COMPUTATIONAL MODEL OF MECHANICAL WALL STRESS IN ABDOMINAL AORTIC ANEURSYM ONE HOUR PRIOR TO RUPTURE

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INTRODUCTION

Abdominal aortic aneurysm (AAA) continues to trouble the medical community because of the difficulty in predicting its severity and likelihood to rupture. Mortality rates of patients that experience rupture may be as high as 90%. A maximum aortic diameter of around 5 cm, as determined from computed tomography (CT) scans, is generally used as the determining factor for assessing surgical need. However, the inaccuracy of this methodology is widely known, and it has been determined that maximum diameters of <4, 4-5, 5-7, and 7-10 cm, correspond to rupture frequencies of 8%, 25%, 50%, and 64%, respectively [1].

Due to the widespread health, and resultant economic effects, of ruptured AAA, combined with the difficulty of effectively diagnosing AAA severity and predicting rupture in individual patients, there has been much effort devoted to generating computational models of AAA that can accurately model this physiological phenomenon. However, ascertaining the validity of these models is a difficult and ambiguous task, due to the lack of conclusive experimental data. The ideal case for determining rupture-prediction capability of these models is to obtain CT scans just prior to rupture, but an occurrence of this sort has yet to be documented.

This study utilized CT scans from a patient who experienced rupture approximately one hour after scan acquisition. The goal of this study was to determine if presently utilized finite element methods could predict rupture likelihood and location, and thus either negate or support the validity of finite element based computation of wall stress. We conducted a blind finite element analysis (FEA), generated a resulting stress distribution, computed a predicted site of rupture, and compared the results with the actual case.

MATERIALS AND METHODS

The subject patient was a 68 year-old male experiencing lumbar back pain. CT scans (General Electric Medical Systems, HighSpeed CT/I) were taken at 3 mm intervals after a physical examination revealed a pulsatile mass. A systolic blood pressure of 145 mmHG was measured at the time of CT acquisition.

Geometrical Model

The lumen and aortic wall boundaries were assigned from the CT scans using segmentation software (SURFdriver 3.5.5, Hawaii/Alberta). The resultant 3-D system of contours was then imported into non-uniform rational B-splines (NURBS) based software (Rhino3D v2.0, Robert McNeel & Associates). Each contour was converted into a periodic curve, insuring reliable smoothness, as shown in Figure 1. Inner (lumen) and outer (aortic) surfaces were then generated from the curves. These surfaces were subsequently smoothed with the software to eliminate irregularities in the geometry. Patran (MSC.Software Corp., Santa Ana, CA) was then used to construct a solid in between the two surfaces. This resulted in a 3-D geometrical model of the aneurysm.

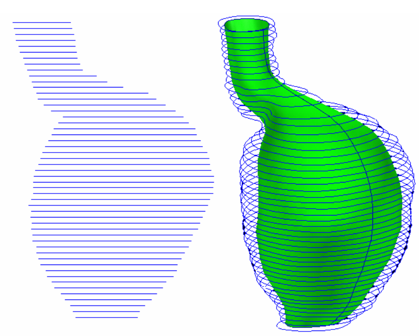

Figure 1. 3-D arrangement of curves with luminal surface

Material Properties

Both the aortic wall and the intraluminal thrombus (ILT) were assumed to be hyperelastic, homogenous, incompressible, and isotropic materials. Incompressibility [2,3] and isotropy [3,4] have been shown to be reasonable approximations for ILT and AAA wall modeling. ILT is not homogenous [3], but this assumption was made due to the inability to differentiate luminal ILT from medial ILT from CT scans. Hyperelastic parameters for ILT and AAA wall, previously determined by Wang et al. [3] and Raghavan et al. [4], respectively, were each averaged to approximate isotropy and ILT homogeneity, and subsequently used to characterize the mechanical response.

Boundary Conditions

A constant intraluminal pressure of 145 mmHG was utilized to simulate an instantaneous systolic blood pressure. Both the proximal and distal ends of the aneurysm were fixed in the vertical direction to mimic anatomical tethering between the renal and iliac arteries.

Finite Element Model

Patran was used to mesh the 3-D solid into approximately 10,000 8-node, hexahedral elements, which were assigned the hyperelastic ILT properties. Since currently utilized CT technology does not enable differentiation of ILT from the aortic wall, a constant wall of 1 mm was assumed over the entire aneurysm. Approximately 1,700 8-node, hexahedral elements were extended 1 mm outward from the outer surface of the ILT, and were assigned the corresponding AAA wall hyperelastic properties. The static, nonlinear geometrical algorithm in ABAQUS 6.1-1 was used to generate the stress distribution of the aneursym.

RESULTS

The analysis converged, and the resulting von Mises stress distribution is displayed in Figure 2. The aneurysm bulge occurs approximately 30º to the patient's right from the midline, with a local maximum stress of 62 N/cm^2 on the distal side of the bulge. The global maximum stress of 180 N/cm^2 occurs anteriorly at the distal end of the model. The next highest stress, 74 N/cm^2 occurs posteriorly beneath the bend in the proximal neck of the aneurysm.

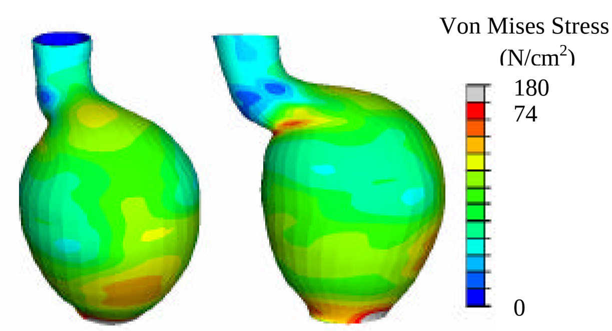

Figure 2. Colored coded von Mises stress distribution, scaled to a maximum of 74 N/cm^2

DISCUSSION

This analysis gave three significant locations of high stress. The maximum at the distal end of the model was contributed to boundary condition restrictions. Due to the extreme irregularity of this aneurysm, it is expected that fixing the distal end in the vertical direction would cause a high stress concentration. The high stress beneath the proximal neck was also attributed to the extreme irregularity of the geometry. Again, vertically restricting the ends of the model would presumably cause the aneurysm to bend in the direction of the bulge, creating a high stress in the model. It was also assumed that the intraluminal pressure experienced at this location would be less than the assigned value, due to the direction of blood flow.

Discounting these high stress values led to the prediction of the local maximum stress on the distal, anterior side of the bulge as the rupture site, as shown in Figure 3. This was the site of rupture in the actual patient.

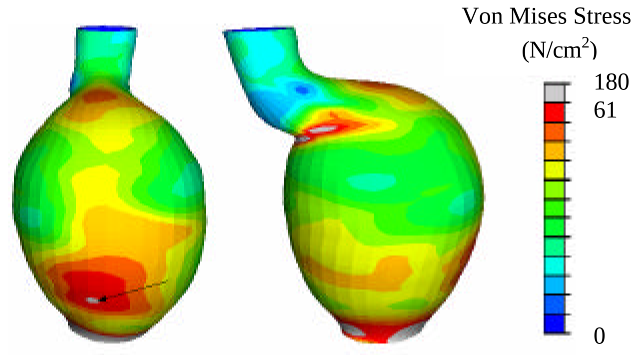

Figure 3. The exact predicted rupture location, marked by the arrow. Note the high stresses underneath the proximal neck bend and at the distal end

The accuracy of the predicted rupture location supports the validity of stress distributions generated by FEA. Furthermore, the maximum of 62 N/cm^2 is near to the previously determined AAA wall failure strength of 65 N/cm^2 [5]. However, because of the inability to verify the assumed value of the wall thickness, the stress maximum itself is an unreliable indicator of rupture likelihood. This method did not allow for a definitive prediction of the site, as is evidenced by the two higher stress locations, although these sites were disregarded due to presumably reasonable explanations. The correct rupture location did have a local minimum of ILT thickness within the aneurysm sac, which corresponds with previous studies that noted the cushioning effect of ILT. In order to obtain a more accurate prediction of the rupture location, a pulsatile generated pressure distribution needs to be incorporated.

Despite the potential errors associated with the utilized assumptions, this experiment suggested that stress distributions generated by FEA are currently reasonably accurate, and should eventually be able to aid AAA diagnosis in patients.

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