Predicting the Risk of Rupture of Abdominal Aortic Aneurysms by Utilizing Various Geometrical Parameters: Revisiting the Diameter Criterion

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The authors estimated noninvasively the wall stress distribution for actual abdominal aortic aneurysms (AAAs) in vivo on a patient-to-patient basis and correlated the peak wall stress (PWS) with various geometrical parameters. They studied 39 patients (37 men, mean age 73.7 ± 8.2 years) with an intact AAA (mean diameter 6.3 ± 1.7 cm) undergoing preoperative evaluation with spiral computed tomography (CT). Real 3-dimensional AAA geometry was obtained from image processing. Wall stress was determined by using a finite-element analysis. The aorta was considered isotropic with linear material properties and was loaded with a static pressure of 120.0 mm Hg. Various geometrical parameters were used to characterize the AAAs. PWS and each of the geometrical characteristics were correlated by use of Pearson's rank correlation coefficients. PWS varied from 10.2 to 65.8 N/cm^2 (mean value 37.1 ± 9.9 N/cm^2). Among the geometrical parameters, the PWS was well correlated with the mean centerline curvature, the maximum centerline curvature, and the maximum centerline torsion of the AAAs. The correlation of PWS with maximum diameter was nonsignificant. Multiple regression analysis revealed that the mean centerline curvature of the AAA was the only significant predictor of PWS and subsequent rupture risk. This noninvasive computational approach showed that geometrical parameters other than the maximum diameter are better indicators of AAA rupture.

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Introduction

The exact timing of surgical or interventional treatment for abdominal aortic aneurysm (AAA) poses a challenge and will continue to do so in the near future. The decision regarding the elective repair of AAAs requires careful assessment of the factors influencing rupture risk, operative mortality, and life expectancy.[1,2] Personalized consideration of these factors in each patient is essential, and the role of patient preference is of major importance. The size of the aneurysm is a universally recognized factor to predict rupture,[3-6] and the general consensus is that patients with large aneurysms should undergo surgery. In particular, based on the latest guidelines for the treatment of AAAs, the 5.5 cm diameter size is the recommended threshold for repair in the "average" patient.[1] However, the real controversy concerns the management of small aneurysms, which are also subject to rupture.[4,7,8] In some series of patients with AAAs, in 10% to 24% of the ruptured aneurysms the maximum diameter was 5.0 cm or less.[8,9]

AAA rupture is a biomechanical phenomenon that occurs when the developing stresses within the aneurysm wall as a result of the exerted pressure exceed the tensile strength of the wall. Accurate prediction of wall stress distribution in patient-specific AAA models could be useful in determining the rupture potential of individual AAAs and provide improved patient management. Stress analysis of the aneurysm through the use of computational models has been previously carried out and has provided insight into this issue.[10-15] Factors that influence AAA rupture are still poorly understood, but it would be clinically convenient to be able to predict stresses and rupture risk on the basis of simple, particularly geometrical, AAA characteristics.[10]

In the present study, we noninvasively estimated the wall stress distribution of 39 patients with AAA by utilizing finite-element analysis (FEA) and correlated the calculated peak wall stress with various geometrical parameters.

Methods

The study included 39 patients (37 men, mean age 73.7 ± 8.2 years) with an intact symptomatic or asymptomatic infrarenal AAA, with mean diameter 6.3 ± 1.7 cm, evaluated preoperatively with spiral computed tomography (CT). Stresses in the aneurysm wall produced by blood pressure were calculated by using FEA. To perform this analysis the following AAA data were utilized: (1) geometry, (2) material properties of the AAA wall, and (3) solid boundary conditions. A number of geometrical parameters were used to characterize the geometry of the applied 3D models, in order to correlate them with peak wall stress values.

AAA Geometry

All CT scans were obtained in the course of routine care and the information was obtained in consecutive but retrospective fashion. Thus, no CT scan was obtained for the purpose of performing stress analysis. Spiral CT data were used to generate the reconstructions of the infrarenal aorta of study subjects. Abdominal CT scanning was performed with a Siemens spiral CT scanner (Volume Zoom 4 slices/spin). Before scanning, 150.0 mL of standard nonionic contrast was administered at 3.5 mL/s. Images were obtained during a single sustained breath hold by the patient to reduce respiratory-induced motion and associated artifact. The collimation was 1.0 mm with a helical pitch of 1.5 and slice thickness for editing 1.25 mm (MPR, MPI, Volume Rendering, Surface Rendering). After the raw spiral CT data were obtained, individual cross-sectional image slices were generated at 3.0 to 5.0 mm slice spacing along the infrarenal aorta. Details of the creation and refinement of the finite-element model are somewhat technical and have been previously published.[16]

Briefly, 2-dimensional cross-sectional images of the abdominal aorta were obtained from the renal arteries down to the iliac bifurcation. Because the human eye, in some applications, as the current one, remains superior to computer-automated edge-detection techniques, the boundaries of the aortic wall were identified with manual tracing with the aid of AutoCAD 2004 software. After segmentation, numerous coordinate points (roughly 50) were identified on each boundary and assigned Cartesian coordinate values associated with their spatial positions. Thereafter, the "stacking" of all 2-dimensional image data in the 3-dimensional (3D) space was performed, resulting in a 3D point cloud, representing the inner wall of the AAA. Each 3D point cloud was transformed into a 3D surface and finally into a volume for subsequent numerical analysis. This was performed with the aid of the solid modeling software Rhinoceros 3.0 (Robert McNeel & Associates, Seattle, USA) for 3D solid reconstruction. The above-cited volumes contained surfaces with sharp corners, which were artifacts from the image processing. Such sharp corners were corrected with the aid of an automating smoothing algorithm (Figure 1). Then, a uniform wall thickness of 1.9 mm was assumed on the basis of the average wall thickness measured in a series of 69 patients.[17] This is the largest series reporting AAA wall characteristics

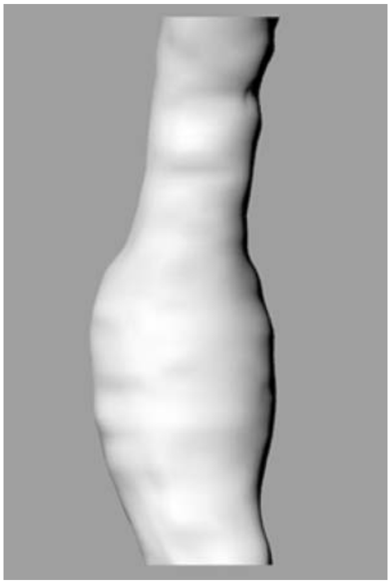

Figure 1. 3D geometry of AAA after surface rendering.

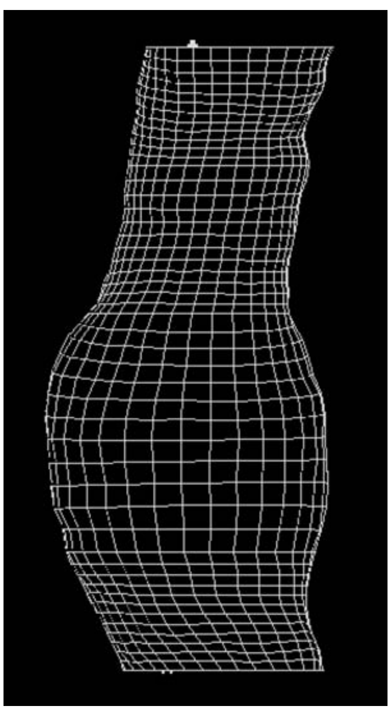

Figure 2. Computational grid of the AAA model used for the finite-element analysis.

to date.[17-19] Thus, a new volume was created and added outwardly to the inner wall.

The reconstructed AAA numerical model was then exported to the mesh generator software Gambit 2.0.4 (Fluent, Inc) for finite-element processing (Figure 2). The aneurysm volume was subdivided into a discrete grid incorporating roughly 15,000–20,000 “finite-elements” or small hexahedral thin-walled shell elements, depending on the complexity of the shape being modeled. The required number of elements was based on a previous study, which showed that increasing the number of elements from 9,000 to nearly 20,000 made only a 1.2% difference in the maximum stress value predicted.[20] Thus, increasing the number of elements beyond this level would provide only a minimal increase in accuracy, prolonging the processing time. The displacement of each load-bearing element was defined for a fixed static blood pressure of 120 mm Hg. The aneurysm was so far considered as an assemblage of elements. The outward displacement of elements in function of pressure load reflects the stress generated at that spot.

Material Properties

The aneurysmal aorta was assumed to be homogeneous and isotropic with linear elastic material properties. The Young modulus of elasticity was set to be 4.66 N/mm^2, while the Poisson’s ratio was set equal to 0.45. Although human arterial tissue behaves as a nonlinear material, at static pressure loads of 80 mm Hg or more, the aorta behaves more like a linearly elastic material.[21]

Boundary Conditions

An internal blood static pressure of 120 mm Hg (or 0.016 N/mm^2) was applied to the aneurysm in order to simulate normal systolic blood pressure. Maximum peak wall stress values occur at systolic blood pressure. In this study, the wall shear stress, induced by blood flow, was neglected, because the effects of this pressure are not expected to affect the stress analysis results.[22] The proximal and distal ends of the virtual AAA were constrained from deforming only in the longitudinal direction to simulate the tethering of the AAA at the renal artery junction and the iliac bifurcation, while they were free to move in the radial direction. Furthermore, the residual stresses that may exist within the aortic wall in vivo, as well as the tethering forces on the posterior surface caused by the lumbar arteries, were neglected. The computational static stress analysis was performed by using the FEM software Fidap 8.6.2 (Fluent, Inc, Lebanon, NH). The stress value used to evaluate the state of the aneurysm was the von Mises stress. This provides a single value of stress at any point calculated from the full 3D-stress tensor and is widely used in engineering to evaluate the state of stress of complex 3D problems. The most useful output from the FEA is a 3D contour plot of wall stress over the volume of each AAA studied (Figure 3).

Geometrical Characteristics

The maximum transverse diameter and the height of the aneurysm were measured on the reconstructed 3D image (Figure 4). The aneurysm height was defined as the distance of a straight line drawn through the center of the most proximal and most distal cross-section. The centerline was defined as the spline line that interpolated the centroids of the cross-sections. Aneurysmal volume, surface area, maximum and minimum cross-sectional areas, and their ratio were calculated by using the Rhinoceros software. The ratio of the maximum transverse aneurysmal diameter to the height of the aneurysm was measured. Furthermore, the maximum anteroposterior and maximum sagittal diameter, the aspect ratio, the centerline length, the maximum and mean centerline curvature, and the maximum and mean centerline torsion were also measured.

Statistical Analysis

The relationship between peak wall stress and each of the above-listed geometrical characteristics was assessed by the use of Pearson's rank correlation coefficients. Multiple regression analysis with a backward stepwise strategy (probability of F for removal 0.1, probability of F for entry 0.05) was used to assess the influence of the baseline variables on the peak wall stress values. Values were considered significant at $p < 0.05$. The SPSS statistical package (SPSS for Windows, statistical package, release 11.0, standard version) was used for all analyses. Data are presented as means ± SEM.

Results

Among patients with AAA, the peak wall stress varied between 10.2 and 65.8 N/cm^2 (mean value

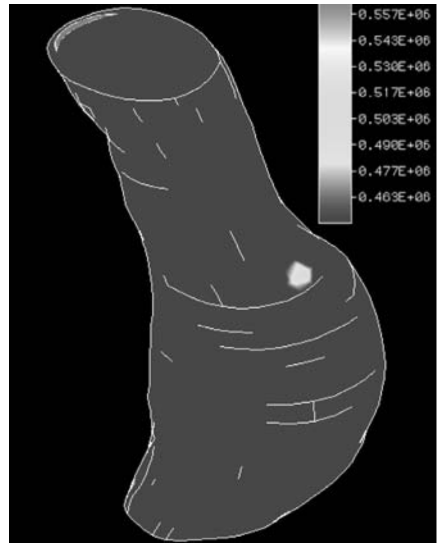

Figure 3. 3D contour plot representing von Mises wall stress (N/m^2) distribution over the volume of an AAA. The wall stress values are color coded, green representing areas of peak wall stress.

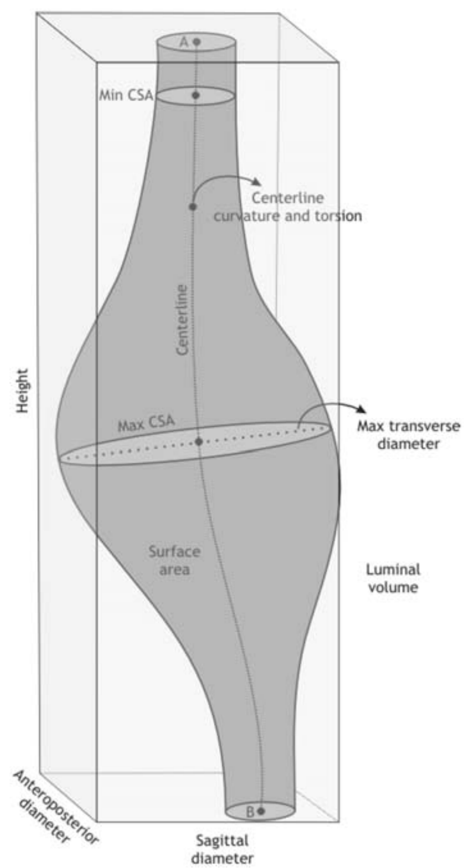

Figure 4. Definitions of selected geometrical characteristics in a schematic illustration. CSA = cross-sectional area.

37.1 ± 9.99 N/cm^2). The peak wall stress of the AAAs was best correlated with the mean centerline curvature ($r = 0.46$, $p = 0.003$) (Figure 5), the maximum centerline curvature ($r = 0.39$, $p = 0.01$) (Figure 6), and the maximum centerline torsion ($r = 0.30$, $p = 0.06$). However, the correlation of the peak wall stress with the maximum diameter was nonsignificant ($r = 0.11$, $p = 0.49$). Multiple regression analysis of all continuous variables revealed that the mean centerline curvature was the only significant predictor of the peak wall stress ($p = 0.003$) and the subsequent risk of rupture. The height of the aneurysm was excluded from the multiple regression analysis model.

Discussion

We utilized a previously described[16] noninvasive methodology to calculate the AAA wall stress distribution on a patient-to-patient basis in a cohort of 39 patients. We then proceeded to the correlation of the calculated peak wall stress values with various geometrical parameters and concluded that the curvature and torsion of the centerline were better predictors of the rupture risk than the maximum transverse diameter. All peak wall stress values, except one, were lower than the failure strength of the AAA wall (65 N/cm^2), which was estimated by ex vivo mechanical testing of aneurysmal abdominal aortic wall specimens.[23]

In a clinical study, Fillinger et al[24] calculated the highest peak stresses in AAAs that evolved to rupture and showed that even with identical diameters, ruptured aneurysms had higher peak stresses than intact aneurysms. A focal peak wall stress of 40 N/cm^2 or more, in a 5.5-cm-diameter AAA, corresponded to an annual rupture risk exceeding 20%. The same authors noticed in an observational study of 103 aneurysms, declined for repair because of small diameter, exaggerated operative risk, or patient refusal, that initial peak wall stress as well as initial diameter, at the beginning of the observation period, were predictive for the ultimate need for operation (mainly based on aneurysm expansion) and for rupture.[25] The initial peak wall stress, as measured by FEA, was 38 N/cm^2 for aneurysms that remained stable during the observation period of 14 months, whereas it reached 42 N/cm^2 for expanding aneurysms and 58 N/cm^2 for aneurysms that ultimately ruptured. Peak wall stress values appeared to differentiate more reliably aneurysms that evolved to rupture, compared to their initial diameter. There is evidence that elevated peak wall stress is not simply an acute event at the time of rupture but can be detected a long time in advance.[25] It is noteworthy that 23% of the AAAs that ruptured were smaller than 5 cm in maximum diameter but were exposed to peak stresses exceeding 45 N/cm^2. High-stress small aneurysms (focal peak stress >45 N/cm^2) had a high rupture risk up to 4% per year, regardless of their size.

In virtual 3D computer simulations of AAA submitted to pressure load, Vorp et al[26] con-

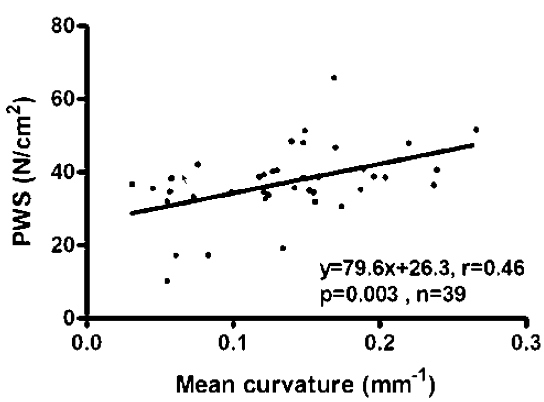

Figure 5. Graphical representation between peak wall stress and mean curvature of the centerline.

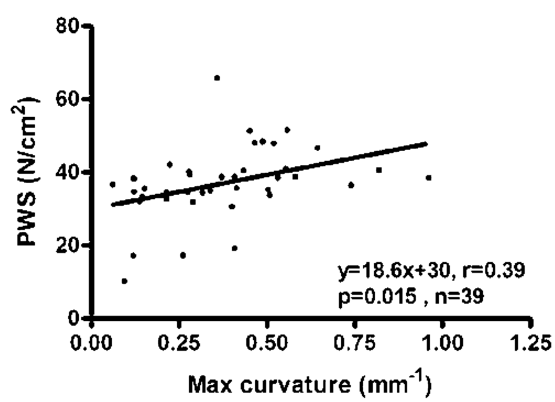

Figure 6. Graphical representation between peak wall stress and maximal curvature of the centerline.

firmed that, besides the diameter, the geometric shape and the eccentricity of the patent lumen correlate with the complex stress distribution on the AAA wall. An aneurysm with an anterior outbulging was submitted to higher focal stress than a spherical axisymmetric aneurysm of the same diameter, at the same pressure load. The peak stress was observed near the aorta-aneurysm inflection point, where the curvature of the aneurysm changes abruptly.[27] This was consistent with the posterolateral location where most ruptures occur.[4] However, such hypothetical representation of an idealized and simplified geometry does not fully correlate with the complex irregular geometry of an AAA. In a later study, the same investigators computed the actual wall stress distribution "in vivo" on a processed 3D reconstruction of spiral CT slices.[16] The wall stress was complexly distributed with large regional variations. This computational study, which included only 6 patients with AAA, concluded that AAA volume, rather than AAA diameter, was the best indicator of peak wall stress and consequently AAA rupture.

The main finding of the previous studies was that AAAs of similar sizes may have dramatically different tensile wall stresses depending on their asymmetry and irregularity. Hua et al[28] used linear FEA to calculate the von Mises stress distribution in a series of homogeneous, isotropic, 3D AAA hypothetical models subject to static loading and concluded that simple geometric criteria and symmetric thin shell analyses are unreliable in predicting AAA stresses. Another study using idealistic axisymmetric and fusiform AAA models suggested that rupture probability should be based on wall curvatures, not on AAA bulge diameter.[10] Realizing the limitations of these research works, we proceeded 1 step further and used detailed modeling of AAAs on an individual patient basis in a cohort of 39 patients.

A multivariate analysis of 40 variables of 259 aneurysms revealed that ruptured aneurysms tend to be less tortuous and have a greater cross-sectional diameter asymmetry.[29] The apparent contradiction of less tortuosity in ruptured AAAs could be explained by the fact that in a tortuous, elongated, and bowed or kinked aorta, the radial forces are reduced.

The same considerations concern brain aneurysms. In a study of 16 brain aneurysms that grew in size, Sarwar et al[30] noted that all the lesions had an irregular shape. Some authors proposed physics-based theories for the shape-rupture correlation. Hademenos et al[31,32] and Chitanvis et al[33] showed that lesion shape can significantly affect wall tension, a finding confirmed by Kyriacou and colleagues,[34] who used rigorous mathematical models. Finally, Raghavan et al[35] concluded that quantified shape is more effective than size in discriminating between ruptured and unruptured brain aneurysms, based on the finding that the lesion's nonsphericity index, undulation index, and ellipticity (ellipticity index and aspect ratio) were the best predictors of rupture risk, whereas size indices like aneurysm volume and maximal aneurysm diameter were poor predictors.

The results of a previous 3-dimensional study revealed that AAA rupture and expansion in diameter or volume could be predicted more precisely by means of a combination of the factors than by means of any single factor.[36] For aneurysmal rupture, the factors included expansion rate of maximal transverse diameter, diastolic blood pressure, and ratio of transverse diameter to longitudinal diameter. For expansion rate in diameter, the factors included cross-sectional area, tobacco use, and tortuosity. For expansion rate in volume, the factors included aneurysmal volume and blood urea nitrogen level.

It is important to realize the limitations of the current study. Perhaps we need better stress and material models regarding thrombus and calcium and better consideration of anisotropy. Some of these issues are controversial, such as inclusion of thrombus, with studies suggesting that it may increase, decrease, or have no effect on stress or rupture risk.[17,37-40] Also, a model incorporating genetic, biologic, and biomechanical aspects of AAA pathophysiology may be possible. Another serious assumption of our model is that of the constant wall thickness. The inability to reliably determine wall thickness from CT images led to the use of population mean values. The current analysis uses the average wall thickness measured in a series of 69 patients.[17] Nonetheless, estimation of wall thickness on the basis of anatomic variables, such as age, gender, and ratio of the AAA diameter to lumbar vertebrae, might further improve the ability of the analysis to distinguish high-risk aneurysms. Also, with the refinement in imaging techniques in the near future we will be able to measure wall thickness more accurately. Because in vivo blood pressure varies periodically, perhaps a dynamic analysis would have been a more realistic one. However, we were interested in the peak wall stress, which occurs at the time of the maximum systolic blood pressure, and according to a recent study, the value and location of the peak wall stress, which is computed by using dynamic analysis, correlates well with the one obtained from static structural analysis.[41] Of course, the implementation of different values of systolic blood pressure would result in different values of peak wall stresses.[42]

Another important assumption is that the mechanical properties do not spatially vary within a given aortic model. However, in order to address this potential problem, tissues from various regions of the same aorta should be excised, mechanically tested, and compared. The assumption that the aortic wall is isotropic is supported from the experimental finding that the mechanical properties of circumferentially oriented aortic tissues were no different than those of the longitudinally oriented ones.[23]

Conclusion

To our knowledge, this is the first computational 3D study in patient-specific AAA models suggesting that the geometrical parameter of curvature plays such an important role in AAA rupture. Long-term follow-up on a large population of patients with unsecured aneurysms will be needed to determine with assurance whether shape analysis can determine the risk of rupture.

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