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EFFECTS OF INTRALUMINAL THROMBUS AND WALL THICKNESS ON WALL STRESS OF HYPOTHETICAL SYMMETRIC AND ASYMMETRIC ABDOMINAL AORTIC ANEURYSM

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ABSTRACT

Abdominal aortic aneurysm (AAA) is an irreversible enlargement of the terminal aortic segment affecting 0.4% of people over the age of 50. It occurs gradually over a span of years and is considered a health risk as it may rupture if not treated.

From a biomechanical point of view, AAA rupture occurs when the induced mechanical wall stress exceeds the local minimum strength of the AAA wall. Knowledge of the biomechanical behavior of AAA tissue may therefore prove very indispensable in understanding the underlying mechanism behind the changes involved with AAA formation. The purpose of this work is to obtain qualitative information on how wall thickness, intraluminal thrombus and asymmetry influence aneurysm wall stress. Four sets of three dimensional hypothetically modeled AAA are the subject of this study. A published hyperelastic strain energy function is used as the material model for the AAA wall. Using finite element method, the stress distribution on the aortic wall under systolic pressure is determined for all 16 AAA models.

Results showed the distribution of wall stresses, with peak wall stresses located at the inner wall of the AAA, for both axially symmetric and asymmetric models. The stress gradient through the AAA wall shows that the wall strength distribution within any particular AAA is spatially variable. The effect of the aneurismal wall thickness and the incorporation of intraluminal thrombus showed profound influence on the magnitude and distribution of stresses on AAA wall

I. INTRODUCTION

Abdominal aortic aneurysm rupture is ranked as the 13th most common cause of death in the United States with an estimated death of 13,000 each year [6]. While AAA rupture may occur without significant warning, its risk assessment is, at present, generally based on critical values of the maximum AAA diameter (>5 cm) and AAA-growth rate (>0.5 cm/year) [10]. These criteria, however, may be insufficient for reliable AAA-rupture risk assessment especially when predicting possible rupture of smaller AAAs [6,12].

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A great deal of research effort in the field of AAA mechanics has been devoted to understanding the factors affecting how the stresses in the aneurysm wall are distributed. Accurate estimation of AAA wall stress distribution may therefore prove useful in predicting when a particular aneurysm will rupture. Detailed three-dimensional model and appropriate constitutive description for the AAA wall is necessary for this task. Key biomechanical factors influencing AAA rupture has been identified to determine when elective repair is necessary [7]. These factors include maximum AAA diameter, expansion rate, mechanical stress, diastolic pressure, asymmetry index, saccular index, wall curvature, and intraluminal thrombus to name a few.

Because it is difficult to directly measure the stresses in AAA, finite element analysis using software packages are used instead. A system such as a pressurized abdominal aortic aneurysm can be modeled using an approximate function instead of an exact mathematical model. Numerous studies have employed this technique to examine wall stress distributions and to determine how biomechanical and geometric factors affect these stresses [13]. These studies have shown the effect of several factors such as diameter, wall thickness, shape and material physical properties on the stress distributions of AAA.

The purpose of this work is to determine the maximum stresses and locations of these stresses on hypothetical aneurysm and how these parameters are affected by the thickness of aneurism wall. The effect of intraluminal thrombus on wall stress distribution is also investigated for both symmetric and asymmetric AAA models.

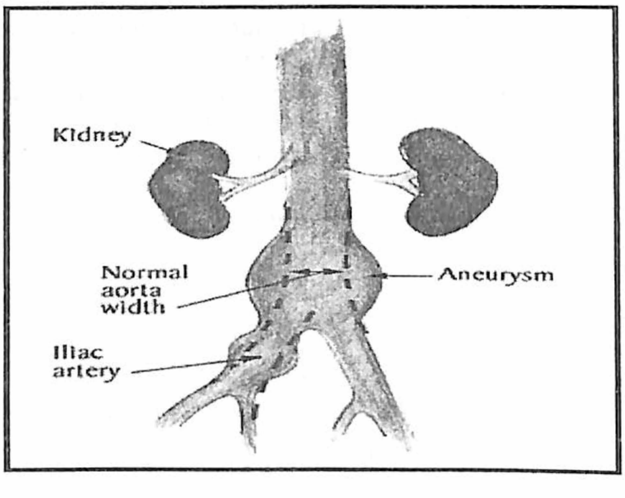

Fig.1 Typical human abdominal aorta [14]

II. METHODOLOGY

The study is divided into four sections designed to systematically evaluate a specific material characteristic and investigate how changes to these physical characteristics influence aneurysm wall stress.

Using the CAD software ProEngineer Wildfire 3, aneurysms were modeled as structures with walls constructed of homogeneous, isotropic materials that exhibit hyperelastic deformation. A total of 16 AAA were generated with a fixed length of 120 mm and undilated diameters of 2 cm at the outlet and inlet sections.

The first part of the analysis focuses on the effect of wall thickness on the walls stresses. This is divided into two separate cases: Case 1 for the AAA models that are symmetric about the longitudinal axis and Case 2 for AAA models with aortic sac that is not axis symmetric. For both cases, AAA models with uniform wall thicknesses are generated with the initial thickness set at 1.5 mm. The thickness of the AAA models is then increased uniformly by 0.2mm up to a maximum thickness of 2.1 mm.

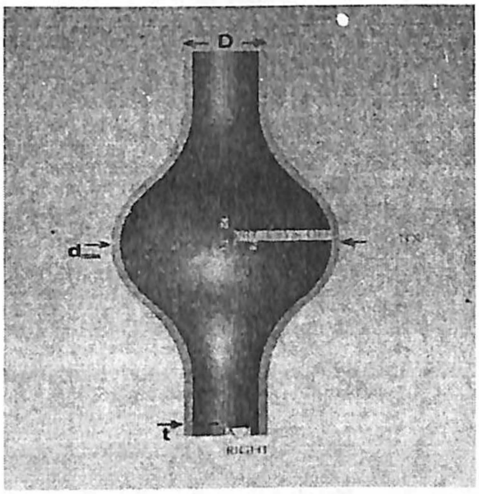

Fig 2 Axis-symmetric AAA model with uniform thickness

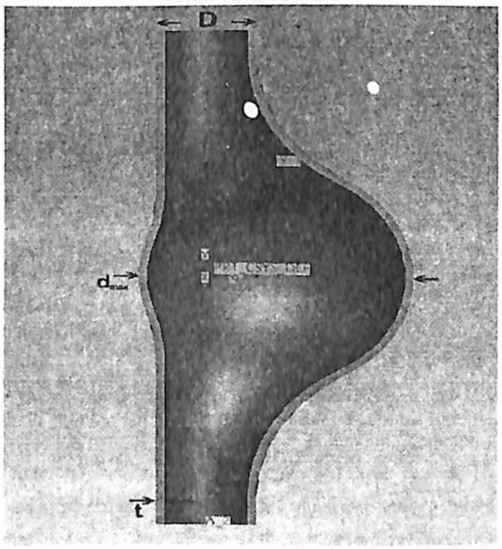

Fig 3 Asymmetric AAA model with uniform wall thickness

The second part of the analysis is focused on the effect of the intraluminal thrombus on the magnitude and distribution of aneurism wall stresses. This is done by incorporating ILT thickness to the two cases mentioned above. The initial thickness is set at 2 mm and gradually increased by 5 mm up to a maximum of 17 mm, measured at the peak diameter of the AAA models.

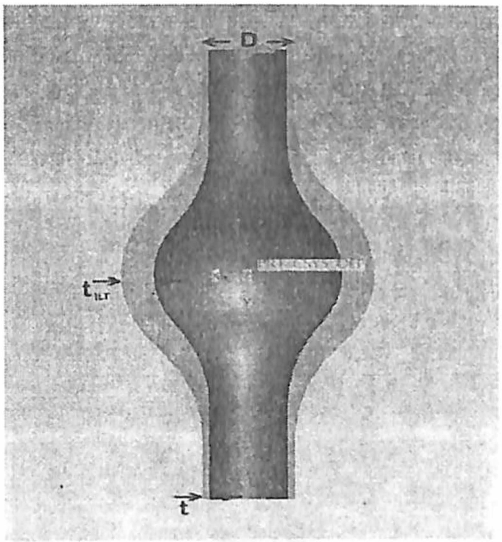

Fig 4 Axis symmetric AAA model with ILT

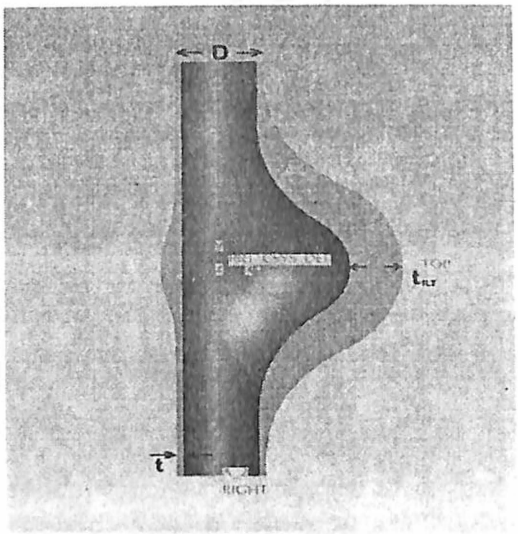

Fig 5 Asymmetric AAA model with ILT

The peak diameter of all AAA models are fixed at 5.5 cm, which is the diameter used by clinicians as a criterion for elective repair. The final models are saved in IGES format for importing to the finite element software.

In this study, an approximate Mooney-Rivlin hyperelastic model was used as outlined by Danao [8]. It was used as a substitute to the published and widely used constitutive model proposed by Raghavan because a user-defined hyperelastic model was not available in the Academic license of the finite element software package used in this study.

The output IGES files were imported to finite element software ANSYS11. An internal systolic pressure of 0.0160 MPa (120 mmHg) was applied to the inner wall to simulate the end systolic conditions that represent the stage in the cardiac cycle in which the largest wall stress is experienced by the AAA. The constraints due to the renal and iliac arteries at the proximal and distal parts of the aneurysm were simulated by constraining the displacements along the longitudinal direction at both ends to zero.

The element type chosen was a 20-node, hyperelastic solid element. All the models were meshed using software's built-in meshing algorithm "SMART SIZING" with setting of "4". Tetrahedral elements were chosen and static, large displacement analyses were performed with a minimum of 100 load sub steps. Nodal contour plots of the von Mises stress were used to evaluate the stress state of the AAA models.

III. RESULTS

To determine the effect of each geometric parameter, the Von Mises stresses were observed and plotted for all the AAA models. Since an AAA is subject to a system of loads in 3 dimensions, a complex 3 dimensional system of stresses is developed. That is, at any point within the body there are stresses acting in different directions, and the direction and magnitude of stresses change from point to point. Even though none of the principal stresses exceeds the yield stress of the material, it is possible for yielding to result from the combination of stresses. The Von Mises criterion is a formula for combining these 3 stresses into an equivalent stress, which is then compared to the yield stress of the material. Von Mises stress therefore sufficiently reflects the potential for material failure.

3.1 Effect of Wall Thickness

Multiple simulations were performed on both symmetric and asymmetric AAA models with increasing values of wall thickness. Peak Von Mises values were recorded and plotted against wall thickness (Figures 6 & 7). As expected, maximum wall stresses decrease with increasing uniform wall thickness for both symmetric and asymmetric AAA models. Specifically, for symmetric AAA models, an increase in wall thickness by a little over 13% exhibits a decrease in peak wall stress by also 13%. However, an increase in wall thickness from 1.9 mm to 2.1mm only contributed to 9.29% decrease in the peak von Mises stress. This reveals a non linear relationship between wall thickness and the maximum stress experienced by the AAA. This result is also in agreement with the findings presented by Danao [8] in his study where a thicker AAA wall experiences smaller peak von Mises stress.

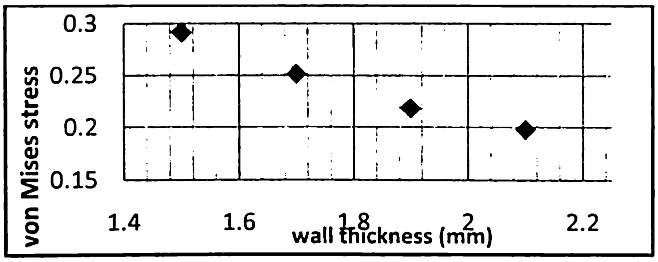

Fig 6. Plot of the maximum von Mises stress for symmetric AAA models with uniform thickness.

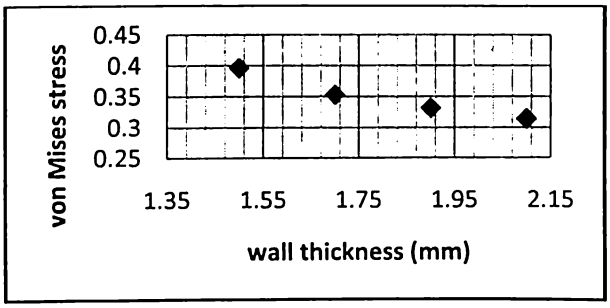

Fig 7. Plot of the maximum von Mises stress for asymmetric AAA models with uniform thickness.

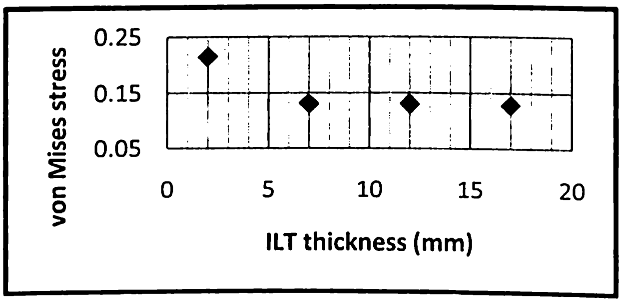

Fig 8. Plot of the maximum von Mises stress for symmetric AAA models with increasing ILT thickness

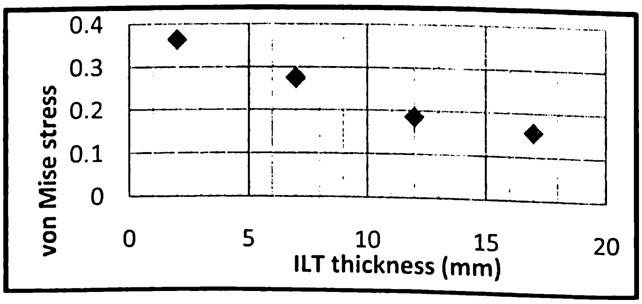

Fig 9. Plot of the maximum von Mises stress for asymmetric AAA models with increasing ILT thickness

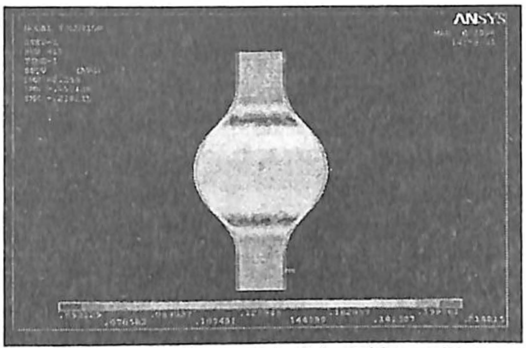

Fig. 10. Axis symmetric model with uniform thickness showing the distribution of von Mises stresses.

For the asymmetric AAA models, an increase in wall thickness by 13.33% yields a decrease of 10.94% in the maximum wall stress. Further increase in wall thickness by 26.67% gives a slight decrease in the maximum wall stress of about 6%, while a 40% increase in wall thickness contributes to only 5.33% decrease of the peak wall stress.

Another interesting observation is the location of the peak wall stresses which is also the location of maximum wall strain. For the symmetric AAA models, the maximum stresses occur near the proximal and distal ends of the aneurysm, whereas for the asymmetric models the peak wall stresses are located at the inflection points in the posterior region.

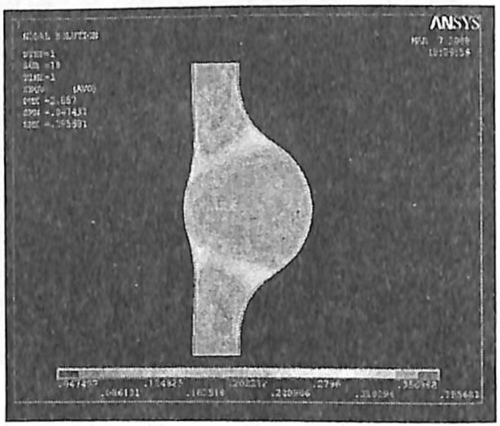

Fig. 11. Model with asymmetric aortic sac with uniform thickness showing von Mises stress distribution

3.2 *Effect of Intra Luminal Thrombus*

To determine the influence of intraluminal thrombus (ILT), multiple simulations were performed on symmetric and asymmetric AAA models with incorporated ILT thickness. Maximum Von Mises stresses were recorded and plotted against ILT thickness (Figures 8 & 9). For symmetric AAA models, increasing ILT thickness from 2 mm to 7 mm corresponds to a considerable decrease in maximum von Mises stress by 38.75%. Further increase in the ILT thickness by 5 mm, however, results only to a little more than 1% decrease of the maximum von Mises stress. The 3D distribution of Von Mises stress (Figure 12) show that peak values are located at the proximal and distal neck of the symmetric AAA models.

For asymmetric AAA models significant decrease in peak wall stress from 0.3639 MPa to 0.1554 MPa is observed when ILT thickness is increased from 2mm to 17mm. Maximum stresses are located at the inner wall of the AAA (Figure 13), specifically, at the inner wall of the posterior region corresponding to the inflection points.

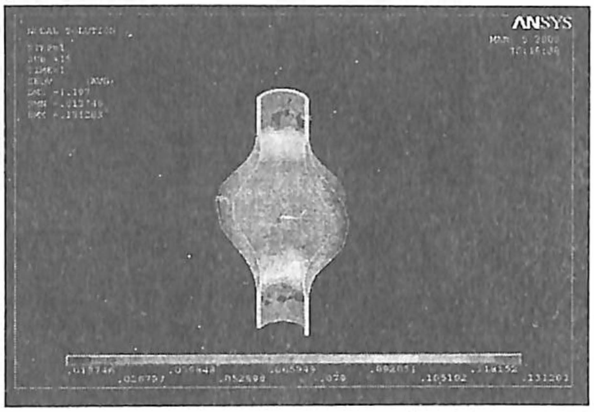

Fig. 12. Axis symmetric model with ILT showing the distribution of von Mises stresses

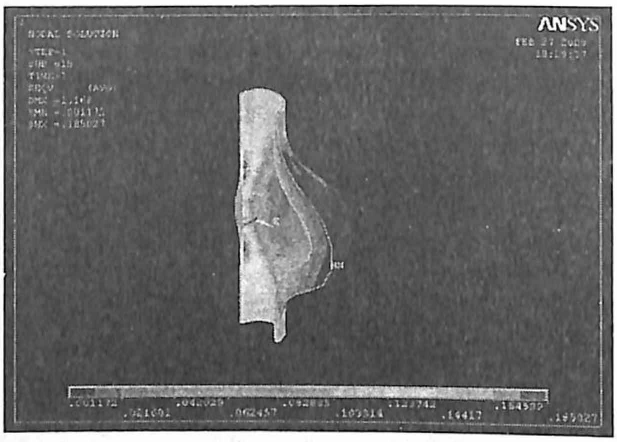

Fig. 13. Model with asymmetric aortic sac with ILT showing the distribution of von Mises stress

IV. DISCUSSION

While the stress analyses using 3D hypothetical AAA models are helpful for the purpose of research, the wall stress distribution in real, *in vivo* AAA is even more complex. Aneurysm rupture takes place when local stresses exceed the material strength of AAA wall tissues. This study contributes to that knowledge by presenting the influence of AAA wall thickness, intraluminal thrombus, and asymmetry on the complexity of the wall stresses experienced by an AAA. The results of this study support the hypothesis that thicker AAA wall experience reduced wall stresses. This, however, is also influenced by the asymmetry of the AAA model as an asymmetric AAA experiences higher peak wall stress as compared to a symmetric model of similar wall thickness. Stress gradients through the wall for all AAA models demonstrate that the wall strength distribution within any particular AAA is spatially variable.

The cushioning effect of intraluminal thrombus as is apparent from the results in this study is also in agreement with findings by Mower et al [13]. Comparison of maximum Von Mises stresses for models with and without ILT confirms the hypothesis that intraluminal thrombus reduces aneurysm wall stress for both axis-symmetric and asymmetric AAA models.

Overall, the results of this study suggest that rupture risk prediction based on peak wall stress is mostly dependent on local geometric parameters of the aneurysm such as wall thickness, thickness of intraluminal thrombus, and asymmetry.

5. LIMITATIONS

The particular aim of this study is to obtain qualitative information on how wall thickness, intraluminal thrombus, and asymmetry influence aneurysm wall stress. Analysis of the detailed quantitative behavior of patient-specific aneurysms is definitely beyond the scope of this study. It should be kept in mind that in reality, aneurysms are not smooth structures that are homogeneous, and isotropic, and they do not exhibit linear elastic deformation. The simplified static models used in this study neglect the possible presence of calcification in the tissue, nor does it allow us to explore the pulsatile flow effects in the AAA. These assumptions make the result of this study quantitatively limited. Thus, it would be imprudent to use the results from this study to predict the stresses that are actually present in individual aneurysms.

Further research is proposed in view of the many limiting assumptions made while doing this study. Simulations using up to date material model is desired to get even more accurate stress values.

6. CONCLUSIONS

The results confidently assert that aneurysm wall thickness and intraluminal thrombus significantly reduce wall stress, and that the degree of stress reduction is related to the asymmetry of the aneurysm. Future studies using patient specific models may be useful in determining the degree of complexity appropriate for individual aneurysm that may be helpful in making quantitative decisions for individual patients.

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