What's New in Finite Element Analysis and Other Indirect Methods for Predicting Abdominal Aortic Aneurysm Rupture Risk

NOTES

Mark F. Fillinger MD, Lebanon, NH

We have previously demonstrated that finite-element analysis of abdominal aortic aneurysm (AAA) wall stress using three-dimensional computed tomography (CT) reconstructions is better than diameter for differentiating AAAs near the time of rupture, and that wall stress is superior to AAA diameter for predicting rupture risk in patients under observation. Work continues in three broad categories: refining AAA stress-analysis techniques to create a more realistic model; developing techniques to allow widespread use in a simple manner; and investigating markers identifiable on two-dimensional imaging (conventional CT or magnetic resonance [MR]) that may improve prediction of rupture risk over maximum AAA diameter alone.

Refining AAA Stress-Analysis Techniques to Create a More Realistic Model

Calcium

Surgeons are well aware that calcified plaque is quite different from the surrounding tissue, and calcific plaque or calcified vascular wall is common in aortic aneurysms. We have investigated the effects of including calcified deposits in the finite-element modeling of abdominal aortic aneurysms and believe that the impact may be significant. Calcified plaque tends to elevate the stress locally owing to the focal stiffness induced by the plaque itself. There may also be effects related to wall strength beyond the effects on wall stress.

Thrombus

Results show that the presence of intraluminal thrombus may reduce and redistribute the stresses in the aortic wall. Although thrombus is clinically heterogeneous within an individual aneurysm and between patients, adopting a nonhomogeneous thrombus model may not alter the stress distribution substantially. Work from the University of Pittsburgh indicates that population mean parameters for thrombus material characteristics might be used to reasonably estimate the wall stresses in patient specific aneurysm models. Again, the relationship between thrombus and aneurysm wall strength may be as important or more important than its effect on wall stress.

Realistic Pressurization

To date, aneurysm wall-stress models have taken the three-dimensional geometry of a pressurized aneurysm and then applied a pressure load. Although this method is not ideal, it has been used because it is impossible to perform a CT or MR scan on an unpressurized aneurysm sac in a living patient. We have developed a method of estimating the appropriate "zero pressure configuration" of an aneurysm as a means of developing a more realistic model. Results to date suggest that incorporation of the zero pressure geometry into the model improves aneurysm wall motion predictions (as confirmed by dynamic MR) but does not have a major influence on predicted wall stress.

Developing Techniques to Allow Widespread Use of FEA in a Simple Manner

More realistic finite element models are a worthwhile goal but will not be helpful if the clinician has to be able to perform this task. A multicenter study is now underway that allows any interested center to obtain automated aneurysm wall stress analysis without cost over and above the three-dimensional reconstruction and without requiring any knowledge of finite element method. The process creates a "rupture risk report," which reports on modifiable risk factors for rupture such as smoking and blood pressure, as well as how blood pressure affects aneurysm wall stress and rupture risk. A number of centers have already joined the study group, but adequate capacity is available to add new centers (Fillinger MF, 2004).

Methods to Evaluate Rupture Risk Based on Conventional Two-Dimensional Imaging

Even with a large database of anatomic data, lack of adequate controls is a frequent problem. For example, women have at least a threefold higher risk of AAA rupture than men, independent of AAA diameter. Other factors such as blood pressure, smoking, and chronic obstructive pulmonary disease affect rupture risk, and aortic dimensions vary with age. Thus, when evaluating morphology of ruptured AAAs, it is appropriate to control for diameter, gender, age, and other demographic variables to the extent that this is possible.

In a recent series, we evaluated the conventional CT morphology of ruptured aneurysms in the context of electively imaged AAAs, matching patients for AAA size, patient gender, and age in an effort to isolate key anatomic variables. Records were reviewed to identify all CT scans at Dartmouth-Hitchcock Medical Center (DHMC) or the referring hospital prior to emergency AAA repair for rupture or acute severe pain (RUP). CT scans prior to elective AAA repair (ELEC) were reviewed for age and gender matches to RUP patients. Over 40 variables were measured on each CT. Diameter matching was achieved by consecutively deleting the largest RUP and the smallest ELEC to avoid bias. CT scans were analyzed for 259 patients with AAAs: 122 RUP and 137 ELEC. Patients were well matched for age, gender, and other demographic variables or risk factors.

Maximum AAA diameter was significantly different in the comparison of all patients (RUP 6.5 ± 2 cm vs ELEC 5.6 ± 1 cm, p < .0001), and the mean diameter for rupture was 5 mm lower in females (6.1 ± 2 cm vs 6.6 ± 2 cm, p = .007). Matching for diameter, gender, and age was possible for 200 patients (100 from each group; maximum AAA diameter 6.0 ± 1 cm vs 6.0 ± 1 cm). Analysis of diameter-matched AAAs indicated that most variables were statistically similar for the two groups, including infrarenal neck length _(17 ± 1 vs 19 ± 1 mm, p =.3), maximum thrombus thickness (25 ± 1 vs 23 ± 1 mm, p = .4), and indices of body habitus such as ([max AAA dia]/[normal suprarenal aorta dia]) or ([max AAA dia]/[lumbar vertebrae L3 transverse dia]). Multivariate analysis controlling for gender indicated the most significant variables were: aortic tortuosity (odds ratio [OR] 3.3, indicating no/mild tortuosity has greater rupture risk); diameter asymmetry (OR 3.2 for a 1 cm difference in major-minor axis); and current smoking (OR 2.7, greater risk for current smokers).

In this study, we found that when matched for age, gender, and diameter, ruptured AAAs tend to be less tortuous and yet have _greater cross-sectional diameter asymmetry. On conventional two-_dimensional CT axial slices, when diameter asymmetry is associated with low aortic tortuosity, the larger diameter on axial slices more accurately reflects rupture risk. When diameter asymmetry is associated with moderate or severe aortic tortuosity, the smaller diameter on axial slices more accurately reflects rupture risk. Current smoking is significantly associated with rupture, even when controlling for gender and AAA morphology. This type of information can be used without relying on high-technology methodology or participation in a multicenter study.

Conclusions

Progress continues in developing better tools for estimating aneurysm rupture risk using noninvasive methods. Some of these tools are not yet ready for regular clinical use, but others can be utilized in a practical manner now.

References

1. Di Martino ES, Vorp DA. Effect of variation in intraluminal thrombus constitutive properties on abdominal aortic aneurysm wall stress. Ann Biomed Eng 2003;31:804-9.
2. Marra SP, Chen DT, Dwyer JM, et al. Effects of including calcified deposits in the finite element modeling of abdominal aortic aneurysms. ASME Bioengineering Conference; June 25, 2005.
3. Marra SP, Raghavan ML, Whittaker DR, et al. Estimation of the zero-pressure geometry of abdominal aortic aneurysms from dynamic magnetic resonance imaging. ASME Bioengineering Conference; June 25, 2005.
4. Fillinger MF, Marra SP, Raghavan ML, Kennedy FE. Prediction of rupture risk in abdominal aortic aneurysm during observation: wall stress versus diameter. J Vasc Surg 2003;37:724-32.
5. Fillinger MF. Aortic aneurysm wall stress analysis: a description and invitation for participation in a multicenter evaluation. Endovascular Today. Available at: www.evtoday.com (accessed April 2004).
6. Fillinger MF, Racusin J, Baker RK, et al. Anatomic characteristics of ruptured abdominal aortic aneurysm on conventional CT scans: implications for rupture risk. J Vasc Surg 2004;39:1243-52.
7. Fillinger MF, Raghavan ML, Marra SP, et al. In vivo analysis of mechanical wall stress and abdominal aortic aneurysm rupture risk. J Vasc Surg 2002;36:589-97.

NOTES