Vessel asymmetry as an additional diagnostic tool in the assessment of abdominal aortic aneurysms

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Objective: **Abdominal aortic aneurysm (AAA) rupture is believed to occur when the local mechanical stress exceeds the local mechanical strength of the wall tissue. On the basis of this hypothesis, the knowledge of the stress acting on the wall of an unruptured aneurysm could be useful in determining the risk of rupture. The role of asymmetry has previously been identified in idealized AAA models and is now studied using realistic AAAs in the current work.**

Methods: **Fifteen patient-specific AAAs were studied to estimate the relationship between wall stress and geometrical parameters. Three-dimensional AAA models were reconstructed from computed tomography scan data. The stress distribution on the AAA wall was evaluated by the finite element method, and peak wall stress was compared with both diameter and centerline asymmetry. A simple method of determining asymmetry was adapted and developed. Statistical analyses were performed to determine potential significance of results.**

Results: **Mean von Mises peak wall stress ± standard deviation was 0.4505 ± 0.14 MPa (range, 0.3157-0.9048 MPa). Posterior wall stress increases with anterior centerline asymmetry. Peak stress increased by 48% and posterior wall stress by 38% when asymmetry was introduced into a realistic AAA model.**

Conclusion: **The relationship between posterior wall stress and AAA asymmetry showed that excessive bulging of one surface results in elevated wall stress on the opposite surface. Assessing the degree of bulging and asymmetry that is experienced in an individual AAA may be of benefit to surgeons in the decision-making process and may provide a useful adjunct to diameter as a surgical intervention guide. (J Vasc Surg 2009;49:443-54.)**

Clinical Relevance. **There is much debate about the most appropriate time to intervene with surgical treatment of abdominal aortic aneurysms. Currently, maximum diameter is deemed the most accurate indicator of rupture potential because size is not only an obvious factor in the decision-making process but is also easy for the clinician to determine from computed tomography scans. The method of determining vessel asymmetry proposed here is easy to interpret and was shown to be as significant as diameter in the cases examined. Therefore, asymmetry could become a useful adjunct to diameter in the decision-making process of the clinician.**

There is currently much debate about the most appropriate time to surgically intervene and repair an abdominal aortic aneurysm (AAA).[1-7] Surgery is often performed when the detected AAA is >5.0 to 5.5 cm in maximum diameter. Previous research[8,9] has shown how AAAs <5.5 cm in maximum diameter can also rupture. The reliability of the maximum diameter as the main criterion for rupture has been questioned recently, and a need for a more reliable clinical predictor of AAA rupture has been identified.[1-7,10-12] Previous work[12,13] has identified the importance of asymmetry in idealized AAA models and also indicated the need to investigate this aspect in realistic models. In this study, we have examined the role of asymmetry and resulting wall stress in realistic patient-specific AAA cases.

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METHODS

Computed tomography (CT) scan data was obtained for 22 patients. For this study, AAAs that were asymmetric in the anterior–posterior plane were deemed applicable. This criterion was used to exclude 7 of the 22 patients from the analysis because their AAAs were asymmetric in other directions. The resulting cohort of 15 patients (10 men, 5 women) and a mean age ± standard deviation (SD) of 73.2 ± 6.7 years. Scans for these patients were obtained from the

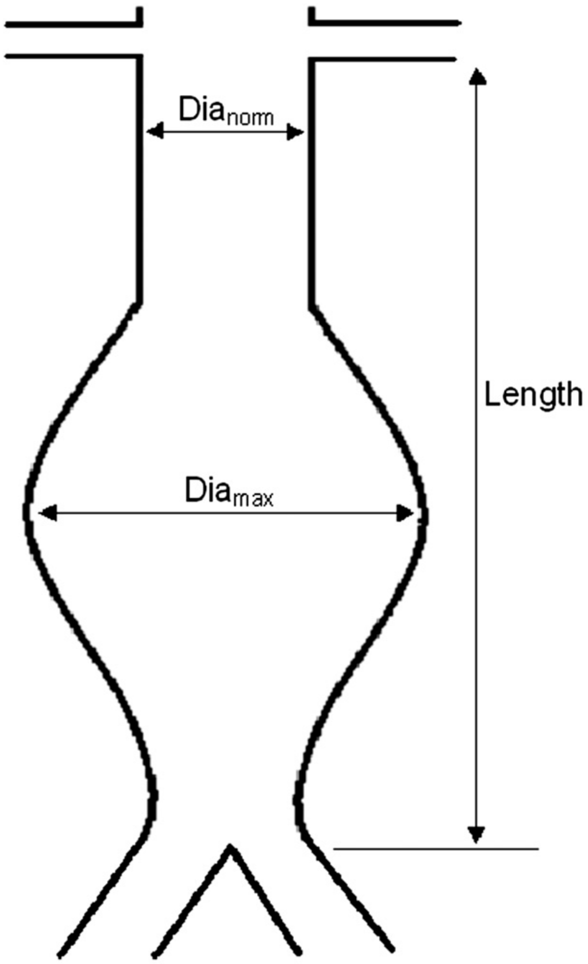

Fig 1. Schematic of representative abdominal aortic aneurysm (AAA) shows how the dimensions are obtained from each AAA model. Surface area and volume both encompass the total surface area or volume of the AAA from immediately below the renal arteries to immediately before the iliac bifurcation. Dia_{norm} is the infrarenal aortic diameter of the particular case.

Midwestern Regional Hospital, Limerick, Ireland, and the University of Pittsburgh Medical Center, Pittsburgh, Pa. All 15 patients were either awaiting or had received AAA repair because their AAA diameters had reached or exceeded the current 5-cm threshold for repair.

The CT scans were acquired using Somatom Plus 4 (Siemens AG, D-91052 Erlangen, Germany) and LightSpeed Plus (General Electric Medical Systems, Waukesha, Wisc) imaging equipment. All scans were single slices with a standard width × height of 512 × 512 pixels. Mean ± SD pixel size of scans was 0.742 ± 0.072 mm. The bodily structures of each subject were made visible using Optiray nonionic contrast dye (Mallinckrodt Inc, Hazelwood, Mo).

These CT data sets were then reconstructed using the commercially available software, Mimics 10.0 (Materialise Technologies, Leuven, Belgium), and these reconstructions allowed the computation of stress distributions within the geometries. The patient-specific details for the cases studied were obtained using the schematic of Fig 1 and are compiled in Table I.

Three-dimensional reconstruction procedure. Spiral CT data were used to reconstruct the infrarenal section of the aorta. Because CT scanning is routine for AAA patients scheduled for repair, collection of this information involved no extra participation by the study subjects. Digital files in the digital imaging and communications in medicine (DICOM) file format, containing cross-sectional information, were imported to the Mimics 10.0 software for reconstruction. All reconstructions were developed from scan positions immediately distal to the lowest renal artery to immediately proximal to the iliac bifurcation. The intraluminal thrombus (ILT) was neglected in this study, as with previous approaches.[6,7,11-13,15] The thickness of the aorta wall is not easily identifiable from CT scans; therefore, the wall was assumed to be uniform throughout the model and set to 2 mm.[16]

Once regions of interest were identified, the three-dimensional (3D) reconstructions were generated. The reconstruction method used here was validated and reported in previous work performed by our group[17-19] along with the effect of geometry smoothing on resulting wall stress.[20] All AAAs underwent the same degree of smoothing. The iliac bifurcation was omitted from this study, as in previous stress analysis work, because it does not significantly affect the wall stress results of the AAA.[7] The influence of asymmetry compared with a symmetric AAA was also examined. The reconstruction of patient 2 was modified using ProEngineer Wildfire 3.0 software (Parametric Technology Corp, Needham, Mass) so that the AAA now formed along a straight central axis, becoming an axisymmetric fusiform aneurysm. This symmetric AAA was created using the same diameter information as the original case. The two forms of this AAA can be seen in Fig 2.

Biomechanical material properties. The AAA material was assumed to be homogenous and isotropic, with nonlinear realistic material properties[5] that have been implemented in many previous publications.[3,6,7,10,11,20-22] The aorta is also known to be nearly incompressible with a Poisson's ratio of 0.49.

Finite element mesh generation. Once the AAA surfaces were imported into ABAQUS 6.6-2 software (Dassault Systemes, SIMULIA, Providence, RI) for stress analysis, a finite element mesh was generated on the AAA model. Because wall thickness cannot be fully determined from the AAA scan data, each shell element was assigned a uniform thickness of 2 mm.[16] Mesh independence was performed by increasing the number of elements in the mesh until the difference in peak stress was <2% of the previous mesh.[10,20,23]

Forces and boundary conditions. The blood pressure within the AAA acts on the AAA inner wall, and therefore pressure was applied to the inner surface of the computational AAA model. A static peak systolic pressure of 120 mm Hg (16 KPa) was used. To simulate the teth-

Table I. Details for study patients

Patient	*Sex*	*Age*	*Max diameter, cm*	*Total length, cm*	*Total volume, cm³*	*Total SA,[a] cm²*	*Diam/length*	*ROD*
1	M	66	5.6	13.2	176.7	19.8	0.425	1.533
2	M	78	6.1	11.2	192.4	18.5	0.544	2.071
3	M	70	5.7	13	194.9	19.1	0.439	1.752
4	F	65	5.6	9.3	136.9	14.8	0.606	2.474
5	M	81	5.9	12.8	220.9	21.8	0.463	1.772
6	F	68	5.7	10	148.2	16.3	0.570	2.953
7	F	67	5.3	10.5	137.9	15.5	0.505	2.000
8	M	70	6.0	11.1	216.7	20.4	0.541	1.508
9	F	77	5.8	8.8	94.2	12.6	0.661	2.535
10	M	87	9.0	11.7	445.5	32.4	0.769	1.768
11	M	66	6.5	10.5	207.6	19.2	0.617	1.952
12	M	81	6.8	14	267.6	25.2	0.484	1.994
13	M	77	6.2	16.8	320.8	27	0.371	1.757
14	F	72	5.7	11.4	143.8	16.7	0.497	2.675
15	M	73	7.9	11.8	286.5	24.3	0.671	2.865

F, Female; *M,* male.
[a]*SA* is the total AAA surface area, *Diam/length* is the ratio of maximum diameter to total abdominal aortic aneurysm (AAA) length, and *ROD* is the ratio of maximum AAA diameter to infrarenal diameter of that patient.[14]

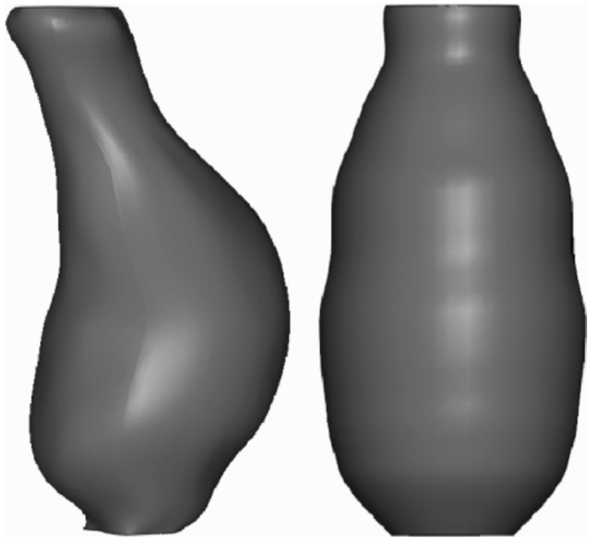

Fig 2. Left, Original asymmetric abdominal aortic aneurysm (AAA) of patient 2 and **(right)** the modified axisymmetric AAA.

ering of the AAA to the aorta at the renal junction and iliac bifurcation, the AAA model was fully constrained in the proximal and distal regions.

Asymmetry definition. Most AAAs are constrained from radial expansion in the posterior direction due to the spinal column; therefore, AAAs predominantly dilate in the anterior plane. All AAAs studied in this analysis were naturally asymmetric in the anterior–posterior direction. To examine the effect asymmetry has on wall stress, the centerline of each AAA was automatically found using the Mimics 10.0 software. The centerline passes through the centroid of each polyline slice in the series. Asymmetry is defined, in this case, as the perpendicular distance from the proximal and distal points of the centerline to a defined point on the centerline. Figs 3-5 show how these asymmetry measures are obtained.

This method of determining asymmetry was adapted from previous work by Young Suh et al.[24] Starting with the 3D AAA model in Fig 3, *A*, a centerline is automatically created through the polyline centroids of Fig 3, *B*, thus creating Fig 3, *C*. Then these polylines are exported from Mimics 10.0 to ProEngineer Wildfire 3.0. Next, the software is used to connect the endpoints of the centerline with a straight line (Fig 3, *D*), and a perpendicular line is extended from this connecting line to predetermined points along the centerline (Fig 3, *E* and *F*).

The asymmetry at a specified distance along the AAA model is regarded as this perpendicular distance and is measured in millimeters. This method of determining AAA asymmetry is shown for patient 3 in Figs 4 and 5. Fig 4 shows the creation of the polylines on the CT scan after the thresholding and segmentation process in Mimics 10.0 and also the resulting model of polylines and AAA centerline. Fig 5 shows the measurement process of asymmetry for patient 3 and the resulting asymmetry plot. Maximum asymmetry for this case was 24.5 mm.

Statistical analysis. The statistical significance of the wall stress results was evaluated with SPSS 14.0 software (SPSS Inc, Chicago, Ill). This allowed any significant correlations within the results to be identified. Correlations between various geometric parameters with both peak wall stress and posterior wall stress were assessed for significance. Mean values are presented with the SD.

RESULTS

The results from the geometrical examination of each case are summarized in Table I. The finite element analysis using ABAQUS 6.6-2 software produced a detailed stress pattern on each of the aneurysmal models under the pressure loading.[25] These stress results could be used to examine factors affecting wall stress, in particular, the role of asymmetry.

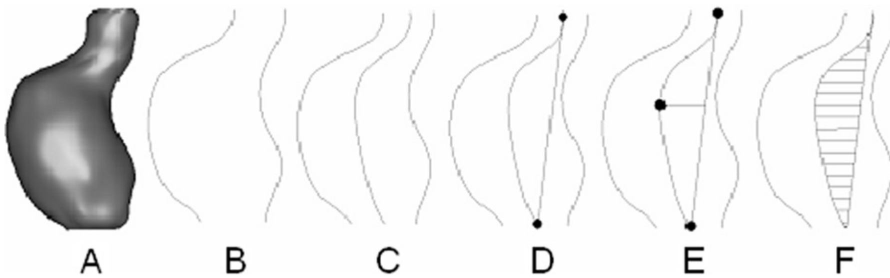

Fig 3. Simple illustration showing the method of obtaining asymmetry measurements. **A,** Three-dimensional abdominal aortic aneurysm (AAA) model and **(B)** line drawing. **C,** A centerline is automatically created through the polyline centroids. **D,** The endpoints of the centerline are connected with a straight line. **E,** and **F,** A perpendicular line is extended from this connecting line to predetermined points along the centerline.

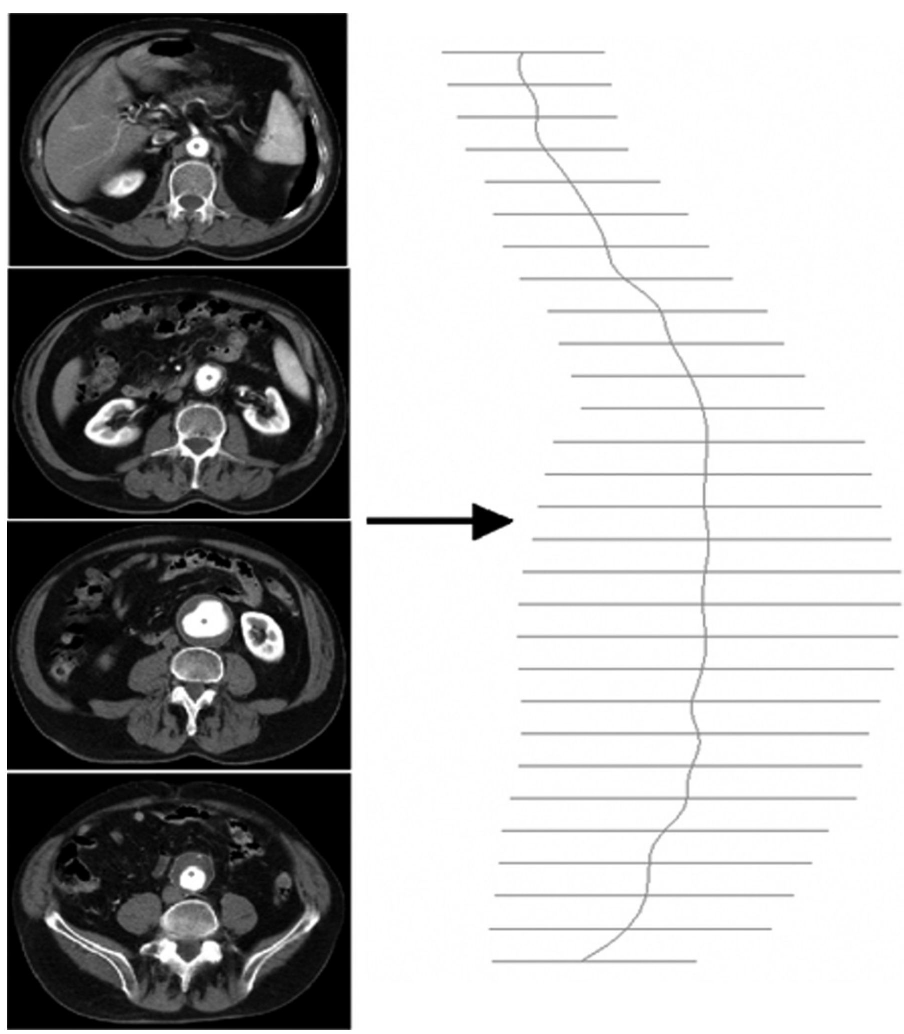

Fig 4. Computed tomography scans for patient 3 show the creation of polylines on each slice, together with the center point of each polyline. Once the polylines are created on each scan in the series, the slices are stacked to form the model on the right.

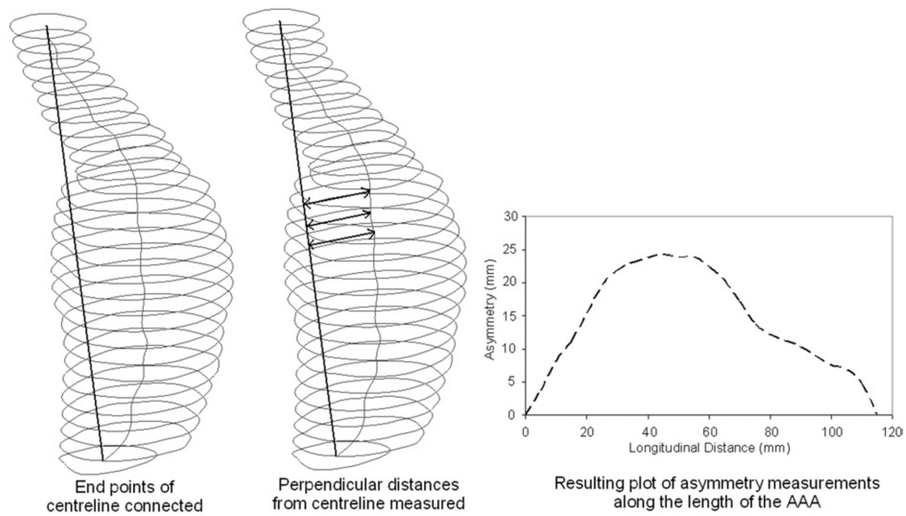

Fig 5. Diagrams depict how measurements of asymmetry are determined once the abdominal aortic aneurysm *(AAA)* centerline is created. The example shown is for patient 3. **Left,** Endpoints of the centerline are connected. **Middle,** Perpendicular distances from the centerline are measured. **Right,** Asymmetry measurements along the length of the AAA are plotted.

Table II. Aneurysm diameters and wall stress variables for study patients

Patient	*Max diameter, cm*	*Peak wall stress, MPa*	*Location of peak wall stress*	*Diameter at peak wall stress, cm*
1	5.6	0.4018	Anterior-right	3.8
2	6.1	0.4213	Anterior-right	4.1
3	5.7	0.5524	Posterior	5.3
4	5.6	0.3157	Posterior	4.9
5	5.9	0.3822	Posterior	5.3
6	5.7	0.3823	Left	5.8
7	5.3	0.3621	Left	4.8
8	6.0	0.3872	Posterior	4.6
9	5.8	0.4093	Posterior-right	5.5
10	9.0	0.9048	Posterior	6.2
11	6.5	0.4608	Left	5.8
12	6.8	0.4991	Left	5.6
13	6.2	0.4523	Left	6
14	5.7	0.3703	Posterior	5.4
15	7.9	0.4747	Left	7.6

Peak wall stress. The computed stress results showed that the regions of peak wall stress occurred at regions of inflection on the surface of the AAA models. Inflection points are defined as points on the AAA surface at which the local AAA wall shape changes from concave outward to concave inward.[12] The peak stress occurring at regions of inflection was also observed by previous researchers in idealized models.[12,13,26,27] The von Mises peak wall stress, diameter at peak stress, and location were recorded for each AAA and were compared with the maximum diameter in Table II. All peak stress values are recorded at the peak systolic pressure of 120 mm Hg (16 KPa). Shown also is the diameter of the region through which the peak wall stress occurred. The mean von Mises peak wall stress was 0.4505 ± 0.14 MPa (range, 0.3157-0.9048 MPa). The mean circumferential stress was also recorded for each case and was 0.1176 ± 0.061 MPa (range, 0.07-0.3271 MPa).

Wall stress–asymmetry relationship. Figs 6-8 show how the von Mises wall stress varies with respect to the asymmetry of the AAA centerline. Regions of elevated centerline asymmetry experienced a region of elevated posterior wall stress.

Effect of asymmetry on wall stress. To gauge the effect of asymmetry on resulting wall stress, the AAA of patient 2 was modified into a symmetric aneurysm, as described earlier. The symmetric wall stress can be seen compared with that of the posterior wall stress in the asymmetric case in Fig 9. Peak stress increased from 0.2186 MPa to 0.4213 MPa when asymmetry was introduced into the AAA. This resulted in a 48% increase in peak wall stress in the asymmetric model. There was also a noticeable increase of 38% from 0.2186 to 0.3527 MPa in posterior wall stress between the two models.

Statistical analysis. A Spearman ρ correlation test was considered to assess any relationships evident between both peak and posterior wall stress and various patient-specific measurable parameters. Correlations are deemed significant when $P < .05$. The P values of this study are compiled in Tables III and IV. No significant correlation was noted between peak circumferential stress and either maximum asymmetry ($P = .0708$) or maximum diameter ($P = .5197$). The relationship between posterior wall stress with both asymmetry and diameter was also examined using a Spearman ρ correlation test. Coefficients were found using a bivariate correlation test to compare posterior wall stress with both asymmetry and diameter at 10-mm intervals along the longitudinal distance of each patient. These results can be seen in Table V. The significance of the

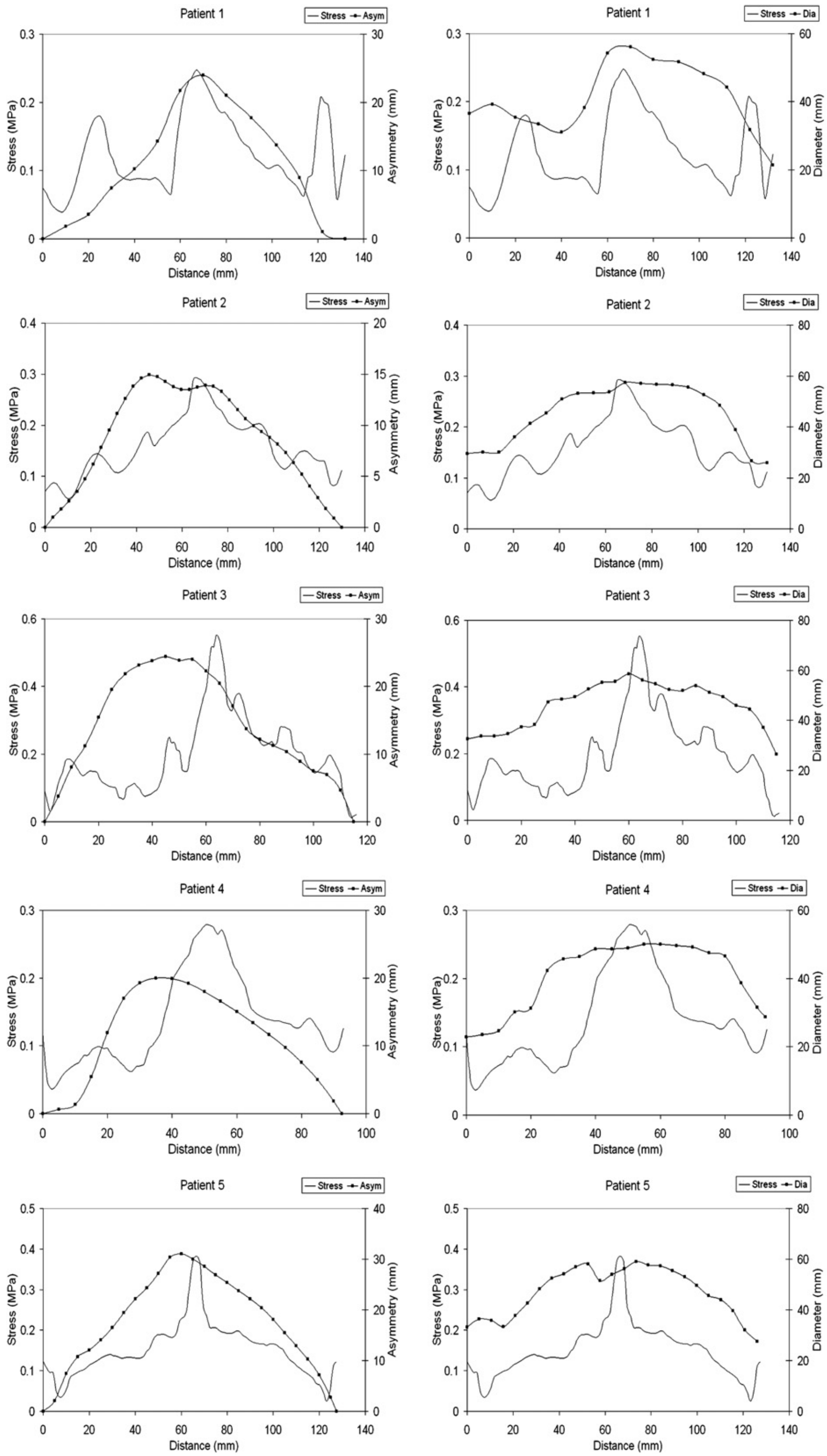

Fig 6. Relationships between **(left column)** posterior wall stress and anterior asymmetry and **(right column)** posterior wall stress and diameter for patients 1 through 5.

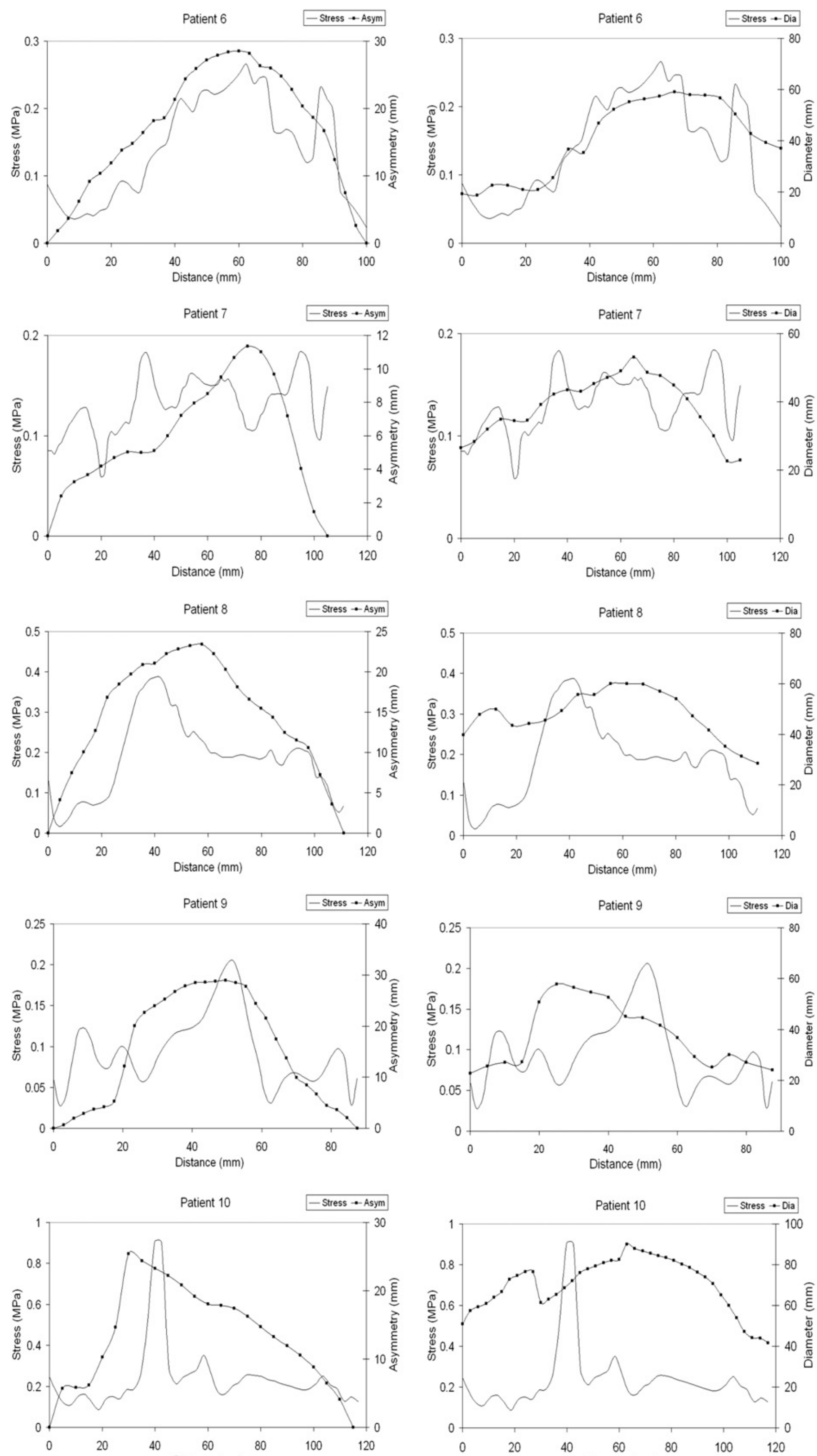

Fig 7. Relationships between **(left column)** posterior wall stress and anterior asymmetry and **(right column)** posterior wall stress and diameter for patients 6 through 10.

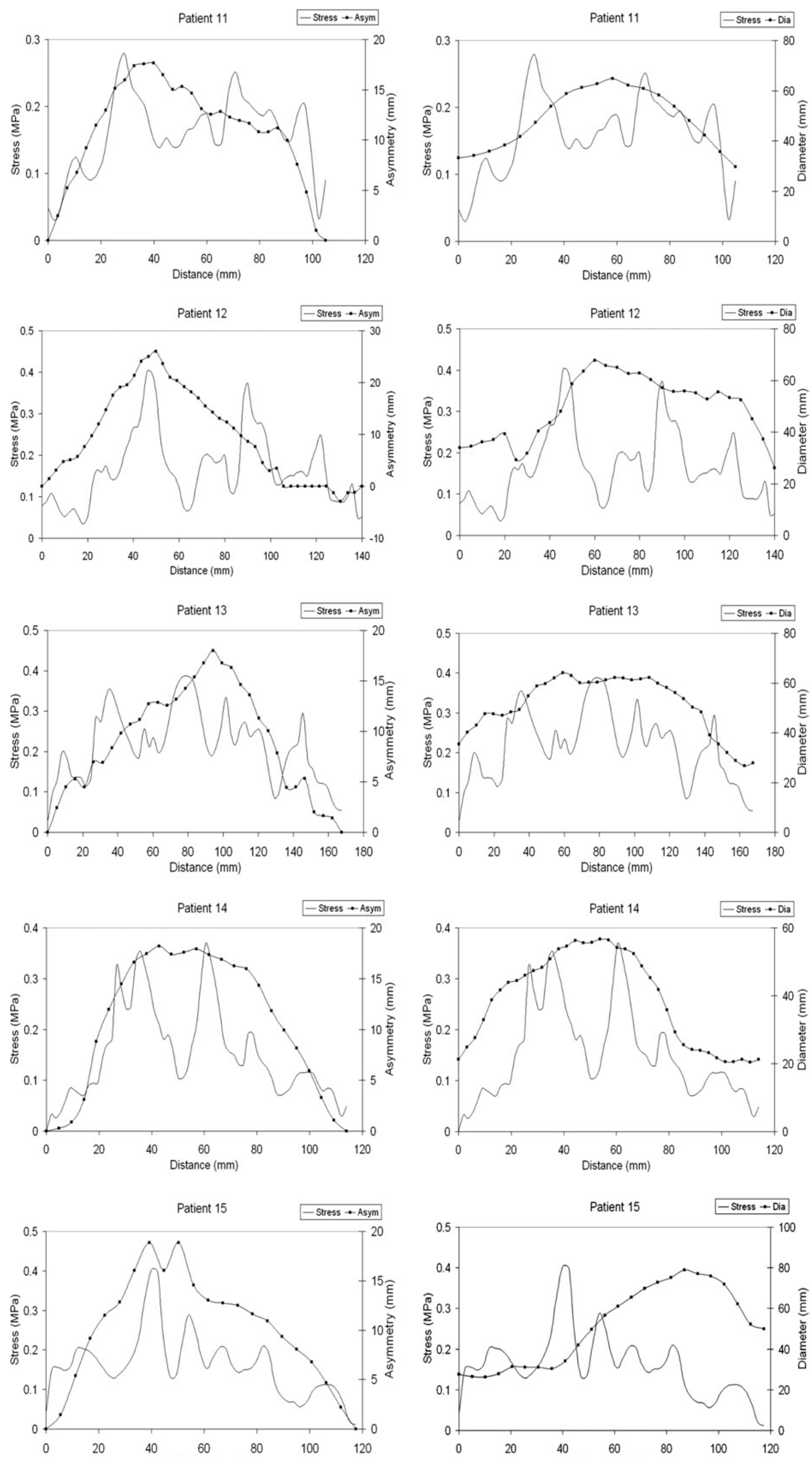

Fig 8. Relationships between **(left column)** posterior wall stress and anterior asymmetry and **(right column)** posterior wall stress and diameter for patients 11 through 15.

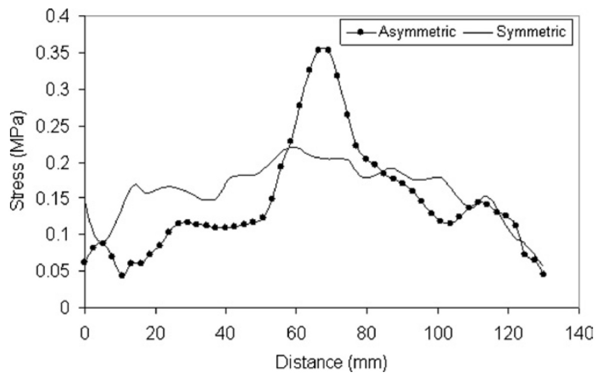

Fig 9. Comparison of the posterior wall stress for the symmetric and asymmetric *(circles)* abdominal aortic aneurysm (AAA) for patient 2. Peak stress for this asymmetric AAA was located on the anterior-right wall.

Table III. Statistical analysis of patient-specific parameters and peak wall stress

Variable	P
Maximum diameter	.0003
Peak posterior stress	.0021
Asymmetry at peak circumferential stress	.0036
AAA volume	.0043
Sex	.0061
Maximum CSA	.0126
AAA surface area	.0130
ILT volume	.0232
AAA length	.0961
Peak circumferential stress	.1580
Lumen volume	.1658
ROD	.3307
Asymmetry at peak von Mises stress	.4384
AAA diameter/AAA length	.5409
Peak stress location	.5814
Peak asymmetry	.6384
AAA volume/ILT volume	.8994
Average asymmetry	.9345

AAA, Abdominal aortic aneurysm; *CSA,* cross-sectional area at the region of maximum diameter; *ILT,* intraluminal thrombus; *ROD,* ratio of maximum AAA diameter to infrarenal diameter.

Table IV. Statistical analysis of patient-specific parameters and posterior wall stress

Variable	P
AAA volume	.0002
AAA surface area	.0008
Lumen volume	.0012
Maximum CSA	.0013
Peak stress	.0021
Maximum diameter	.0028
Sex	.0081
Asymmetry at peak circumferential stress	.0136
AAA length	.0144
Peak circumferential stress	.0378
AAA volume/ILT volume	.0983
ILT volume	.1728
ROD	.2597
Peak stress location	.5399
Peak asymmetry	.6025
Asymmetry at peak von Mises stress	.7466
AAA diameter/AAA length	.9295
Average asymmetry	.9496

AAA, Abdominal aortic aneurysm; *CSA,* cross-sectional area at the region of maximum diameter; *ILT,* intraluminal thrombus; *ROD*, ratio of the maximum diameter to the infrarenal diameter.

Table V. Correlation coefficients for posterior wall stress and asymmetry and diameter

Patient	*Asymmetry*	P	*Diameter*	P
1	0.574	.032	0.420	.135
2	0.781	.003	0.895	.000
3	0.175	.587	0.755	.005
4	0.37	.293	0.733	.016
5	0.862	.000	0.820	.000
6	0.82	.002	0.609	.047
7	0.464	.151	0.573	.066
8	0.834	.001	0.573	.051
9	0.474	.166	0.529	.116
10	0.443	.130	0.505	.078
11	0.683	.014	0.811	.001
12	0.411	.128	0.593	.020
13	0.411	.128	0.593	.020
14	0.834	.000	0.709	.007
15	0.667	.013	−0.132	.668

relationship between asymmetry and diameter was also assessed using a nonparametric correlation test (Table VI). In 11 of the 15 AAAs, a significant correlation was revealed between asymmetry and diameter. Patient age also correlated well with both maximum diameter ($P = .009$) and peak posterior wall stress ($P = .028$).

The statistical significance between peak stress and other relevant parameters was also assessed. The rate of change of both asymmetry and diameter along the length of the AAA were not statistically significant ($P = .089$ and $P = .501$, respectively). The diameter at which peak stress occurred was significant ($P = .039$).

DISCUSSION

This study reconstructed 15 patient-specific AAAs, and wall stress distributions in each aneurysm were estimated using the finite element method. From the von Mises wall stress distributions, the peak stress occurred at regions of inflection. This finding is consistent with previous research, both numeric[12,26] and experimental.[27] The mean values of peak wall stresses found in this study were 0.482 ± 0.197 MPa (range, 0.3157-0.9584 MPa). The AAA in patient 4 had the lowest peak wall stress (0.3157 MPa) and also had the second smallest maximum AAA diameter (5.6 cm); whereas, the AAA in patient 10 had the highest peak stress (0.9048 MPa) and had the largest AAA diameter (9 cm).

These findings may suggest that the maximum diameter criterion may be a good predictor of AAA rupture. From the previous research into this hypothesis,[9] it is known that this may not always be the case, because small AAAs can also rupture. Fillinger et al[7] performed stress analysis on an

Table VI. Correlation between abdominal aortic aneurysm asymmetry and diameter for each patient

Patient	*Coefficient*	P
1	0.801	.001
2	0.823	.001
3	0.755	.005
4	0.612	.060
5	0.935	.000
6	0.752	.008
7	0.9	.000
8	0.806	.002
9	0.799	.006
10	0.627	.022
11	0.746	.005
12	0.391	.150
13	0.391	.150
14	0.889	.000
15	0.066	.830

AAA with a 4.8-cm diameter, which was smaller than the current 5.5-cm threshold. This particular AAA experienced a peak wall stress of 0.335 MPa, which is within 10% of the peak stress found in patients 4, 7 and 14 of this study.

It is important to note that ruptures do not necessarily occur at the region of peak wall stress, but in fact occur where the locally acting wall stress exceeds the locally acting wall strength. This study examined the role of realistic asymmetry on posterior wall stress in patient-specific cases. To determine the effect the asymmetry of the AAA has on posterior wall stress, a simple method of calculating asymmetry was established. Figs 3-5 show the approach used to plot the degree of asymmetry in each AAA, and these results were then coupled with the posterior wall stress results. These stress-asymmetry relationships are shown in Figs 6-8, which also show the relationship between diameter and posterior wall stress.

Raghavan et al[28] reported that the posterior wall tends to be the higher stressed region and also the rupture site, even though the bulge is predominantly anterior. Vorp et al[12] identified the link between asymmetry and wall stress in idealized AAA models using finite element mesh, with Scotti et al[13] using a fluid-structure interaction approach to highlight the relationship in idealized models. Scotti et al[13] concluded that AAAs experiencing asymmetry may be exposed to higher mechanical stresses and increased risk of rupture than more fusiform AAAs. This current work agrees with this hypothesis and has furthered the work of idealized AAAs to that of realistic AAA geometries, with results suggesting that an intrinsic relationship may exist between asymmetry and posterior wall stress.

Darling et al[9] determined from 118 AAA autopsies that 82% of ruptures occur on the posterior wall, indicating that these ruptures may have resulted from elevated posterior wall stress. Of the 22 patients examined for this study, 15 (68%) experienced posterior–anterior bowing, resulting in elevated posterior wall stress. Raghavan et al[29] recently reported that the posterior and right regions of AAAs are regionally thinner than the anterior and left regions. They also reported that failure tension might be a better indicator of rupture rather than failure stress, with failure tension described as: peak wall tension = peak wall stress × wall thickness. Applying this failure tension to this study results in failure tensions ranging from 0.6314 to 1.8096 N/mm, compared with the range of 0.42 to 1.48 N/mm observed by Fillinger et al.[6] Actual failure stress of AAA tissue has been shown to be a median of 1.266 MPa (range, 0.336-2.351 MPa).[29]

Giannoglou et al[30] also determined that mean AAA curvature may be a better predictor of AAA rupture risk, although this previous study implemented linearly elastic material properties. AAA centerline curvature was also analyzed as part of this present study using the curvature analysis function in ProEngineer Wildfire 3.0. The resulting centerline curvature readings are difficult to interpret because minor changes in the centerline result in large spikes of curvature. Gaussian surface curvature was also examined using ProEngineer Wildfire 3.0, as previously reported.[22] Rapid changes in surface curvature may indicate regions of high wall stress.[22] As with centerline curvature, the model geometries are too complex to achieve surface curvature results with any quantifiable meaning. The definition of asymmetry in this study is a measurement that is easy to interpret and calculate and shows good agreement with wall stress results.

As the anterior region of the AAA bulges outwards, the posterior region is often constrained from radial expansion by the spinal column and results in elevated posterior wall stress. AAAs may also rupture at regions experiencing a wall stress that is less than that of the peak wall stress because AAAs are known to rupture when the local stress exceeds the local wall strength, with AAAs experiencing regional variations in wall strength.[29]

Two AAAs in this study experienced peak wall stress on the anterior-right wall. Peak stress can occur at any region along the AAA surface but is predominantly found at regions where there is high local surface curvature or asymmetry. Therefore, when patient-specific AAAs are analyzed, it is difficult to predetermine the location of peak stress. Results in six cases showed peak stress on the left wall of the AAA. Again, these locations of elevated stress are due to the local topology of the surface. Even though peak stress does not necessarily occur along the posterior wall, in all AAAs examined there was an increase in posterior stress along the length of the particular AAA in relation to anterior asymmetry.

From the results of the statistical analysis summarized in Tables III and IV, one can determine that the significant parameters that relate to peak wall stress are maximum diameter (P = .0003), peak posterior wall stress (P = .0021), asymmetry at the region of peak circumferential stress (P = .0036), AAA volume (P = .0043), sex (P = .061), maximum cross-sectional area (P = .0126), AAA surface area (P = .013), and also the ILT volume (P = .0232). In comparison, the significant relationships with posterior wall stress are AAA volume (P = .0002), AAA surface area (P = .0008), lumen volume (P = .0012), maximum cross-sectional area (P = .0013), peak wall stress (P = .0021), maximum diameter (P = .0028), sex (P = .0081), asymmetry at the region of peak circumferential stress (P = .0136), AAA length (P = .0144), and also peak circumferential stress (P = .0378). From these results, maximum diameter appears to be significantly related to peak stress, but if the sample size of 15 used in this study were increased to much larger numbers, this relationship might not be as strong. Most of these parameters are also based on diameter; therefore, if diameter returns a strong correlation with peak stress, it may be obvious that similar parameters will also score highly. No statistical significance was noted between peak wall stress and the rate of change of diameter (P = .501) or rate of change of asymmetry (P = .089).

Closer examination of the relationship between both asymmetry and diameter with posterior wall stress involved analyses using a nonparametric Spearman ρ correlation. These results are presented in Table V and show how asymmetry and diameter are both comparable in their significance towards posterior wall stress. From the resulting correlations in the 15 AAAs, eight show asymmetry is significant and nine show that diameter is significant. These results suggest that if posterior wall stress is to gain clinical acceptance as a possible high-risk rupture indicator, asymmetry and diameter may both be as important in determining the posterior wall stress and therefore may both equally contribute to AAA rupture. Both Vorp et al[25] and Fillinger et al[6,7] have previously postulated that the biomechanics of the AAA may provide useful clinical guidance over the maximum diameter criteria. This work supports this biomechanics-based approach and in particular suggests that posterior wall stress may be clinically important. The results presented also suggest that if peak wall stress is to remain the primary purpose of AAA stress analyses, then diameter remains a significant factor.

Although ideally, stress analysis should be done on every AAA detected, the reality is that the decision to repair lies with the surgeon. The use of the maximum diameter criterion is very easy to implement for the surgeon, in that he or she must simply measure the maximum diameter from CT scans. The asymmetry condition described in this study could also be readily incorporated into the surgeon's decision making. The clinician can identify this dilation and, ultimately, asymmetry from a basic 3D reconstruction, which could greatly aid in the decision to surgically intervene. A method of determining asymmetry from 2D CT scans is also currently under development within our group.

Our group is also developing an approach that accounts for asymmetry in all directions, and therefore, the relationship between asymmetry and wall stress can be assessed in all AAAs regardless of orientation. Once detected, the degree of bulging could be incorporated into the surgeon's decision-making process, and may refine and improve the current system of deciding on surgical intervention solely on the basis of maximum diameter. It is suggested that to include AAA asymmetry as another means of assessing the rupture potential of AAAs could serve as a useful adjunct to the maximum diameter criterion, and may ultimately lead to improved surgical decision making.

Our study has some limitations. Similar to previous work,[6,7,11-13,15] this study did not include ILT in the AAA 3D reconstructions. The ILT has been shown to reduce wall stress by up to 30%[10,30] and can act as a "mechanical cushion"[31] for the AAA wall. The realistic AAA has a nonuniform median wall thickness[29] of 1.48 mm, varying regionally from 0.23 mm at a rupture site to 4.26 mm at a calcified site, and also has nonuniform material properties due to regions of calcifications,[32] which can lead to alterations in stress distributions.[32,33]

This study examined AAA wall stress using a static analysis. It is possible that a dynamic loading, such as a realistic infrarenal aortic pulse, may influence the stress distributions. Researchers have shown that the use of fluid-structure interaction methods to determine wall stress can give more accurate results.[3,13,34] Computational time is increased by as much as 2500-fold[13] from that of a static pressure finite element analysis, with maximum stress locations found to be the same using both methods. Variations in maximum wall stress in realistic models have been reported in prior studies to range from 1% to 25%.[3,21,33]

To establish the suitability of this method for clinical applications, a larger cohort of patient data is required. We are investigating the possibility of applying this method to a database of previously screened patients, with a view to enhancing confidence in the asymmetry approach. Applying this study to a larger cohort may also significantly alter the statistical results because only 15 patients were studied here.

CONCLUSIONS

Most AAA ruptures occur on the posterior wall. We have showed here how posterior wall stress can be related to anterior asymmetry in patient-specific cases. Results suggest that an increase in asymmetry may cause increases in posterior wall stress. Statistical analyses revealed that the maximum diameter still significantly influences wall stress, particularly peak wall stress, but that asymmetry may also have a significant role in posterior wall stress. This study suggests that AAA asymmetry may be an important criterion in AAA assessment and could possibly be included as a factor in the clinicians' decision to surgically intervene. Further evaluation is needed to determine clinical applicability.

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AUTHOR CONTRIBUTIONS

Conception and design: BD
Analysis and interpretation: BD, AC, TM

Data collection: PG, DV, PB
Writing the article: BD
Critical revision of the article: BD, TM, AC, MW, PB, PG, DV
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