Wall Stress Studies of Abdominal Aortic Aneurysm in a Clinical Model

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To estimate when an abdominal aortic aneurysm (AAA) may rupture, it is necessary to understand the forces responsible for this event. We investigated the wall stresses in an AAA in a clinical model. Using CT scans of the AAA, the diameter and wall thickness were measured and the model of the aneurysm was created. The wall stresses were determined using a finite element analysis in which the aorta was considered isotropic with linear material properties and was loaded with a pressure of 120 mmHg. The AAA was eccentric with a length of 10.5 cm, a diameter of 2.5 to 5.9 cm, and a wall thickness of 1.0 to 2.0 mm. The aneurysm had specific areas of high stress. On the inner surface the highest stress was 0.4 N/mm² and occurred along two circumferentially oriented belts—one at the bulb and the other just below. The stress was longitudinal at the anterior region of the bulb and circumferential elsewhere, suggesting that a rupture caused by this stress will result in a circumferential tear at the anterior portion of the bulb and a longitudinal tear elsewhere. In the mid-surface the highest stress was 0.37 N/mm² and occurred at two locations: the posterior region of the bulb and anteriorly just below. The stress was circumferential, suggesting that the rupture caused by this stress will produce a longitudinal tear. The location and orientation of the maximum stress were influenced more by the tethering force than by the wall thickness, luminal pressure, or wall stiffness. In conclusion, the rupture of an AAA is most likely to occur on the inner surface at the bulb. Such analytical approaches could lead to a better understanding of the aneurysm rupture and may be instrumental in planning surgical interventions.

INTRODUCTION

The timing of surgical intervention for an abdominal aortic aneurysm (AAA) continues to pose a challenge. Although presence of an AAA of a 7-cm or greater diameter is generally regarded as indication for surgery, aneurysms of smaller diameter also rupture, though less frequently. While the rupture of an AAA carries a very high mortality, surgical intervention is also associated with a significant risk. The search thus continues for the best assessment of which aneurysm is likely to rupture and when. Since the rupture occurs when the stress in the wall exceeds its strength, the more we know about this stress the closer we come to predicting the risk of rupture.

In reviews on pathophysiology and surgical treatment of an AAA,1–4 it has been established that the risk of rupture increases with the size of the aneurysm.5–8 Darling et al. reported that for an AAA of diameter <4, 4-5, 5-7, and 7-10 cm, the frequency of rupture was 8%, 25%, 50%, and 64%, respectively.5 Scott et al.8 reported that for an AAA of diameter 3-4.4 cm and 4.5-5.9 cm, the ac-
tual rupture plus the elective surgery rate was, respectively, 2.1%/year and 10.2%/year. Such studies have led to the use of the diameter as the main criterion for judging the necessity of surgical intervention in asymptomatic AAAs. Although an AAA of 7 cm or greater diameter is considered a definite candidate for operation by most surgeons, Cronenwett et al. suggested that elective repair should be carried out when the diameter reaches 5-6 cm, whereas Scott et al. suggested that for patients with aneurysms between 4.5 and 6 cm, elective surgery should be considered only if symptoms develop.

Following the above guidelines leaves a large number of aneurysms of 4-6 cm in diameter untreated, and unfortunately a significant number of these do rupture. The challenge is to identify those 4- to 6-cm aneurysms that carry a high risk of rupture, so as to avoid immediate death or the need of emergency repair.

To better understand the chances of rupture, several authors have investigated parameters other than aneurysm diameter, such as the rate of aneurysm expansion and the presence of thrombus. A faster increase in diameter is considered to indicate a higher risk of rupture. Wolf et al. describe a higher rate of expansion, >0.5 cm/year, in 19% of AAA cases and also suggest that the “arc of thrombus” is one of the predictors of rapid expansion. Scott et al. regarded a “growth” rate of ≥ 1 cm/year for AAAs as one of the principal indicators for operation.

Compared to enlargement, the role of thrombus in the rupture of an AAA has remained controversial. Dobrin suggested that mural thrombus in the aneurysm neither reduces the luminal pressure exerted on the wall nor offers a retractive force and thus it has no effect on the wall stress. Schurink et al. reported that thrombus does not reduce the pressure near the aneurysmal wall and thus will not reduce the risk of aneurysm rupture. Contrary to this, Mower et al. stated that thrombus indeed reduces wall stress by decreasing the diameter of the effective lumen. On the basis of numerical analysis, Di Martino et al. predicted that thrombus reduces the effect of the pressure load on the aneurysmal wall. According to Satta et al., thrombus thickness is greater in ruptured (3.5 cm) than in expanding (2.0 cm) AAAs. Pillari et al. found that for aneurysms >7 cm, the increase in sac diameter was associated with an increase in lumen diameter without any change in the thrombus volume; in contrast, for an AAA of <5 to 7 cm, the increase in sac diameter was associated with the increase in thrombus volume without any change in the lumen diameter.

Stress analysis of the aneurysm through the use of models has been carried out by us as well as by others and has provided insight into this problem. In the present study, we have created an aneurysm model based on computed tomography (CT) scans of one clinical case of an AAA. This model represents the geometry in vivo. Wall stress was determined using finite element analysis (FEA), a method previously applied by us and others to investigate similar problems.

MATERIALS AND METHODS

Stresses in the aneurysm wall produced by internal pressure were determined using FEA. This required the following information: geometry of the aneurysm, material properties of the aneurysm wall, internal pressure, and boundary conditions.

Geometry

Several CT scans of an AAA of one clinical case under investigation were obtained. The patient was an 80-year-old male, 5 ft 6 in. in height and weighing 150 lbs. His aneurysm occupied most of the infrarenal region and extended close to the aortic bifurcation. From these scans 11 sections, each 1 cm apart, were selected (Fig. 1). These sections were enlarged and used for the measurement of the diameter, wall thickness, and distance of the center of each cross section from the examining table. Whenever a section was not perfectly circular, an average diameter was used for that section. This approximation is justified because the cross sections were almost circular. To define the geometry more accurately, 11 additional cross sections were created and placed alternately with the measured sections so that, in the composite model, each section was only 5 mm apart. Of the 11 additionally created cross sections, 10 had dimensions that were average of the two adjacent measured cross sections. The bottom one had dimensions assigned to produce a smooth geometry. These 22 cross sections were connected to create the surface of the aneurysm. Thus, the surface of the AAA was made up of 21 circumferential belts or areas, each bordered by two cross sections (Fig. 2). The values of the wall thickness and radius of various cross sections are shown in Figure 2 and Table I. Figure 2 shows the mid-surface (half the wall thickness is added on each side of this surface for analysis) of the aneurysm. The presence of the clot in the aneurysm (Fig. 1) is ignored, primarily because our own (unreported)