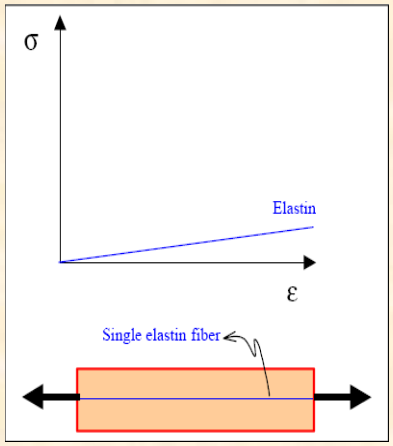
Using Abaqus

Abaqus requires the following input parameters to run a stress analysis:

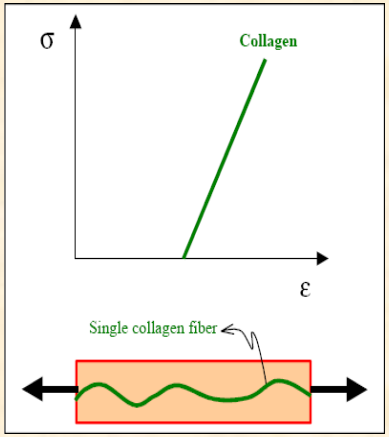
- Blood pressure
- Wall thickness
- Mechanical properties (linear or non-linear elastic)
- Model parameters:
  - Boundary conditions
  - Finite element mathematical control parameters

Why Not Linear Elastic?

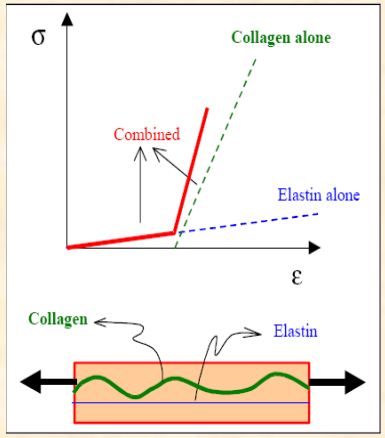
Elastin



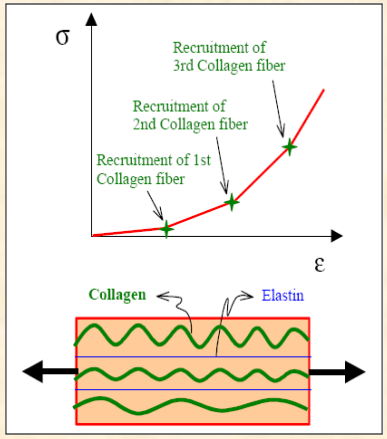
Collagen



Elastin and Collagen



Recruitment



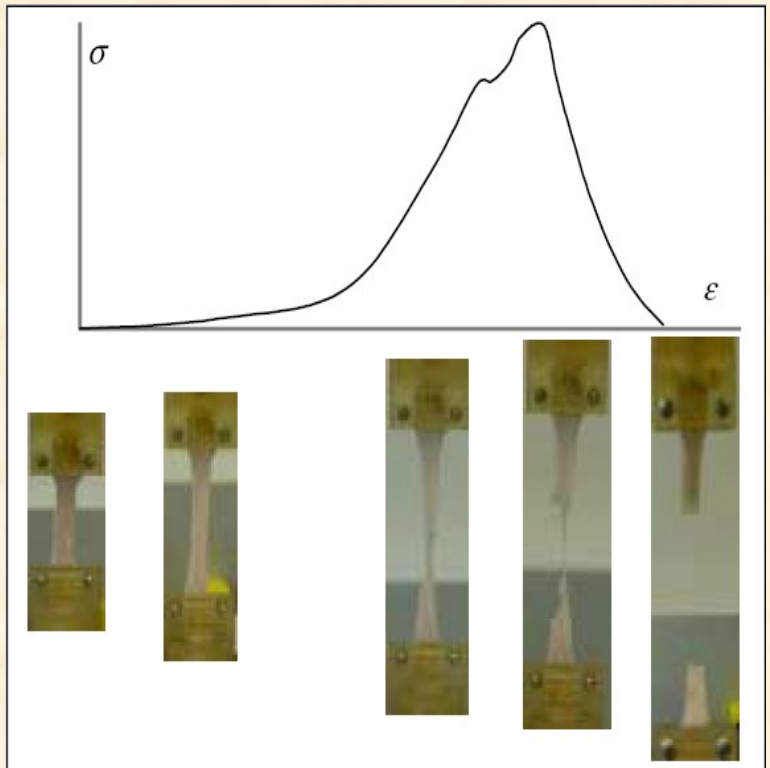
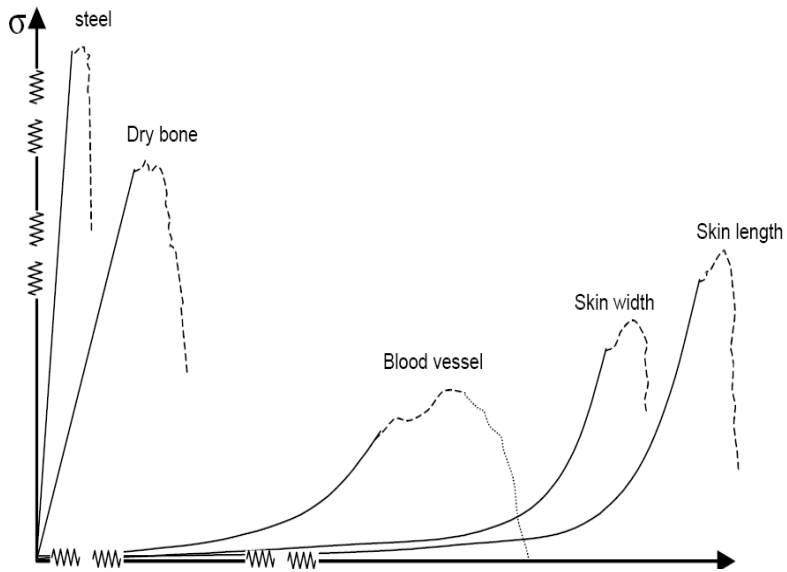


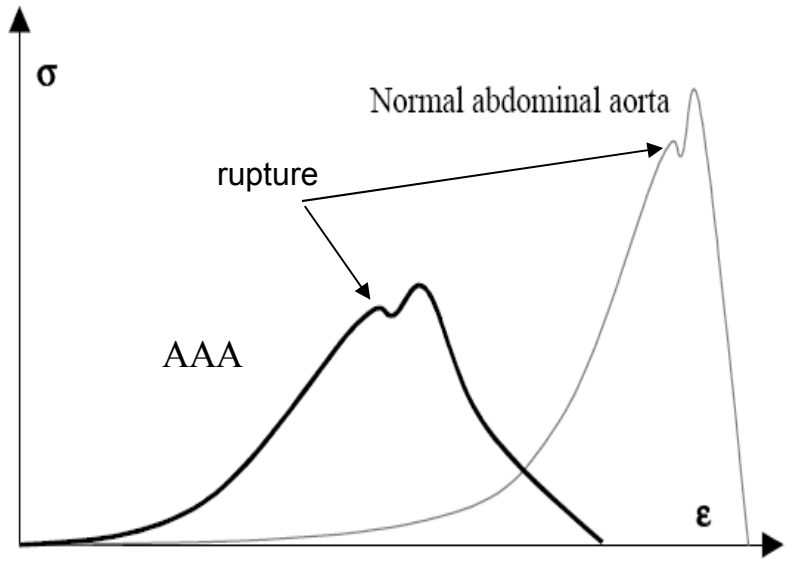
Illustration of a uniaxial extension test with the corresponding elastic curve. The images show various stages during the testing of pig thoracic aorta and correspond to the portion of the curve right above them

Figures referenced from Raghavan, ML Lecture Notes

The Hyper-elastic Model for AAA



Comparison of stress-strain curve for steel, dry bone, blood vessel, skin width, skin length



Comparison of elastic curves for normal and aneurysmal abdominal aorta

Figures referenced from Raghavan, ML Lecture Notes

What is a Parametric Study?

- Single values replaced with a range or set of values for optimization
- Blood pressure (BP) varies continuously
- Parameters other than BP were patient-averaged values evaluated at the mean and both ends of the standard deviation

Hyper-elastic Mooney Rivlin Model

$$W = c_1(I_1 - 3) + c_2(I_2 - 3) + D_1\{\exp[D_2(I_1 - 3)] - 1\}$$

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \qquad I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2$$

***I*1 and *I*2 are the first and the second invariant of Finger tensor:**

What is a Parametric Study?

```
# script to run blood pressure study on AAA

# parameters used in the study

# BP = 120 mmHg = 0.016 MPa

blood_press=0.016
ET=0.2
EW=5.0
PRT=0.49
PRW=0.49

#create the parametric study  MAKE SURE TO ADD THE OTHER PARAMETERS!

pressure_study=ParStudy( par = ( 'blood_press','ET','EW','PRT','PRW'))
```

```
*HEADING
Patient 2 Wall Surface & Thrombus: hyperelastic, 10.2K nodes, 7.5 K elem
** using surfaces generated in Rhino3D
** solid elements are hex, 8-node
**
**
**
*PREPRINT,ECHO=YES,HISTORY=YES,MODEL=YES
*****************************************
**        MATERIAL DESCRIPTION
*****************************************
*****************************************
** - SYSTEM OF UNITS
```

```
#sample the parameters

pressure_study.sample( VALUES, par='blood_press' , values = (0.016, 0.01933) )
pressure_study.sample( VALUES, par='ET' , values = (0.1, 0.2, 0.3) )
pressure_study.sample( VALUES, par='EW' , values = (4., 5., 6.) )
pressure_study.sample( VALUES, par='PRT' , values = (.4, .45, .5) )
pressure_study.sample( VALUES, par='PRW' , values = (.4, .45, .5) )
```

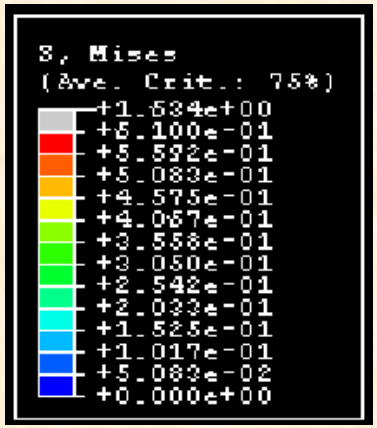
```
pressure_study.sample( VALUES, par='EW' , values = (4., 5., 6.) )
pressure_study.sample( VALUES, par='PRT' , values = (.4, .45, .5) )
pressure_study.sample( VALUES, par='PRW' , values = (.4, .45, .5) )

#combine the samples into designs

pressure_study.combine( MESH, name= 'BP')

# generate input deck

pressure_study.generate( template='all4e_crse1_lin')

#execute runs sequentially

pressure_study.execute( ALL )

#set output source to odb database Gather results

pressure_study.output( file=ODB, step= 1 )

# gather results for 1 node

pressure_study.gather( results='stress', variable='S', element=6985)

#write to database *.odb file

pressure_study.report( FILE, results=('stress.1'), file='stress_results')
```

```
** Thrombus
**
*MATERIAL, NAME=THROMBUS
**
*ELASTIC, TYPE=ISO
          <ET>,          <PRT>
*****************************************
** Wall
**
```

```
*MATERIAL, NAME=THROMBUS
**
*ELASTIC, TYPE=ISO
          <ET>,          <PRT>
*****************************************
** Wall
**
*MATERIAL, NAME=WALL
**
*ELASTIC, TYPE=ISO
          <EW>,          <PRW>
*****************************************
```

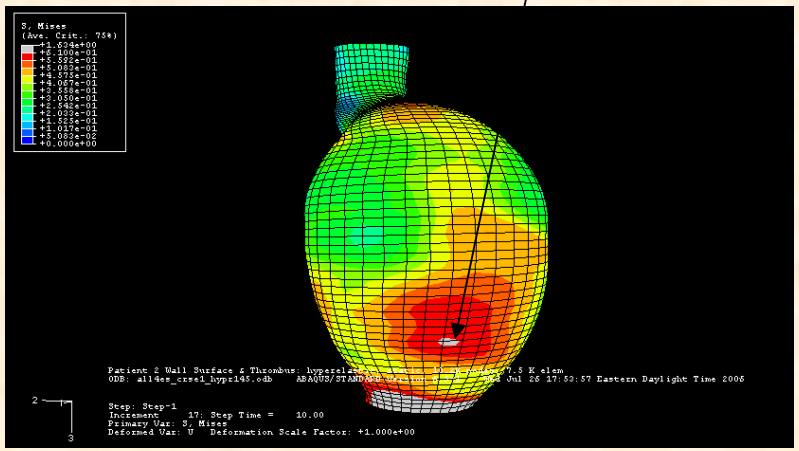
What Was Found

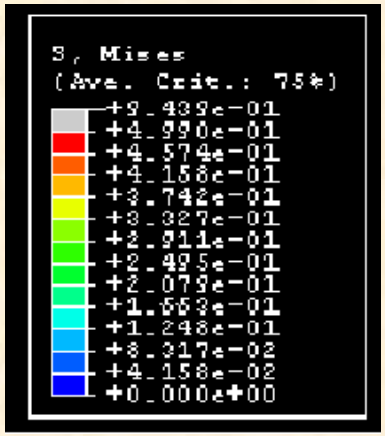
Hyper-elastic model produced higher stress concentrations at the same location (node 9718)



Hyper-elastic:

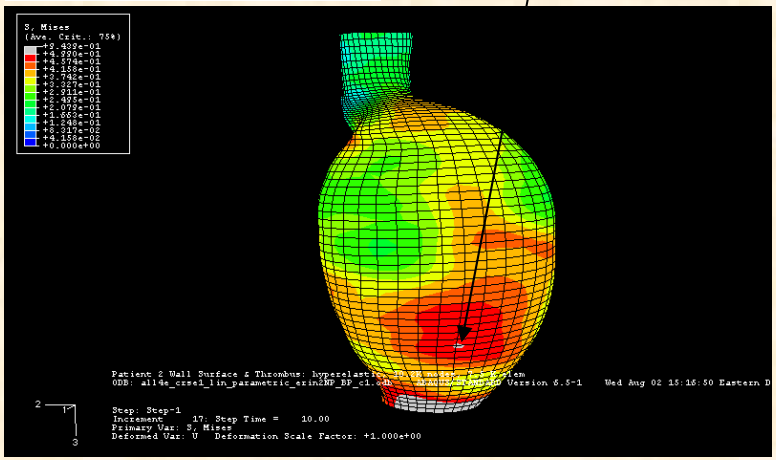
0.61328 MPa





Linear elastic:

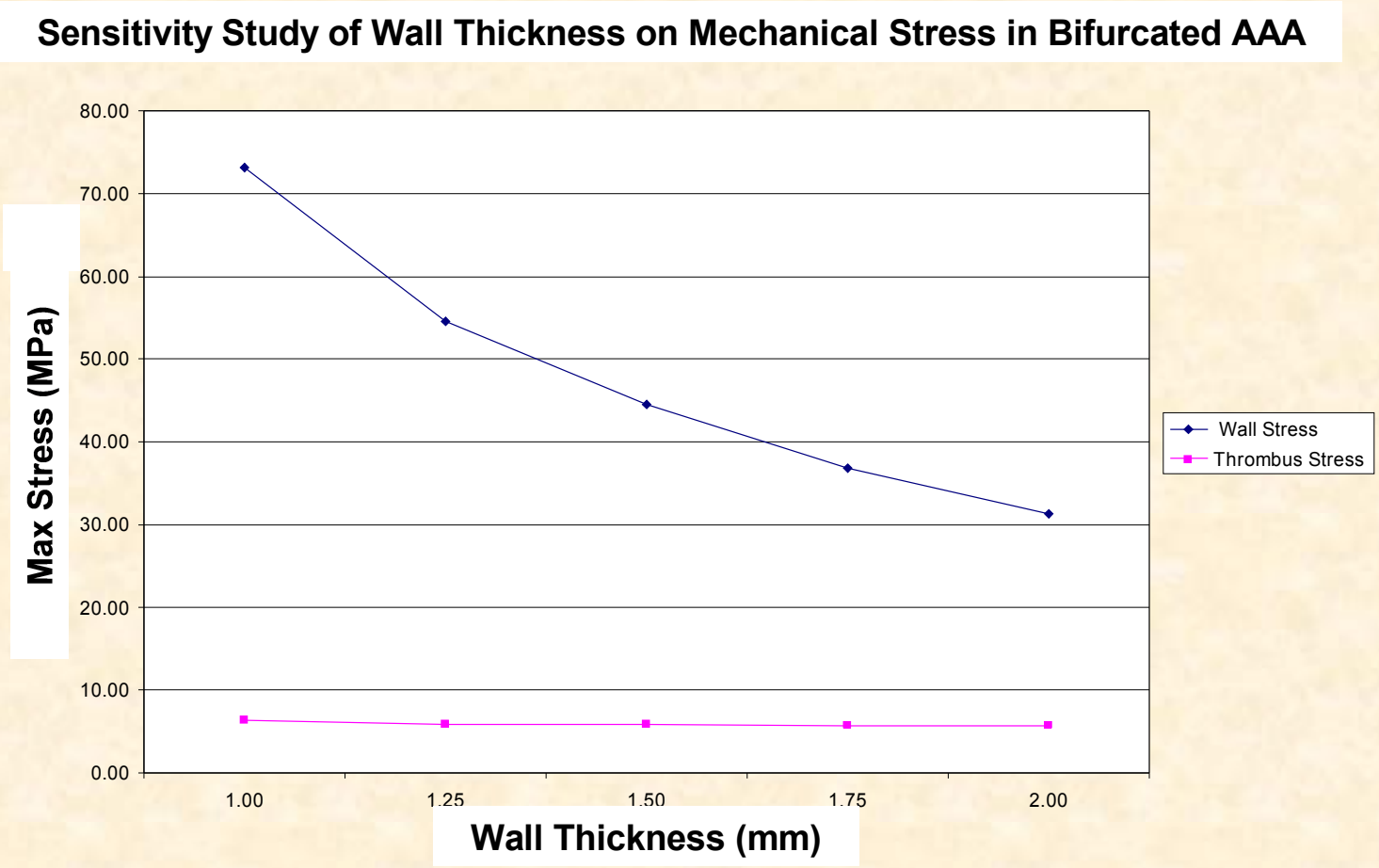
0.494614 MPa



Abaqus stress computations

What Was Found

Wall thickness had the greatest effect on mechanical stress



What Was Found

Equation parameters had little effect on stress concentrations, blood pressure had great effect

Parametric study: parametric_erin

blood_press	ET	EW	PRT	PRW	stress.1
0.016	0.1	4	0.4	0.4	0.175047
0.01933	0.1	4	0.4	0.4	0.216607
0.016	0.2	4	0.4	0.4	0.16889
0.01933	0.2	4	0.4	0.4	0.198262
0.016	0.3	4	0.4	0.4	0.148912
0.01933	0.3	4	0.4	0.4	0.186653
0.016	0.1	5	0.4	0.4	0.174737
0.01933	0.1	5	0.4	0.4	0.217516
0.016	0.2	5	0.4	0.4	0.163746
0.01933	0.2	5	0.4	0.4	0.179282
0.016	0.3	5	0.4	0.4	0.154405
0.01933	0.3	5	0.4	0.4	0.187488
0.016	0.1	6	0.4	0.4	0.175608
0.01933	0.1	6	0.4	0.4	0.210643
0.016	0.2	6	0.4	0.4	0.166592
0.01933	0.2	6	0.4	0.4	0.202083
0.016	0.3	6	0.4	0.4	0.158216
0.01933	0.3	6	0.4	0.4	0.192403
0.016	0.1	4	0.45	0.4	0.176387
0.01933	0.1	4	0.45	0.4	0.217985
0.016	0.2	4	0.45	0.4	0.155613

Future Endeavors

- Run more tests on these two models using different parameters and different models for strain energy
- Develop models for other geometries
- Optimize procedure for developing these models, to allow fast and accurate predictions

Summary

- Maximum diameter is not a complete criterion for predicting rupture
- Non-invasive technique for measuring stress is possible, however higher resolution CT scans would provide a more consistent model
- Patient-averaged mechanical parameters are a good indicator of rupture site and predicting stress
- Blood pressure and wall thickness have greatest effect on mechanical stress

Thank you

Special thanks goes to Kara L. Kruse and Dr. Richard Ward without whose guidance and support this project would not have been possible. Many thanks also goes to the UT medical center for their collaboration. Lastly, the author would like to thank not only the sponsors of the RAMS program for the opportunity to conduct research at the ORNL facility, but the people that oversee the daily operation of the program, especially Debbie McCoy and Judy Burns.

Questions?

Acknowledgments

The Research Alliance in Math and Science program is sponsored by the Mathematical, Information, and Computational Sciences Division, Office of Advanced Scientific Computing Research, U.S. Department of Energy.

The work was performed at the Oak Ridge National Laboratory, which is managed by UT-Battelle, LLC under Contract No. De-AC05-00OR22725. This work has been authored by a contractor of the U.S. Government, accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S Government purposes.