Anatomic characteristics of ruptured abdominal aortic aneurysm on conventional CT scans: Implications for rupture risk

Mark F. Fillinger, MD, Jessica Racusin, MD, Robert K. Baker, MD, Jack L. Cronenwett, MD, Arno Teutelink, MD, Marc L. Schermerhorn, MD, Robert M. Zwolak, MD, PhD, Richard J. Powell, MD, Daniel B. Walsh, MD, and Eva M. Rzucidlo, MD

**Objective:** The purpose of this study was to analyze anatomic characteristics of patients with ruptured abdominal aortic aneurysms (AAAs), with conventional two-dimensional computed tomography (CT), including comparison with control subjects matched for age, gender, and size.

**Methods:** Records were reviewed to identify all CT scans obtained at Dartmouth-Hitchcock Medical Center or referring hospitals before emergency AAA repair performed because of rupture or acute severe pain (RUP group). CT scans obtained before elective AAA repair (ELEC group) were reviewed for age and gender match with patients in the RUP group. More than 40 variables were measured on each CT scan. Aneurysm diameter matching was achieved by consecutively deleting the largest RUP scan and the smallest ELEC scan to prevent bias.

**Results:** 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 comparisons of all patients (RUP, 6.5 ± 2 cm vs ELEC, 5.6 ± 1 cm; P < .0001), and mean diameter of ruptured AAAs was 5 mm smaller in female patients (6.1 ± 2 cm vs 6.6 ± 2 cm; P = .007). Two hundred patients were matched for diameter, gender, and age (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 in the two groups, including infrarenal neck length (17 ± 1 mm vs 19 ± 1 mm; P = .3), maximum thrombus thickness (25 ± 1 mm vs 23 ± 1 mm, P = .4), and indices of body habitus, such as [(maximum AAA diameter)/(normal suprarenal aorta diameter)] or [(maximum AAA diameter)/(L3 transverse diameter)]. Multivariate analysis controlling for gender indicated that the most significant variables for rupture were aortic tortuosity (odds ratio [OR] 3.3, indicating greater risk with no or mild tortuosity), diameter asymmetry (OR, 3.2 for a 1-cm difference in major-minor axis), and current smoking (OR, 2.7, with the greater risk in current smokers).

**Conclusions:** When matched for age, gender, and diameter, ruptured AAAs tend to be less tortuous, yet have greater cross-sectional diameter asymmetry. On conventional two-dimensional CT axial sections, it appears that when diameter asymmetry is associated with low aortic tortuosity, the larger diameter on axial sections more accurately reflects rupture risk, and when diameter asymmetry is associated with moderate or severe aortic tortuosity, the smaller diameter on axial sections more accurately reflects rupture risk. Current smoking is significantly associated with rupture, even when controlling for gender and AAA anatomy. (J Vasc Surg 2004;39:1243-52.)

Abdominal aortic aneurysm (AAA) is a leading cause of death in the United States. Evaluating rupture risk is critically important in reducing aneurysm-related mortality without unnecessarily increasing the rate of surgical intervention. The current standard for estimating rupture risk is maximum AAA diameter, but this standard is clearly not ideal. Even with a high rate of intervention in patients undergoing frequent and reliable surveillance, the rupture rate may still be greater than 2% per year in some patient populations. The risk for rupture during follow-up occurs because of two reasons: small AAAs can and do rupture, and some patients are at high risk for AAA repair and have larger AAAs that are not repaired. In older patients at high surgical risk, more than 50% of aneurysms greater than 5.5 cm will rupture when surgery is deferred because of high operative risk, many within the first year of observation.

We have previously demonstrated that finite element analysis of AAA wall stress with three-dimensional (3D) computed tomography (CT) reconstructions is better than diameter for differentiating AAAs near rupture and that wall stress is superior to AAA diameter for predicting rupture risk in patients under observation. While work continues on refining AAA stress analysis techniques to enable widespread use, we are often asked if there are any markers...
identifiable on two-dimensional (2D) images (ie, conventional 2D CT scans) that may improve prediction of rupture risk over maximum AAA diameter alone. During our work on aneurysm rupture risk we have collected a large number of conventional CT scans in patients referred to our center from outside hospitals. Although these CT studies often are not useful for stress analysis or 3D reconstruction because of technical reasons, they can be used for more traditional 2D analysis of aneurysm anatomy. By studying this larger database of conventional CT data, we hoped to gain greater insight and statistical power than with smaller, more restricted studies designed to evaluate AAA wall stress.

Even with a large database of anatomic data, lack of adequate controls is frequently a problem. For example, women are at least threefold higher risk for AAA rupture than men are, independent of AAA diameter. Other factors such as blood pressure, smoking, and chronic obstructive pulmonary disease affect rupture risk, and aortic dimension varies with age. Thus, when evaluating anatomy of ruptured AAAs, it is appropriate to control for diameter, gender, age, and other demographic variables, to the extent that this is possible. In this series, we evaluated the anatomy of ruptured aneurysms in the context of electively imaged AAAs, matching for AAA size, and patient gender and age, in an effort to isolate key anatomic variables.

METHODS

Patient population and screening. The study was approved by our institutional review board. Records from 1990 to 2002 were reviewed to identify all patients who had undergone CT at Dartmouth-Hitchcock Medical Center or a referring institution before emergency AAA repair because of rupture or acute, severe pain (RUP group). To provide a comparable control group, CT scans obtained electively for AAAs from the same time period (ELEC group) were reviewed, and were added to the database on the basis of age and gender match with the RUP group. Retrospective chart review began in 1996 to create the initial database, with prospective or concurrent data entry since that time. Patients who underwent elective CT but had emergency surgery because of rupture or acute symptoms within a year were excluded from the ELEC group. A larger number of CT scans in the ELEC group than in the RUP group were evaluated to obtain appropriate matching. The initial criteria for age was within 2 years, and was expanded to within 5 years in an effort to limit the number of CT scans required for screening. The number of female patients in the ELEC group was based on the number of female patients in the RUP group (for gender matching). For patients with multiple elective CT scans over the time period, only the initial scan data were collected, to avert bias for patients with multiple scans.

This investigation provided CT scans for 122 patients in the RUP group and 137 patients in the ELEC group (screening 257 ELEC patients to obtain 137 that appeared to meet appropriate age and gender requirements, choosing 15 additional apparent matches in an effort to increase the odds of actual matches). For context, approximately 1200 elective AAA repairs were performed during this period. Patients were not initially screened for the ELEC group on the basis of AAA diameter. Diameter matching for maximum AAA diameter was achieved after creating the database by consecutively deleting the largest AAAs in the RUP group and the smallest AAAs in the ELEC group, to avert selection bias. Deletion was continued until AAA diameters were identical in the two groups, maintaining gender match.

Systolic and diastolic blood pressure data were obtained by review of patient 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 CT scan. For the sake of simplicity, results are reported for blood pressure values recorded closest to the time the CT scan was obtained, and most of these were recorded on the day of CT. Before starting the study, approval was obtained from the institutional review board (Committee for the Protection of Human Subjects).

CT measurements. All CT scans were obtained during the course of routine care, and no CT scans were obtained for the purpose of the study. Scan protocols varied over time and by institution, but almost all CT scans were contrast agent–enhanced, with collimation from 5 to 10 mm, covering the length from the celiac artery to the iliac arteries. Elective CT scans from our institution were contrast-enhanced, with Smart Prep or other timing mechanism, collimation from 3 to 7 mm, pitch 1 to 2, and included the length from the supraceliac aorta to the femoral arteries. During this period all scans were obtained with single-detector scanners.

More than 40 variables were measured on each CT scan, primarily involving length and diameter measurements, but also including details such as apparent rupture location, if identifiable (see Results). All measurements were made on axial sections with calipers and magnification. Length measurements were obtained with the table position and distance recorded on the sections, except for tortuous vessels when the vessel traversed more than two vessel diameters on a single axial section. In these cases the total length was calculated with a combination of the z axis distance (head to foot) and the x-y distance (measured on the axial section). Maximal thrombus circumference was measured as the included angle (eg, 360 degrees would be circumferential thrombus lining the entire lumen, 180 degrees would be thrombus covering half the lumen; Fig 1A). The transverse diameter of the body of the L3 vertebra was measured as an index of body habitus (Fig 1B). Cross-sectional diameter asymmetry of the AAA was calculated as the difference between the major and minor axes at the point of maximum AAA diameter (Fig 1C). In cases of asymmetry, the minor axis of the ellipse was recorded as the more accurate AAA diameter, per current standards and evidence from 3D studies.
Fig 1. A, Illustration of measurements for thrombus thickness (white arrow) and “included angle” of thrombus (measured in degrees). B, Measurement of transverse diameter, body of L3 vertebra. C, Measurement of major and minor axes at point of maximum diameter, to determine cross-sectional asymmetry.
Aortic and iliac tortuosity was categorized as none, mild, moderate, or severe. Aortic tortuosity was defined as none, mild (lumen center moves no more than one normal aortic diameter from renal to aortic bifurcation), severe (vessel makes a nearly right angle from 1 axial section to the next), or moderate (the remainder). Iliac tortuosity was defined as none, mild (lumen center moves no more than one normal vessel diameter from renal to aortic bifurcation), severe (vessel makes a nearly right angle from 1 axial section to the next), or moderate (the remainder). These definitions were based on agreement of observers on a "definition set" of films. As an approximation, for no or mild iliac tortuosity the vessel major axis could not be more than twice the minor axis on a single axial CT section, and severe tortuosity was recorded when a vessel was visualized for a lengthy distance in the axial section (several vessel diameters) or had two visible cross-sections on a single axial section.

**Interobserver variability, film vs electronic imaging.** Interobserver variability was determined to ensure that accuracy of anatomic data was comparable with other published reports. Comparison of AAA diameter measurements with a radiology report was available for 131 patients. Interobserver variability compared with radiology reports was 4 ± 4 mm for AAAs with mean diameter of 56 mm, which is comparable with published reports.16–18

**Statistical analysis.** All statistical analysis was performed with a standard software program (Statview, version 5.0; SAS Institute, Cary, NC). The groups were compared with analysis of variance with post hoc analysis for continuous variables or contingency table analysis for nominal variables. Values are reported as mean ± SD, unless otherwise specified. Association with rupture was evaluated with univariate and multivariate analyses, with stepwise regression with deletion of variables. P < .05 was considered significant. As per the Uniform Requirements for Manuscripts Submitted to Biomedical Journals, the authors were involved in the study design; had full access to all of the data in the study; and take full responsibility for the integrity of the data, accuracy of the data, and accuracy of data analysis and interpretation, and for writing the manuscript and submitting it for publication.

## RESULTS

**Demographic and physiologic variables.** CT scans were analyzed for 259 patients with AAAs, 122 in the RUP group and 137 in the ELEC group. Patients were well-matched for demographic variables such as age, gender, chronic obstructive pulmonary disease, family history, and heart disease, whether in the overall comparison or in the diameter matched comparison (Table I). Smoking history was similar in the two groups, but patients in the RUP group were significantly more likely to be current smokers. A history of hypertension was slightly more common in the RUP group, but systolic and diastolic blood pressure values were not higher in this group. Blood urea nitrogen, creatinine, and cholesterol concentrations, if known, were also similar between groups, with only creatinine concentration approaching significance for the diameter-matched control subjects (Table I). Of patients with ruptured AAAs, 47% were known to have an AAA according to medical records before presentation.

**Anatomic variables.** 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), as expected. Gender differences were apparent: mean diameter for ruptured AAAs was 5 mm smaller in female patients than in male patients (6.1 ± 2 cm vs 6.6 ± 2 cm; P = .007). Of patients in the RUP group, rupture was noted on CT scans or at operation in 70%, and the remainder underwent emergency surgery because of acute, severe pain. There were no significant differences for diameter or any other anatomic variable between patients with documented rupture versus those undergoing emergency surgery because of acute severe pain, similar to our previous analysis of anatomic factors and aneurysm wall stress in a smaller group of patients.8

Matching for gender, age, and AAA diameter was possible for 200 patients (100 from each group; maximum AAA diameter, 6.0 ± 1 cm vs 6.0 ± 1 cm). Analysis of matched AAAs indicated that most anatomic variables were
statistically similar in the two groups, including infrarenal neck length (1.7 ± 1 cm vs 1.9 ± 1 cm; P = .3), AAA length (9.5 ± 3 cm vs 9.9 ± 2 cm; P = .4), and maximum thrombus thickness (2.5 ± 1 cm vs 2.3 ± 1 cm; P = .4). Even with identical maximum AAA diameter, however, patients with ruptured AAAs had some significant anatomic differences, including slightly larger supraceliac aorta diameter (2.9 ± 0.5 cm vs 2.7 ± 0.3 cm; P < .001), infrarenal aortic diameter (2.7 ± 0.6 cm vs 2.4 ± 0.4 cm; P < .001), and lumbar vertebrae (L3 transverse diameter, 4.5 ± 0.5 cm vs 4.3 ± .4 cm; P = .001). Anatomic measurements for the groups before and after matching are shown in Table II. When matched for gender, diameter, and age, fewer variables were statistically significant. Even those that were significantly different were not well differentiated between the RUP and ELEC groups when the ranges of measurements were compared (Fig 2).

**Indices of body habitus and AAA anatomy.** Multiple calculated indices of AAA anatomy were evaluated, based on indices previously proposed in the literature. When comparing the groups before matching, almost all of these indices demonstrated statistical differences between the RUP and ELEC groups. When matched for gender, diameter, and age, however, indices that relate AAA size to normal aorta or body habitus, such as [(maximum AAA diameter)/(normal suprarenal aorta diameter)] or [(maximum AAA diameter)/(L3 transverse diameter)], were no longer significantly different between the RUP and ELEC groups (Table III).

**Tortuosity and cross-sectional diameter asymmetry.** Some variables evaluated as possible 2D surrogates of 3D shape (eg, aortic tortuosity, diameter asymmetry) were significantly different in matched AAAs, whereas others were not (eg, iliac tortuosity, orientation of the axis of diameter asymmetry). For tortuosity variables, the number of vessels with no or severe tortuosity was too small for useful statistical evaluation; thus categories were grouped as none-mild and moderate-severe for both aortic and iliac tortuosity. Unlike other anatomic measurements or indices, aortic tortuosity and AAA cross-sectional diameter asymmetry did not lose statistical significance when evaluating data for control subjects matched for gender, maximum AAA diameter, and age (Table III).

Aortic tortuosity was different only in patients matched for gender, age, and AAA diameter. Patients in the RUP group were less likely to have moderate-severe tortuosity (RUP, 23% vs ELEC, 45%; P < .03). Quantitating aortoiliac tortuosity numerically, as in reporting standards for endovascular AAA repair,14,15 also indicated similar tortuosity for the entire population (RUP, 4.5 ± 1.6 vs ELEC, 4.9 ± 1.6; P > .15), but slightly less tortuosity in the RUP group compared with control subjects matched for gender, age, and AAA diameter (RUP, 4.4 ± 1.6 vs ELEC, 5.1 ± 1.5; P < .02).

The AAA cross-sectional diameter asymmetry index was evaluated to compare the difference between the major and minor axes of AAAs on axial cross-section at the point of maximal AAA diameter. This index also differed for patients matched for gender, age, and AAA diameter (RUP, 5.8 ± 5.7 vs ELEC, 3.7 ± 3.7; P < .01). Thus diameter asymmetry was greater in the RUP group, despite less tortuosity than in the ELEC group.

**Location of rupture.** The location of rupture could be identified in 65 patients. The rupture was posterolateral.
Table II. Morphologic data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ruptured AAA (n = 122)</th>
<th>Elective CT (n = 137)</th>
<th>P</th>
<th>Diameter-matched ruptured AAA (n = 100)</th>
<th>Diameter-matched elective CT (n = 100)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum AAA diameter (cm)*</td>
<td>6.5 ± 2</td>
<td>5.6 ± 1</td>
<td>.001</td>
<td>6.0 ± 1</td>
<td>6.0 ± 1</td>
<td>.8</td>
</tr>
<tr>
<td>Suprarenal aortic diameter (cm)</td>
<td>2.9 ± 5</td>
<td>2.7 ± 3</td>
<td>.001</td>
<td>2.9 ± .5</td>
<td>2.7 ± .3</td>
<td>.001</td>
</tr>
<tr>
<td>Suprarenal aortic diameter (cm)</td>
<td>2.6 ± 6</td>
<td>2.5 ± 4</td>
<td>.02</td>
<td>2.6 ± .5</td>
<td>2.5 ± .4</td>
<td>.2</td>
</tr>
<tr>
<td>Infra-renal aortic diameter, normal (cm)</td>
<td>3.8 ± 2</td>
<td>3.1 ± 1</td>
<td>.001</td>
<td>3.5 ± 1</td>
<td>3.2 ± 1</td>
<td>.06</td>
</tr>
<tr>
<td>AAA only length (cm)</td>
<td>1.5 ± 6</td>
<td>1.6 ± 6</td>
<td>.3</td>
<td>1.4 ± 6</td>
<td>1.5 ± 7</td>
<td>.3</td>
</tr>
<tr>
<td>Infra-renal neck length (cm)</td>
<td>1.7 ± 1</td>
<td>2.1 ± 1</td>
<td>.02</td>
<td>1.7 ± 1</td>
<td>1.9 ± 1</td>
<td>.3</td>
</tr>
<tr>
<td>AAA only length (cm)</td>
<td>9.8 ± 3</td>
<td>9.5 ± 3</td>
<td>.5</td>
<td>9.5 ± 3</td>
<td>9.9 ± 2</td>
<td>.4</td>
</tr>
<tr>
<td>Renal-aortic bifurcation length (cm)</td>
<td>12.4 ± 3</td>
<td>12.1 ± 2</td>
<td>.4</td>
<td>12.1 ± 3</td>
<td>12.2 ± 2</td>
<td>.8</td>
</tr>
<tr>
<td>AAA diameter/infra-renal length (cm)</td>
<td>3.6 ± 1.8</td>
<td>5.0 ± 1.7</td>
<td>.001</td>
<td>3.5 ± 2</td>
<td>4.9 ± 2</td>
<td>.001</td>
</tr>
<tr>
<td>Maximum thrombus thickness (cm)</td>
<td>2.6 ± 1</td>
<td>2.2 ± 1</td>
<td>.04</td>
<td>2.5 ± 1</td>
<td>2.3 ± 1</td>
<td>.4</td>
</tr>
<tr>
<td>Thrombus circumference (cm)†</td>
<td>290 ± 100</td>
<td>290 ± 100</td>
<td>.7</td>
<td>290 ± 100</td>
<td>300 ± 90</td>
<td>.7</td>
</tr>
<tr>
<td>L3 transverse diameter (cm)§</td>
<td>4.6 ± .7</td>
<td>4.3 ± .4</td>
<td>.001</td>
<td>4.5 ± .5</td>
<td>4.3 ± .4</td>
<td>.005</td>
</tr>
</tbody>
</table>

‡AAA, Abdominal aortic aneurysm; CIA, common iliac artery.
§Maximum AAA diameter is based on the smaller “diameter” or axis if AAA cross-section is elliptical on axial CT sections.
‡AAA normal diameter and normal length refer to nonaneurysm segment, and was not available for all ruptured AAAs (n = 71 matched cases).
§Circumference of AAA lumen contacting thrombus at point of its greatest extent (eg, 360 degrees is circumferential thrombus).

Table III. Calculated indices

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ruptured AAA (n = 122)</th>
<th>Elective CT (n = 137)</th>
<th>P</th>
<th>Diameter-matched ruptured AAA (n = 100)</th>
<th>Diameter-matched elective CT (n = 100)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum AAA/suprarenal diameter (cm)</td>
<td>2.3 ± 5</td>
<td>2.1 ± 3</td>
<td>.01</td>
<td>2.1 ± .6</td>
<td>2.2 ± .4</td>
<td>.2</td>
</tr>
<tr>
<td>Maximum AAA/infra-renal diameter (cm)</td>
<td>2.5 ± 7</td>
<td>2.3 ± 5</td>
<td>.006</td>
<td>2.4 ± .7</td>
<td>2.5 ± .5</td>
<td>.6</td>
</tr>
<tr>
<td>Maximum AAA/infra-renal length (cm)</td>
<td>2.4 ± 7</td>
<td>2.4 ± 5</td>
<td>.6</td>
<td>2.4 ± .7</td>
<td>2.6 ± .5</td>
<td>.08</td>
</tr>
<tr>
<td>AAA diameter/AAA length (cm)</td>
<td>.74 ± 4</td>
<td>.64 ± 2</td>
<td>.01</td>
<td>.72 ± .4</td>
<td>.65 ± .3</td>
<td>.2</td>
</tr>
<tr>
<td>AAA diameter/AAA length (cm)*</td>
<td>1.4 ± 3</td>
<td>1.3 ± 2</td>
<td>.002</td>
<td>1.4 ± .3</td>
<td>1.4 ± .2</td>
<td>.2</td>
</tr>
<tr>
<td>Aortic tortuosity (moderate/severe) (%)</td>
<td>24</td>
<td>37</td>
<td>.2</td>
<td>23</td>
<td>45</td>
<td>.03</td>
</tr>
<tr>
<td>Iliac tortuosity index (moderate/severe) (%)</td>
<td>6</td>
<td>59</td>
<td>.8</td>
<td>58</td>
<td>59</td>
<td>.6</td>
</tr>
<tr>
<td>Aortoiliac tortuosity index†</td>
<td>4.5 ± 1.6</td>
<td>4.9 ± 1.6</td>
<td>.2</td>
<td>4.4 ± 1.6</td>
<td>5.1 ± 1.5</td>
<td>.02</td>
</tr>
<tr>
<td>AAA minor axis, anteroposterior (%)§</td>
<td>60</td>
<td>65</td>
<td>.5</td>
<td>59</td>
<td>67</td>
<td>.3</td>
</tr>
<tr>
<td>AAA diameter asymmetry (cm)§</td>
<td>0.6 ± 0.7</td>
<td>0.4 ± 0.4</td>
<td>.02</td>
<td>0.6 ± 0.6</td>
<td>0.4 ± 0.4</td>
<td>.02</td>
</tr>
</tbody>
</table>

‡AAA, Abdominal aortic aneurysm.
*Distance from lowest renal artery to aortic bifurcation (see text).
†See Fig 1, B.
§Percentage of cases in which minor axis of AAA cross-section is more closely oriented anteroposterior, rather than transverse. ‡Difference between major and minor AAA “diameter” on axial CT section.

or lateral in the large majority of patients. Anterior or anterolateral rupture was identified in only seven patients (11% of patients with identifiable rupture location, and 6% of all patients in the RUP group with available CT scans). In the remainder of patients there was no clear specification of rupture site in the operative report, and the hematoma was too diffuse to determine even a general location on CT scans.

Multivariate analysis. Multivariate logistic regression analysis was performed to determine which variables were pertinent among those that were statistically significant at univariate analysis. In this analysis the only variables that remained significant were aortic tortuosity, cross-sectional diameter asymmetry, and current smoking (Table IV). The odds ratio (OR) for AAA cross-sectional diameter asymmetry is shown for a 1-cm difference, to place it in context with other variables. Accrual of data was purposely performed for matching gender and maximum AAA diameter, so these variables are not part of this analysis.

DISCUSSION

Maximum AAA diameter has been the standard index of AAA rupture risk for four decades, 19 but it remains far from ideal. Other anatomic indices of rupture risk have been proposed in an effort to improve on diameter, 13,20 but thus far none have been validated in other studies. We have previously shown that noninvasive in vivo analysis of 3D AAA wall stress from 3D CT scans is superior to AAA...
diameter for predicting rupture risk in patients under ob-
observation, but stress analysis remains relatively complex and
time-consuming compared with measurements that
can be obtained from a conventional CT scan. Comparison
of diameter-matched AAAs in control subjects is a powerful
technique for studying anatomic variables of AAAs, but a
study of this type still requires a large series of ruptured
AAAs. To our knowledge, a study of this many anatomic
variables in such a large number of ruptured AAAs is
unprecedented, diameter-matched or not.

In this study some anatomic variables were significantly
different for ruptured AAAs at univariate analysis, which
initially seemed promising. However, none of these vari-
ables are useful clinically for prediction of rupture risk,
because of substantial overlap between the RUP and ELEC
groups. For example, supraceliac aortic diameter is statisti-
cally different between the two groups to \( P < .001 \), yet
values for the ELEC group are entirely within the range of
the RUP group (Fig 2). This is unlike AAA wall stress
results, where we found much less overlap between rupture-
ted and electively repaired AAAs.8,9

One method that has been proposed to improve differ-
entiation with anatomic analysis of AAAs is the use of
morphologic indices comparing AAA diameter with nor-
amal aortic size or with a surrogate for body size, such as the
width of the L3 vertebral body. Of interest, in this study
many of these indices demonstrate remarkable statistical
significance in unmatched patients, but fail to achieve sig-
ificance when patients in the RUP and ELEC groups are
matched for gender, age, and maximum AAA diameter
(Table III). It appears that statistical comparisons of these
indices are heavily influenced by aneurysms with very large
diameter, likely present in any series of ruptured aneurysms.
When we remove the largest ruptured aneurysms and the
smallest nonruptured aneurysms (consecutively, to avoid
bias during diameter matching), the proposed indices are
no longer significantly different for ruptured AAAs. Thus
the statistical comparison seems worthwhile, but the calcu-
lated index turns out to be unhelpful clinically.

Despite these problems, two indices were significantly
different in the matched-group comparison. One of these
variables is degree of aortic tortuosity, which was not
different in unmatched AAAs but was significantly different
in matched AAAs (Table III). Because aortic asymmetry is
likely a risk factor for aneurysm wall stress, one might
initially expect ruptured AAAs to be more tortuous. Our
results suggest the opposite. Ruptured AAAs had less tor-
tuous anatomy, even when matched for diameter. Another
apparent contradiction is that although ruptured AAAs are
less tortuous, diameter asymmetry on axial sections is more
pronounced, rather than less pronounced, in ruptured
AAAs.

The reason for these apparent contradictions is easily
explained, however, because a more tortuous aorta will not
necessarily have a large discrepancy in the major and minor
axes at the site of maximum AAA diameter. The aorta could
bow substantially, yet still be relatively orthogonal (perpen-
dicular) to an axial section at the point of maximum diam-
eter. We easily found examples of this by evaluating a few
3D reconstructions of AAAs. Evaluation of 3D reconstruc-
tions was purposely not part of this study, but readily
illustrates the difference between tortuosity and asymmetry
(Fig 3). Initially, one might suspect that ruptured AAAs
tend to be less tortuous in the aortic segment, because they
are more saccular. This does not appear to be the case, nor
was aortic saccularity a significant risk factor for rupture in
this study or others. It does appear, however, that asymmetry increases rupture risk if, and only if, the asym-
metry on axial cross-sections is not an artifact of tortuosity.
A 3D analysis may enable demonstration of this differ-
ce, but a 2D analysis requires a sophisticated observer
to distinguish the difference.

How then, can one make use of the information in this
study? Although the shape-based morphologic indices
(aortic tortuosity, cross-sectional diameter asymmetry) are
not simple to interpret, they were the only anatomic vari-
ables that remained significant at multivariate analysis. The
OR for aortic tortuosity places this variable on a par with
other important risk factors such as smoking and gender.
Diameter asymmetry is also important when it is not a result of
tortuosity. We believe trained observers can evaluate
these variables when viewing a series of axial cross-sections
in a given patient. Simply put, ruptured AAAs tend to be
less tortuous, yet have greater diameter asymmetry. On
conventional 2D CT axial sections, when diameter asym-
metry is associated with low aortic tortuosity, the larger
diameter on axial sections more accurately reflects rupture
risk; when diameter asymmetry is associated with moderate
or severe aortic tortuosity, the smaller diameter on axial
sections more accurately reflects rupture risk. This is of
course more easily determined when sophisticated 3D tools
are available (Fig 4), but not everyone has access to these
tools. It is important to note that this simplified anatomic
interpretation of maximum AAA diameter does not enable
determination of rupture risk as effectively as AAA wall
stress does, and in fact these shape-based anatomic variables
are likely a surrogate for 3D shapes that impart a higher
stress to the aneurysm wall. Until stress analysis techniques
are validated and made available on a broad scale, however,
we believe this simple 2D interpretation may be helpful.
A discussion of rupture risk would not be complete
without mentioning key demographic variables. Gender
influences rupture risk, so we specifically enrolled a

<table>
<thead>
<tr>
<th>Variable</th>
<th>( P )</th>
<th>Odds ratio</th>
<th>95% Confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aortic tortuosity (none/mild)</td>
<td>.01</td>
<td>3.3</td>
<td>1.3–8.4</td>
</tr>
<tr>
<td>Aneurysm cross-sectional diameter asymmetry</td>
<td>.03</td>
<td>3.2</td>
<td>1.1–8.9</td>
</tr>
<tr>
<td>Current smoking</td>
<td>.04</td>
<td>2.7</td>
<td>1.02–7.1</td>
</tr>
</tbody>
</table>

**Table IV. Multivariate analysis**

\*Patients matched for gender, AAA diameter.
†Lower tortuosity worse.
‡For 1-cm difference.
similar percentage of female patients in the ELEC group to control for this variable. Thus, while it is difficult to make substantive conclusions about gender in this study, it is interesting that the average diameter of ruptured AAAs in female patients was 5 mm smaller than in male patients. With regard to other demographic and physiologic variables, only current smoking and hypertension history were significantly different for patients with ruptured AAAs, consistent with other studies.2,10,23 As with anatomic variables, there was substantial overlap in the two groups; thus it is difficult to make a clinical decision on the basis of history alone. For smokers, however, the data clearly lend weight to efforts aimed at smoking cessation. Multiple studies now confirm a statistically significant increase in rupture risk for current smokers, and the OR of 2.7 in our study is similar to the risk reported by others.2,24 For patients with a history of hypertension, the data are slightly less clear, because of similar systolic and diastolic blood pressure values in the two groups in the current study. Blood pressure control has an effect on AAA wall stress, which may be a reason why blood pressure or hypertension is a frequent risk factor for rupture in clinical studies.2,10,23,24

**Similarities and differences with other studies.** It is worth mentioning similarities and differences with other studies that have not yet been mentioned. Hinchcliffe et al25 found that ruptured AAAs tend to be larger in maximum diameter and have shorter but narrower infrarenal necks. Our results also demonstrate that ruptured AAAs tend to be larger, but the infrarenal aortic necks were only statistically shorter in unmatched patients, again implying that the largest aneurysms affect statistical comparisons in these groups. We also found that infrarenal aortic diameter tends to be slightly larger for ruptured AAAs, not smaller, but the range of values totally overlaps between the groups anyway.

As in other studies, we found that rupture location is usually posterolateral, at least in patients stable enough to undergo CT. Rupture is usually posterolateral at autopsy studies also,5 however, suggesting that anatomic variables in this study are not critically skewed by the bias of having CT scans available. The role of thrombus in clinical and theoretical models has been reported as potentially beneficial, harmful, or irrelevant in terms of rupture risk.26-31 Our results do not suggest that thrombus is a key factor in rupture risk, because thrombus thickness and the degree of circumference covered by thrombus were not significantly different for ruptured aneurysms. This may be a limitation of 2D analysis, however, and we would not rule out potential importance with more sophisticated technology.

**Limitations.** As with all analyses of this type, there are limitations to this study. Ideally we would have anatomic data for all ruptured AAAs, not just for AAAs in patients stable enough to undergo CT. Over time, however, CT has become much faster, and trends in limited resuscitation32 have enabled increasingly more patients to undergo CT.
We would have preferred optimum quality CT scans for all patients (ie, thin collimation, small re-format intervals, spiral CT datasets, covering the area from the supraceliac aorta to the femoral arteries), but the quality of the CT scans was good in most cases, and adequate for the measurements in this study. Our analysis of CT scans with both 2D and 3D measurements indicates that our accuracy for these 2D measurements was good.

CONCLUSION

When matched for patient age and gender, and AAA diameter, ruptured AAAs tend to be less tortuous, yet have greater cross-sectional diameter asymmetry than AAAs evaluated electively. On conventional 2D CT axial sections, when diameter asymmetry is associated with low aortic tortuosity, it appears that the larger diameter on axial sections more accurately reflects rupture risk. When diameter asymmetry is associated with moderate or severe aortic tortuosity, the smaller diameter on axial sections more accurately reflects rupture risk. The average diameter of ruptured AAAs in women was 5 mm smaller than in men in this study, consistent with the thought that, at a given AAA diameter, women are at higher risk for AAA rupture than men are. The clinical utility of anatomic variables for prediction of aneurysm rupture risk remains limited, because of substantial overlap between the RUP and ELEC groups. Nonetheless, this type of anatomic analysis may be helpful until more sophisticated methods are available. Current smoking is significantly associated with rupture, even when controlling for patient gender and AAA anatomy; thus counseling and therapy remain extremely important.

REFERENCES
