Prediction of rupture risk in abdominal aortic aneurysm during observation: Wall stress versus diameter

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Objectives: **We previously showed that peak abdominal aortic aneurysm (AAA) wall stress calculated for aneurysms in vivo is higher at rupture than at elective repair. The purpose of this study was to analyze rupture risk over time in patients under observation.**

Methods: **Computed tomography (CT) scans were analyzed for patients with AAA when observation was planned for at least 6 months. AAA wall stress distribution was computationally determined in vivo with CT data, three-dimensional computer modeling, finite element analysis (nonlinear hyperelastic model depicting aneurysm wall behavior), and blood pressure during observation.**

Results: **Analysis included 103 patients and 159 CT scans (mean follow-up, 14 ± 2 months per CT). Forty-two patients were observed with no intervention for at least 1 year (mean follow-up, 28 ± 3 months). Elective repair was performed within 1 year in 39 patients, and emergent repair was performed in 22 patients (mean, 6 ± 1 month after CT) for rupture (n = 14) or acute severe pain. Significant differences were found for initial diameter (observation, 4.9 ± .1 cm; elective repair, 5.9 ± .1 cm; emergent repair, 6.1 ± .2 cm; $P < .0001$) and initial peak wall stress (38 ± 1 N/cm^2, 42 ± 2 n/cm^2, 58 ± 4 N/cm^2, respectively; $P < .0001$), but peak wall stress appeared to better differentiate patients who later required emergent repair (elective vs emergent repair: diameter, 3% difference, $P = .5$; stress, 38% difference, $P < .0001$). Receiver operating characteristic (ROC) curves for predicting rupture were better for peak wall stress (sensitivity, 94%; specificity,81%; accuracy, 85% [with 44 N/cm^2 threshold]) than for diameter (81%, 70%, 73%, respectively [with optimal 5.5 cm threshold). With proportional hazards analysis, peak wall stress (relative risk, 25×) and gender (relative risk, 3×) were the only significant independent predictors of rupture.**

Conclusions: **For AAAs under observation, peak AAA wall stress seems superior to diameter in differentiating patients who will experience catastrophic outcome. Elevated wall stress associated with rupture is not simply an acute event near the time of rupture. (J Vasc Surg 2003;37:724-32.)**

Surgical intervention to treat abdominal aortic aneurysm (AAA) is appropriate when cumulative risk for rupture exceeds risk for repair, within the context of overall life expectancy. For young, healthy patients with large aneurysms, the recommendation for intervention is a relatively easy decision. In healthy patients with aneurysms smaller than 5.5 cm in diameter, and in patients with large aneurysms at high surgical risk, however, the decision is not so simple. Large clinical trials have demonstrated relative safety for observation of AAAs with largest diameter less than 5.5 cm.[1-5] In an effort to prevent rupture, however, these studies required frequent observation, including ultrasound studies or computed tomography every 6 months, with surgical intervention for symptoms, rapid expansion, or growth to 5.5 cm. This resulted in a surgical intervention rate in excess of 60% in the “observation” group within several years in both of the major trials. Even with a high rate of intervention in a patient population willing to undergo frequent and reliable surveillance, the rupture rate may still be greater than 2% per year in some patient populations,[2,6] because small AAAs do rupture.[6-9] Although observation is appealing in older patients at high risk, in more than 50% of patients aneurysms larger than 5.5 cm will rupture when surgery is deferred because of high operative risk,[10] many within the first year of observation.[10,11] These issues illustrate the importance of the ability to predict AAA rupture risk.

We recently demonstrated that peak AAA wall stress calculated for aneurysms in vivo is higher at rupture than at elective repair and differentiates these two groups better than current clinical indices do.[12] The mathematical technique used to determine wall stress, finite element analysis, was first applied to AAAs in analysis of simple geometric shapes that approximated AAAs in a two-dimensional model.[13] The method has been refined over time to include theoretical three-dimensional (3-D) shapes, and later to

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actual AAA shapes obtained from CT data.[12,14-19] Although our recent study indicates that peak AAA wall stress calculated for aneurysms in vivo is higher at rupture than at elective repair, we have further refined the technique since our last report, and have applied it in patients under observation for long periods. Thus the purpose of this study was to determine potential clinical relevance in terms of whether stress analysis may be more accurate than diameter for predicting rupture risk over time and whether the difference in wall stress can be detected far enough in advance to allow time for intervention.

METHODS

Patient population. The study included all patients with asymptomatic, infrarenal AAAs evaluated with spiral CT and 3-D reconstruction as part of elective evaluation. Patients were excluded if they were being evaluated for emergent repair of a possible symptomatic or ruptured AAA or were scheduled to undergo elective repair within 1 month, providing 103 patients for study. Patients who underwent observation without any intervention within 1 year composed the observation group (n = 42), and patients who underwent elective repair within 1 year of CT scanning composed the elective repair group (n = 39). Patients with AAAs that ultimately ruptured or who underwent emergent repair because of acute, severe pain composed the ruptured/symptomatic group (n = 22). All patients in this group underwent elective CT while asymptomatic, but subsequently underwent emergent surgery because of a ruptured AAA (n = 14) or a symptomatic AAA (n = 8). Patients in the ruptured/symptomatic group either deferred elective surgery because the AAA was not thought to be large enough to merit repair relative to operative risk (n = 12), were scheduled for elective surgery but the AAA ruptured before elective repair (n = 6), or refused recommended repair (n = 4). Most AAAs (12 of 22) were 6 cm or smaller when the decision was made regarding rupture risk versus operative risk. Thus most of these patients did not meet operative criteria because the true rupture risk was not realized. CT scans were obtained between April 22, 1996, and November 28, 2001, during 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. Systolic and diastolic blood pressure data were obtained from review of outpatient records and available hospital charts, recording values for highest, lowest, and mean blood pressure. When blood pressure data were available over a long period, values were limited to the year before the first CT scan and included values obtained up to the study end point (last follow-up for observed patients or time of repair or rupture for all other patients). For the purposes of this study, maximum peak wall stress occurs at systolic blood pressure. For the sake of simplicity, results are reported only for the highest blood pressure recorded within 1 year of CT scanning, and most of these were obtained on the day when CT was performed. Before starting the study, approval was obtained from the institutional review board (Committee for the Protection of Human Subjects).

Creation and refinement of finite element model. Stress analysis of AAA has three main components: geometry of the AAA under evaluation; material model that characterizes the mechanical behavior of aneurysmal tissue; and boundary conditions, eg, blood pressure. Until recently, work in this field was limited to theoretical models or small numbers of aneurysms, for three major reasons: technologic developments in CT have made precise 3-D modeling feasible only within the last several years; there have been difficulties in "segmenting" the geometry of all elements of the aorta and aneurysm wall, required for an accurate and appropriate model, in a time-effective manner; and there have been difficulties in generating an appropriate finite element mesh that will give reasonable results without computational errors in tortuous anatomy or vessel bifurcations. The first problem was solved by manufacturers of CT equipment within the past several years; the other two major problems have been a focus of our work, resulting in the first large study of patients with finite element analysis.[12]

Details of creation and refinement of the finite element model are somewhat technical, and have been published previously.[12] In brief, there are two major differences between the analysis presented here for large patient populations and previous studies with small numbers of aneurysms. First, a semiautomated process from CT scan to refined 3-D "mesh" is created, including quality assurance and multiple checks by human beings to ensure the accuracy of the process. Second, the mesh and finite element model were modified to include analysis of vessel branch points and extremely tortuous vessels[12] that had produced computational errors with the previous model.[20] This overall semiautomated process, including the novel mesh refinement algorithm, has resulted in a large saving of time (now 2 to 4 hours per patient) and reduction in the number of computational errors (failure to find a solution or artifacts causing large stresses at the model boundaries). More important, the computational issues have been refined so that failure to find a solution did not occur in this series.

Since our last study, further refinements have been made, but the only modification significant to the results is creation of a higher resolution mesh and less "decimation" or elimination of small elements or "nodes" (see other references in this section). Further mesh refinement beyond this point does not appear to significantly change or improve stress results with current meshing techniques. The combination of these factors results in more elements for analysis, but appears to optimize the current mesh without a need to exceed 20,000 elements and seems better able to detect stress concentrations in highly tortuous vessels. The resulting stress analysis enables differentiation of ruptured AAAs slightly better than in our previous series.[12] The values for peak stress are also slightly higher for most aneurysms with this more refined model, which should be taken into account when comparing values in this study with those in our previous study.

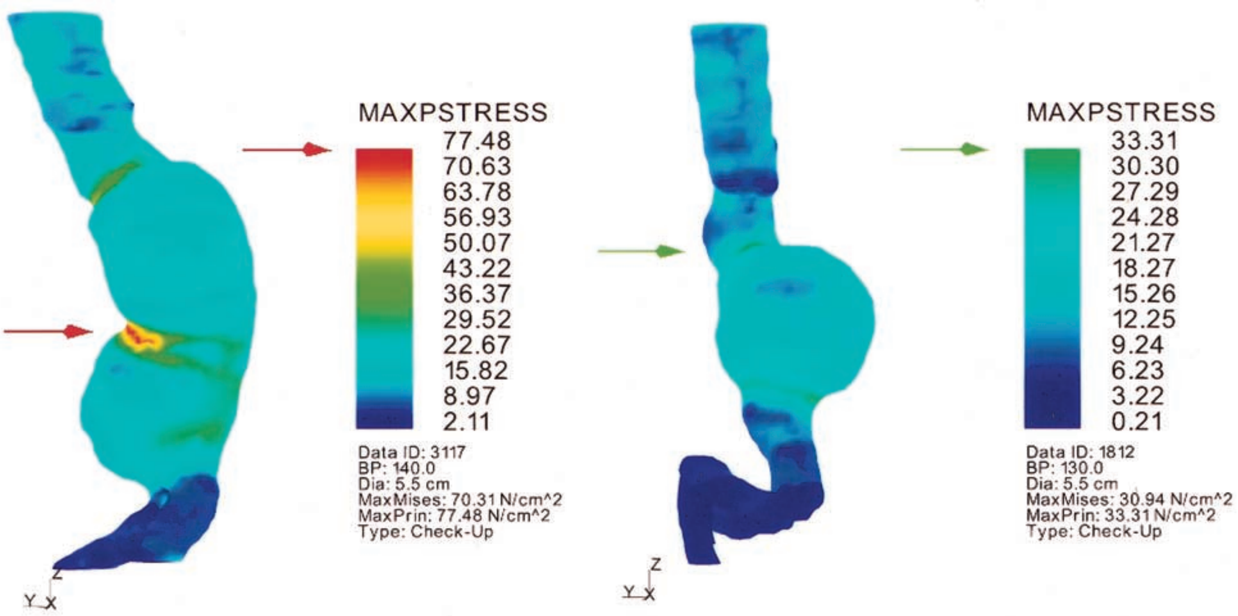

Fig 1. Three-dimensional stress distribution for maximum wall stress at peak systolic blood pressure for two 5.5 cm aneurysms. Stress is mapped to corresponding color, with highest stress shown in red and lowest stress shown in blue. Stress map for patient on the right has been color-coded to correspond with stress map for patient on the left, for ease of comparison.

Statistical evaluation. All statistical evaluation was performed with standard software programs (Statview 5.0, SAS Institute, Cary, NC, for all statistics other than ROC curve area analysis, which was performed with SPSS 11, SPSS, Chicago, Ill). The three groups (observation, elective repair, rupture/symptomatic) were compared with analysis of variance (ANOVA), with post hoc analysis for continuous variables or contingency table analysis for nominal variables. The values are reported as mean ± SE unless otherwise specified. Survival analysis (Kaplan-Meier method with log-rank test) was used to evaluate freedom from rupture or emergency surgery over time. Patients in the elective repair group are censored at the time of elective repair, so the life tables do not include AAAs post-repair. Relative risk for rupture over time was evaluated with proportional hazards analysis, with stepwise regression and deletion of variables with $P < .05$. Unless otherwise reported, all analyses were performed with only the initial scan data, to avert bias for patients with multiple scans. As per the Uniform Requirements for Manuscripts Submitted to Biomedical Journals, the authors (not the sponsoring agency) were involved in the study design; had full access to all of the data in this study; and take complete responsibility for the integrity of the data, accuracy of the data, accuracy of data analysis and interpretation, and for writing the manuscript and submitting it for publication.

RESULTS

Three-dimensional reconstruction and finite element modeling for stress analysis results in a 3-D map of the wall stress that enables evaluation of the location and magnitude of peak wall stress for each aneurysm (Fig 1). The highest stress in the AAA in Fig 1, *A*, is more than twice that in the AAA in Fig 1, *B*, despite identical maximum diameter and similar blood pressure. Both patients were at relatively high risk for surgery and refused repair. The high-stress aneurysm (77 N/cm^2; Fig 1, *A*) ruptured 18 months after this scan was obtained; the low-stress aneurysm (33 N/cm^2; Fig 1, *B*) is still under observation after more than 3 years. Most aneurysms have the highest stress concentration on the posterolateral wall, which is also where most ruptures occur.[7] In cases where the site of rupture could be confirmed with direct visualization or at CT, the site correlated with the location of the highest wall stress with finite element analysis (confirmed in 9 of 14 ruptures; site not recorded or recalled by the surgeon in the other 5 ruptures).

Demographics. Observation with no intervention for at least 1 year (observation only group) occurred in 42 patients (mean follow-up, 28 ± 3 months). Elective repair was performed within 1 year in 39 patients (mean, 4.4 ± 1 months after CT), and emergent repair was necessary in 22 patients (mean, 5.5 ± 1 months after CT) because of rupture (n = 14) or acute severe pain (rupture/symptomatic group). Demographics were similar for patients who underwent observation without intervention, elective repair, or emergent surgery because of rupture or acute symptoms (Table). Although patients selected for elective repair tended to be younger and had better renal function, there were no statistically significant differences between

Table 1. Demographics

Variable	*Observation only* *(n = 42)*	*Elective repair* *(n = 39)*	*Rupture or symptoms* *(n = 22)*	P
Age (y)	75 ± 1	72 ± 1	75 ± 2	.1
Female gender (%)	26	21	41	.2
Known heart disease (%)	52	69	47	.2
Hypertension (%)	36	28	35	.7
Systolic BP (mm Hg)	138 ± 3	134 ± 2	150 ± 6	.02
Diastolic BP (mm Hg)	76 ± 2	80 ± 2	84 ± 2	.03
Smoking (current) (%)	26	21	36	.5
COPD diagnosis (%)	24	43	38	.2
Creatinine concentration (mg/dL)	1.3 ± .12	1.0 ± .05	1.5 ± .4	.07
Follow-up (mo)	28 ± 3	4 ± 1	5 ± 1	<.01

BP, Blood pressure; *COPD*, chronic obstructive pulmonary disease.

groups with respect to age, sex, heart disease, hypertension history, smoking history, chronic obstructive pulmonary disease, or creatinine concentration. The only variables that reached statistical significance were systolic and diastolic blood pressure, which was higher in the rupture/symptomatic group. Mean time between CT and intervention was similar for patients who underwent delayed elective repair and those who ultimately had acute symptoms or ruptured AAAs.

Differences at elective evaluation: Diameter and stress. Significant differences were found for diameter (observation only vs elective repair vs rupture/symptomatic: 4.9 ± 0.1 cm, 5.9 ± 0.1 cm, 6.1 ± 0.2 cm; $P < .0001$) and peak wall stress (38 ± 1 N/cm^2, 42 ± 2 N/cm^2, 58 ± 4 N/cm^2; $P < .0001$), but peak wall stress appeared to better differentiate AAAs that ultimately required emergent repair (elective repair vs rupture/symptomatic: diameter, 3% difference, not significant; stress, 38% difference, $P < .0001$). Because of differences in systolic blood pressure, which is one of the data used to determine wall stress, comparison was also performed for maximum wall stress at a uniform pressure of 120 mm Hg. Even with stress analysis at uniform blood pressure, there was still significantly higher stress in aneurysms that subsequently ruptured (32 ± 2 N/cm^2, 37 ± 2 N/cm^2, 46 ± 3 N/cm^2; $P < .0001$ for all groups, $P < .005$ for elective repair vs rupture/symptomatic groups, despite nearly identical mean diameter in these two groups).

Distribution of diameter measurements (Fig 2) demonstrates that 90% of AAAs under observation had a diameter larger than the lowest recorded diameter for AAAs that subsequently ruptured or became symptomatic, which was 4.4 cm in maximum diameter. In the ruptured/symptomatic group, 5 of 22 (23%) AAAs were 5 cm or less in maximum diameter. There was much less "overlap" between observation and rupture groups with regard to peak wall stress (Fig 2). The box plot for peak wall stress demonstrates that 75% of AAAs under observation had stress lower than the lowest recorded stress for AAAs that subsequently ruptured or became symptomatic. Our previously reported concept of "equivalent diameter," comparing calculated stress with the diameter of the average AAA with an equivalent stress,[12] remains useful. The smallest ruptured AAA was 4.4 cm in maximum diameter but had stress equivalent to an AAA twice that size.

Predicting rupture: ROC analysis. To better evaluate the difference in accuracy for predicting rupture, ROC analysis was performed. ROC analysis demonstrates superior sensitivity, specificity, and accuracy for peak wall stress in comparison with diameter throughout the clinically important range (Fig 3). The optimal AAA diameter threshold from this analysis was 5.5 cm, consistent with data from large clinical trials. ROC curves for predicting rupture were worse for diameter (sensitivity, 81%; specificity, 70%; accuracy, 73%; positive predictive value [PPV], 58%; negative predictive value [NPV], 88%, with >5.5 cm threshold) than for peak wall stress (sensitivity, 94%; specificity, 81%; accuracy, 85%; PPV, 71%; NPV, 96%, with 44 N/cm^2 threshold). Similarly, area under the ROC curve was lower for diameter (0.741 ± 0.05) than for stress (0.884 ± 0.03), although both curves were highly significant compared with the null hypothesis.

Rupture risk over time: Life table analysis. Kaplan-Meier analysis was performed to evaluate rupture risk over time. Optimal thresholds based on ROC analysis were used to group AAAs in terms of small and large diameter (≥5.5 cm), and low or high stress (≥44 N/cm^2). When examined as a function of time, larger diameter was a highly significant predictor for rate of rupture or emergency surgery because of threatened rupture (Fig 4, *A*). The difference between aneurysms with high and low stress is even more dramatic, demonstrating that aneurysms with high stress have a markedly higher rate of rupture than aneurysms with low stress (Fig 4, *B*). Only 2 aneurysms ruptured or became acutely symptomatic in the low- stress group, and both had a peak stress of ≥40 N/cm^2, compared with the optimal threshold of 44 N/cm^2 selected with ROC analysis.

To investigate the interaction between diameter and wall stress further, subgroups were analyzed for combinations of small and large diameter and low and high wall stress, with the same thresholds presented above. Low-stress aneurysms had a low rupture rate whether they had

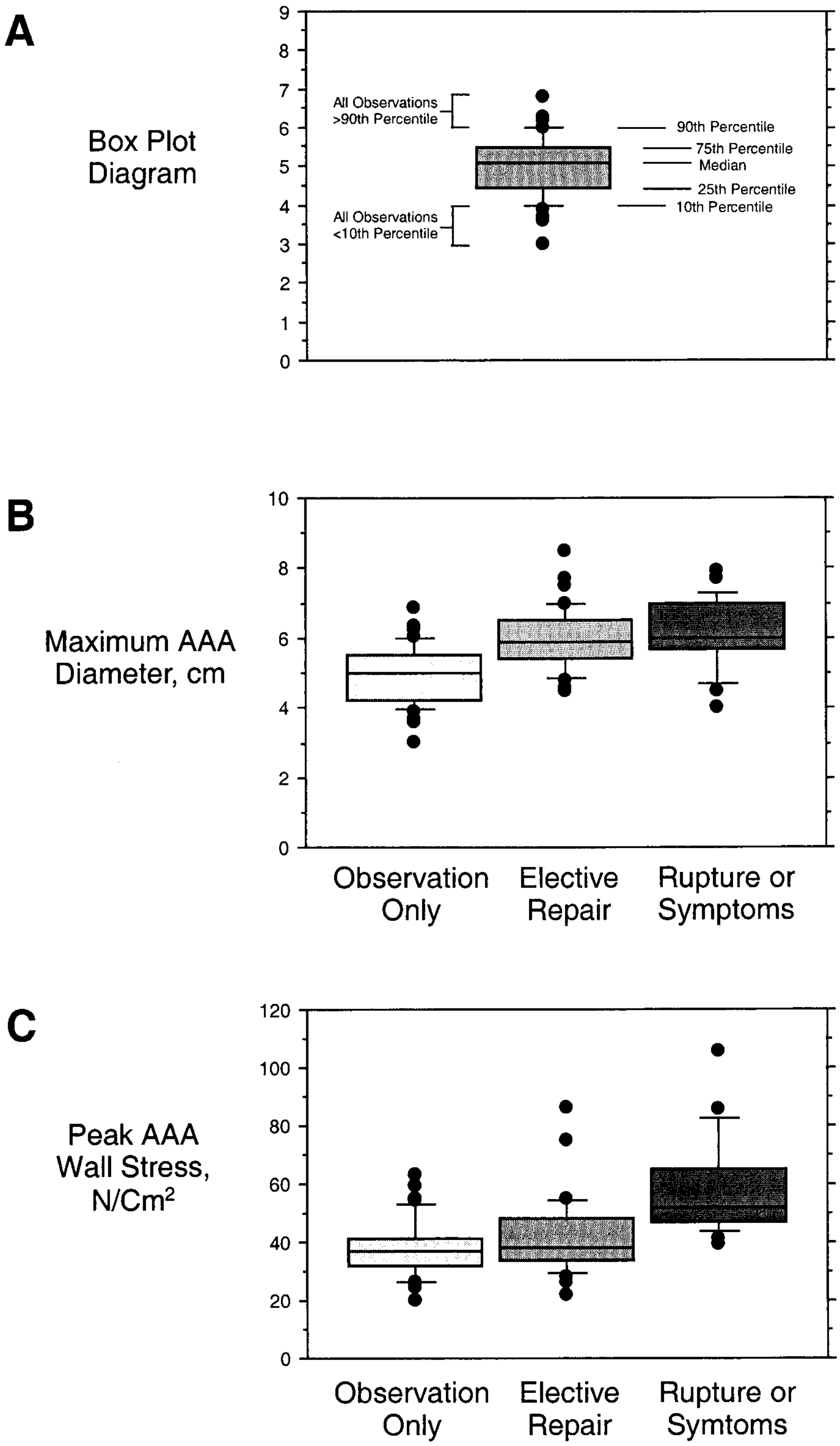

Fig 2. **A,** Box plot. *Rectangles,* 25th to 75th percentile of data; *horizontal bar within rectangles,* median of data; *short horizontal bars outside rectangles,* 10th and 90th percentiles of the data; *solid circles,* any value below the 10th or above the 90th percentile. **B,** Box plot for AAA diameter demonstrates that 90% of AAAs under observation have diameter larger than the lowest recorded diameter for an AAA that subsequently ruptured or became symptomatic, which was 4.4 cm in maximum diameter. **C,** Box plot for peak AAA wall stress demonstrates that 75% of AAAs under observation have stress lower than the lowest recorded stress for an AAA that subsequently ruptured or became symptomatic.

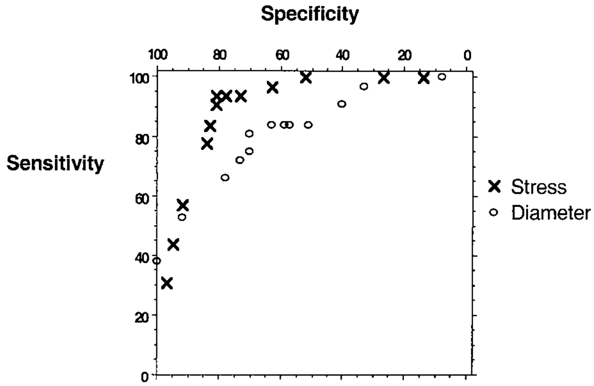

Fig 3. Comparison of receiver operating characteristic curves shows superior sensitivity and specificity of peak wall stress in comparison with diameter throughout the clinically important range.

small or large diameter, and high- stress aneurysms had a high rupture rate regardless of diameter (Fig 4, *C*).

Relative risk: Proportional hazards analysis. Multivariate analysis demonstrates that peak wall stress and gender were the only significant independent predictors of rupture risk over time, with stress demonstrating a much greater effect (RR for high stress group, 25×; 95% confidence interval [CI], 5.7-110×; $P < .0001$, and RR for female gender, 3×; 95% CI 1.3-7.4×; $P < .005$). The model was tested for interaction, and there was no significant interaction between stress and gender (ie, gender effect appears to be independent of stress). To evaluate the effect of blood pressure versus 3-D shape on stress, maximum peak wall stress, at actual systolic blood pressure, was manually removed as a variable, and stress at uniform pressure, 120 mm Hg, was added. Stress and gender remained the dominant factors, with systolic blood pressure now also a significant independent variable. When all stress-related and 3-D shape–related variables were purposely removed from the analysis, diameter, systolic blood pressure, and gender were all retained as significant variables, and this is the only way diameter could be retained. In this scenario, RR for rupture was 9× for large (>5.5 cm) aneurysms.

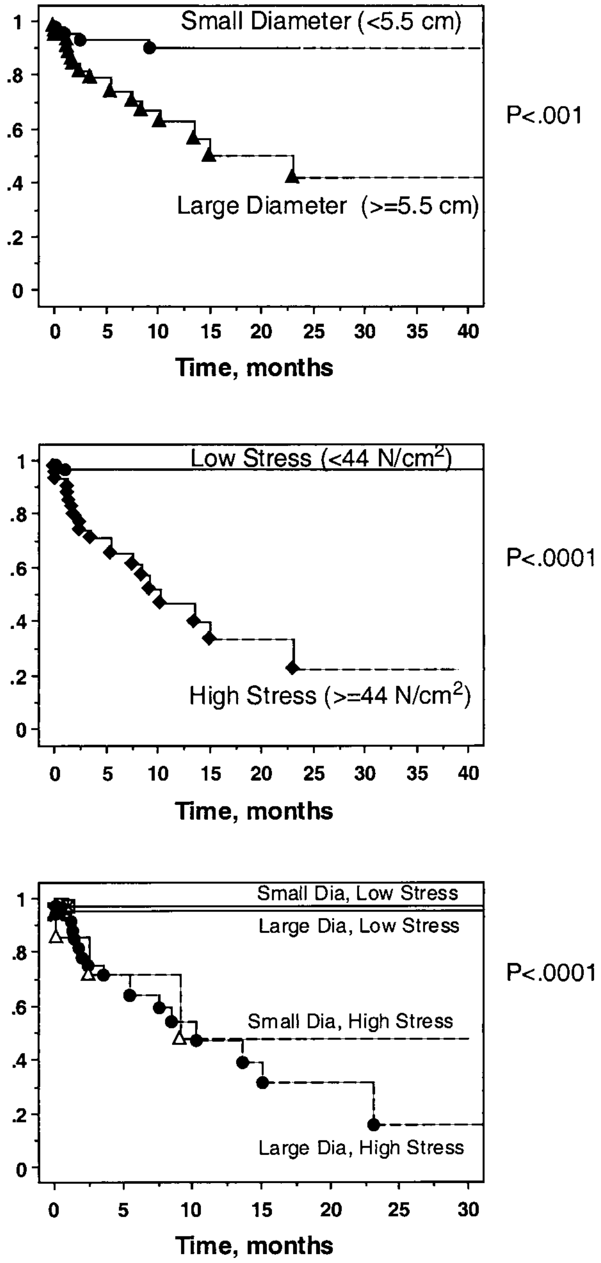

Fig 4. Life tables for freedom from rupture or emergency surgery because of acute symptoms. *Top,* Larger diameter was a highly significant predictor for rate of rupture, as shown for aneurysms larger than 5.5 cm. *Middle,* High stress was also a highly significant predictor for the rate of rupture. *Bottom,* Subgroups were analyzed for combinations of small and large diameter and low and high wall stress, with the same thresholds as used in the other life tables. Low-stress aneurysms had a low rupture rate whether they were small or large, and high-stress aneurysms had a high rupture rate regardless of size.

DISCUSSION

Maximum AAA diameter is a reasonable index of AAA rupture risk, but it is not ideal. This study indicates that a noninvasive analysis of 3-D AAA wall stress is superior to maximum diameter for determining AAA rupture risk. Although our previous study demonstrated differences in aneurysms undergoing elective repair and aneurysms at or near rupture, it remained unclear whether important differences in wall stress would be seen earlier in aneurysms undergoing observation. The current study not only demonstrates statistically significant differences at the initial evaluation, but, more important, indicates that these differences have clinical use for aneurysms that might safely be observed for long periods or may need surgical repair to prevent rupture within a relatively short time. The sensitivity and specificity of peak aneurysm wall stress are superior to aneurysm diameter when determining which aneurysms are at risk for rupture. More important, life table analysis and proportional hazards analysis, which add the key element of elapsed time from evaluation to rupture, also indicate that stress is superior in predicting rupture.

Of interest, the only variable independently predictive of rupture in our analysis, other than peak wall stress, was female gender. Women in this study were three times more likely to experience AAA rupture during surveillance, which is strikingly similar to the 3-4× RR for rupture reported in the UK Small Aneurysm Trial.[4,6] Women are also at higher risk for death after elective repair, however; thus a uniform policy of repairing all small aneurysms in women is not likely the best strategy.[21,22] In our previous study,[12] nearly all of the women had high AAA wall stress, but in the current study many women had low aneurysm wall stress. Analysis of the data thus far suggests that women have a higher percentage of "high stress" aneurysms than men do, but stress of the average aneurysm at any given size is not markedly higher. We are currently directing analysis toward determining whether there are significant gender differences in aneurysm wall thickness, wall strength, or both.[12] Wall thickness difference is especially likely, because the relationship of aneurysm size to body habitus is often different in women than in men.

Another interesting difference between groups was significantly higher blood pressure in AAAs that subsequently ruptured or required emergent surgery because of acute symptoms. At first glance, one might infer that higher blood pressure is the only reason for higher stress in aneurysms in the rupture group, because mean diameter was almost identical to that in the elective repair group. When analyzed at uniform pressure, however, AAAs that ultimately ruptured or became acutely symptomatic still had significantly higher stress. Moreover, when peak wall stress is purposely removed from proportional hazards analysis and the components of wall stress at uniform pressure and blood pressure are retained, wall stress is still the most significant variable. Thus the effect of 3-D shape appears to dominate the effect of blood pressure in the analysis. The importance of blood pressure in determining wall stress should not be overlooked, however, because it has important implications for medical management. The risk for aneurysm rupture in patients with severe hypertension can be lowered significantly with proper blood pressure control. Conversely, patients with high stress who continue to have labile hypertension may merit earlier aneurysm repair.

It is important to realize the limitations of the current study. The data for 3-D shape, segmentation, and 3-D reconstruction, which determine wall stress distribution, were obtained prospectively, but this is not a strictly prospective study. Because patients at higher operative risk were more likely to be referred to our tertiary center, the study appears to have a high percentage of ruptured AAAs because it captures only a fraction of those undergoing observation and repair. There may be a bias toward identifying smaller diameter aneurysms that rupture, because larger aneurysms are repaired. Conversely, it is unclear what the "denominator" of small aneurysms should be, because many patients with small aneurysms are not referred to a tertiary center. However, 10% to 24% of ruptured aneurysms are 5 cm or less in maximum diameter, with the highest percentage for aneurysms under observation.[6,9] Thus the percentage of ruptured AAAs 5 cm or less in this study (23%) is not unusual. Also, several aspects of the data indicate that this study accurately represents relative risks. The best threshold for diameter determined with ROC analysis is in the 5.5 to 5.6 cm range, agreeing quite well with published reports of rupture risk in large multicenter clinical series.[3-5,10,11,23,24] The relative rupture risk in women was threefold higher, also in agreement with the literature.[4,6] It should not be disturbing that diameter is not retained in our hazards analysis. Diameter is retained in the proportional hazards model if, and only if, stress analysis of any kind is removed from the variable list. Then the proportional hazards model retains diameter, blood pressure, and gender, in that order. These variables are all important factors in predicting rupture risk in previous studies,[4-8,10,11,23-26] which reinforces the validity of our findings.

Several opportunities exist to refine our stress analysis methods, as outlined in our last study.[12] Our group and others are currently working on noninvasive predictors of wall thickness and strength; better stress models and material models with regard to thrombus and calcium, which are currently contained within our standard 3-D model but not yet used in the stress analysis; anisotropy; serial measurements of AAAs undergoing observation; and assessment of biologic activity, eg, matrix metalloproteinases.[12,20,27-36] Some of these issues are controversial, such as inclusion of thrombus, with studies suggesting it may increase stress or rupture risk, decrease wall stress, or have no effect.[29-32,37] Shear stress could be added to the model, but physiologic shear stress on the inner wall is a tiny percentage of the tensile stress within the wall due to pressure in an AAA. Ultimately, a model incorporating genetic, biologic, and biomechanical aspects of AAA pathophysiology may be possible. Despite all of these opportunities for improving stress analysis, we are encouraged in that the current model already appears superior to current methods.

Although these results are preliminary, the potential clinical application of this technology is clearly appealing. Risk stratification with this method is noninvasive, so risk of the study should not be a deterrent to patients or clinicians. Intravenous contrast medium is not necessary for the stress analysis, so more expensive magnetic resonance studies are not required in patients with renal insufficiency, although the technology could be used with magnetic resonance imaging also. At this point, it does not appear necessary to analyze data at multiple times for each patient, so decisions can be made within a relatively short time. The biggest impediment to clinical use is that the method is currently somewhat time-consuming and labor-intensive, but much of the software used to create and display the stress analysis is already commercially available and many of the processes are partially or fully automated. Stress values may be somewhat cumbersome to use initially, because they are not intuitive to the clinician. This problem may be solved by using a proxy for stress, such as equivalent diameter,[12] which is clinically intuitive and simple to understand. For example, the smallest ruptured AAA was 4.4 cm maximum diameter but had stress equivalent to a typical AAA twice the size. Another solution to the problem of interpreting stress is to use a simple threshold for "critical" or "significant" stress, just as velocity thresholds are currently used for carotid duplex scanning. This will require standardization of the technique, because each time we refine the stress analysis model the critical threshold for stress may change.

Should all aneurysms undergo stress analysis? The answer is likely no. Young healthy patients with large aneurysms clearly have a risk-benefit ratio that favors surgery, and stress analysis is unlikely to change plans for repair, unless it would be to make repair more urgent in aneurysms with very high stress. Stress analysis does have the potential to detect smaller aneurysms (<5.5 cm) that cannot safely be observed because of high risk for rupture. Stress analysis also has the potential to aid management in patients who are at high risk for surgery and have moderate or large aneurysms. In these patients with shorter life expectancy, patients with larger diameter but low peak wall stress may be able to avert the risk for morbidity and mortality from surgery, which is significant even for endovascular repair.[38,39] Overall, we believe stress analysis is practical and feasible and that it will become an important clinical tool.

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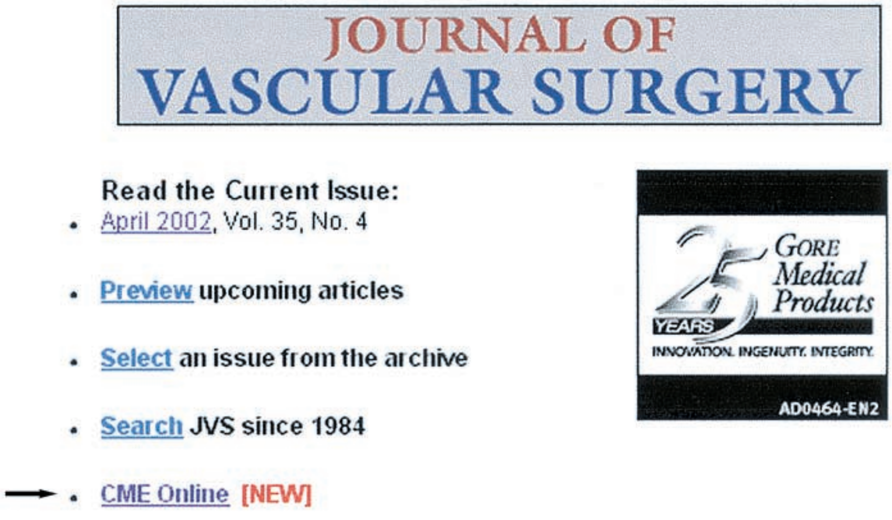

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