Peak wall stress measurement in elective and acute abdominal aortic aneurysms

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Background: **Abdominal aortic aneurysm (AAA) rupture occurs when wall stress exceeds wall strength. Engineering principles suggest that aneurysm diameter is only one aspect of its geometry that influences wall stress. Finite element analysis considers the complete geometry and determines wall stresses throughout the structure. This article investigates the interoperator and intraoperator reliability of finite element analysis in the calculation of peak wall stress (PWS) in AAA and examines the variation in PWS in elective and acute AAAs.**

Method: **Full ethics and institutional approval was obtained. The study recruited 70 patients (30 acute, 40 elective) with an infrarenal AAA. Computed tomography (CT) images were obtained of the AAA from the renal vessels to the aortic bifurcation. Manual edge extraction, three-dimensional reconstruction, and blinded finite element analysis were performed to ascertain location and value of PWS. Ten CT data sets were analyzed by four different operators to ascertain interoperator reliability and by one operator twice to ascertain intraoperator reliability. An intraclass correlation coefficient was obtained. The Mann-Whitney U test and independent samples t test compared groups for statistical significance.**

Results: **The intraclass correlation coefficient was 0.71 for interoperator reliability and 0.84 for intraoperator reliability. There was no statistically significant difference in the mean (SD) maximal AAA diameter between elective (6.47 [1.30] cm) and acute (7.08 [1.39] cm) patients ($P = .073$). The difference in PWS between elective (0.67 [0.30] MPa) and acute (1.11 [0.51] MPa) patients ($P = .008$) was statistically significant, however.**

Conclusion: **Interoperator and intraoperator reliability in the derivation of PWS is acceptable. PWS, but not maximal diameter, was significantly higher in acute AAAs than in elective AAAs. (J Vasc Surg 2008;47:17-22.)**

Abdominal aortic aneurysm (AAA) rupture is a common cause of preventable death in men >65 years.[1] After AAA rupture, 50% of patients die before reaching the hospital; in addition, the mortality rate after emergency repair is 40% to 50%. This contrasts with a 3% to 6% mortality rate after elective AAA repair; hence, decision making about elective AAA repair requires careful assessment of operative mortality, rupture risk, and life expectancy.[2]

Currently, AAA repair in fit patients is recommended when AAA diameter is ≥5.5 cm or the patient becomes symptomatic.[3] Although AAA diameter is an important predictor of rupture,[4] not all large AAAs rupture, whereas 10% to 24% of ruptured AAA are <5.5 cm in diameter.[5,6] No reliable criterion therefore exists to accurately predict rupture risk for the individual patient, and thus, the decision to operate on the basis of AAA diameter alone may subject a significant proportion of patients to unnecessary surgery with significant mortality and morbidity. Patients with a stable aneurysm are more likely to die of other causes[7]; hence, the arbitrary setting of a single threshold diameter for elective AAA repair in all patients seems inappropriate.[2]

An AAA acts as a thin-walled pressure vessel and develops hoop and longitudinal stresses. Classic engineering stress analysis of simple axisymmetric shapes suggests that the stress in both directions is directly proportional to the diameter and inversely proportional to the thickness of the aneurysm wall. The relationship, however, is more complicated because AAAs have convoluted asymmetric shapes and the stress in an AAA will depend on the entire geometry, not just the maximum diameter.[8] The wall stress in the complex geometries of real aneurysms thus cannot be predicted by simple analytic techniques; instead, finite element analysis (FEA) must be used.[9-11] FEA is a numeric modelling technique that is used regularly by engineers in the design and analysis of structural components in many engineering applications, many of which are safety critical, for example, in the automotive, aerospace, and nuclear industries.[12] FEA is accurate and reliable, provided the problem is modelled with sufficiently fine discretization and valid representation.

We and others have suggested that PWS is a better predictor of rupture than maximum AAA diameter.[13,14] This article reports our investigation of the interoperator and intraoperator reliability of FEA in the calculation of PWS in AAA and examines the variation in PWS in a large cohort of elective and acute AAAs.

METHODS

Ethics. Full local ethics committee approval was obtained for this study, together with approval from the institutional research and development departments (Hull

Academic Vascular Surgery, Hull Royal Infirmary,[a] Department of Engineering, University of Hull.[b]

Competition of interest: none.

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and East Yorkshire Hospitals NHS Trust and the University of Hull).

Patient population. The study included 70 patients with infrarenal AAA who had had an abdominal computed tomography (CT) scan. Forty patients were prospectively recruited before undergoing abdominal CT scan for AAA imaging, and 30 patients were recruited retrospectively after being admitted with symptoms of an acute or leaking aneurysm and undergoing CT AAA imaging. Information collected on each patient included demographics, medical history, systolic blood pressure closest to time of CT imaging (and during admission if acute), and CT images.

Material properties. We used a mathematic model for AAA tissue properties developed by Raghavan and Vorp,[15] a two-parameter, nonlinear hyperelastic, isotropic, incompressible constitutive model on which the finite element analysis was performed. The material behavior is governed by the Mooney-Rivlin equation, which in uniaxial tension is given by:

$$\sigma = \left[2A + 4B(T^2 + 2T^1 - 3)\right] \times \left[T^2 - T^1\right],$$

where σ is stress, A and B are constants, and T is stretch (final length/original length = 1 + strain).

Raghavan and Vorp found the coefficients of the equation to vary as follows: $(0.15 < A < 0.22)$ and $(1.18 < B < 3.56)$ N/mm^2, with peak wall stresses changes by <4% when material properties were varied within this range.[13,15] We used values of 0.185 for A and 2.37 for B.

Finite element analysis. The finite element method works by dividing the geometry into a finite number of elements, and as the number of elements increases and the size of each individual element decreases, the accuracy of the solution improves. As a result, the number of elements used in an analysis is critical and was thus examined previously. This demonstrated that increasing the element mesh density from 9000 to nearly 20,000 elements (using seven models of increasing mesh density) made only a 1.2% difference in calculated PWS.[13] Thus, increasing the number of elements beyond this level would only marginally improve accuracy. Our aneurysm models were therefore analyzed with between 20,000 and 30,000 elements depending on geometry complexity. The type of element used was ANSYS (ANSYS, Inc, Canonsburg, Pa) type SHELL 93 with a quadratic interpolation function. The thickness of aneurysm walls is difficult to measure but is generally reported to be of the order of 2.0 mm; therefore, this was the thickness that we used.

Generation of the finite element models. Full details of the procedure used to produce the finite element models are reported elsewhere.[13] Briefly, abdominal CT scans are acquired using the standard AAA protocol, including bolus tracking (scan initiation at the peak of contrast uptake) with a nominal slice thickness of 3.2 mm (elective imaging) with 50% overlap with a helical pitch of 0.875. The abdomen and pelvis are imaged to visualize the infradiaphragmatic aorta down to the common iliac artery; however, CT images are only analyzed from the most proximal renal artery origin to the aortic bifurcation. These CT images are imported into Scion Image 4.0 image-processing software (Scion Corp, Frederick, Md), and each cross section of the AAA is opened as a separate image file. The wall of the AAA is marked manually to give its (*x-y*) profile in two-dimensions (2D), which is output as a text file. The process is repeated for each slice of the AAA, and the *z* coordinate of each slice is added subsequently using the slice thickness information by a simple in-house program (Visual Basic 6.0, Microsoft Corp, Redmond, Wash).

The full set of data points thus created is then imported into 3D image-rendering Rhinoceros 2 software (Robert McNeel & Assoc, Seattle, Wash) to create a 3D surface representation of the aneurysm. The resultant surface data is exported in a RAW-triangle format, which is then converted directly into a format suitable for reading into the ANSYS finite element software. Again, the software to convert the RAW data into the finite element model has been developed in-house (Visual Basic 6.0) and generates an ANSYS script file which includes not only details of the element mesh but also specification of the material properties, the constraints, and the loading conditions. The result is a detailed map of the stress and strain fields throughout the aneurysm. In common with other researchers in this field, we use the von Mises stress to give a single value reflecting the full 3D stress field at each point in the model. The whole process, from CT data to patient-specific aneurysm model, typically takes 90 minutes.

Interoperator and intraoperator reliability. Manual extraction of the AAA geometry CT slices inevitably provides the opportunity for errors to be introduced into the analysis. To assess the repeatability of this extraction process, interoperator and intra-operator reliability was assessed. Reliability is defined as the extent to which a measurement made repeatedly in identical circumstances will yield concordant results. The only variable for interoperator reliability was the operator, and the only variable for intraoperator reliability was the timing of the analysis.

For interoperator reliability, 10 CT data sets were analyzed by four different operators with different backgrounds and experience of the method. Operator 1 was the clinical research fellow with in depth knowledge of the process and wide experience of the aneurysm edge extraction technique. Operator 2, a postgraduate engineering student, had in-depth knowledge of the process and reasonable experience of the technique, whereas operator 3, another postgraduate engineering student, had vague knowledge of the process but no experience of this method of edge extraction. Finally, operator 4, a postdoctoral engineer, had no knowledge of the process or any experience of edge extraction. The 10 CT data sets were selected randomly during the study of 70 patients, with no reference to the geometry of the aneurysm concerned. A briefing meeting for the four operators before this process demonstrated the AAA edge extraction method. The operators did their analyses during a 2-week period.

Intraoperator reliability was assessed by analyzing 10 CT data sets on two occasions, 6 months apart, with no

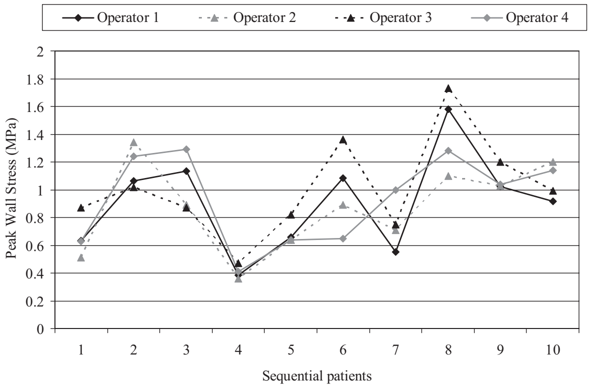

Fig 1. Interoperator variability: peak wall stress calculated after edge extraction by four different operators on 10 separate aneurysms.

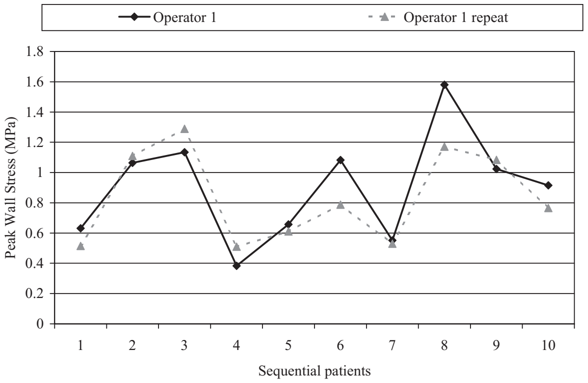

Fig 2. Intraoperator variability: peak wall stress calculated after repeated edge extraction by one operator on 10 separate aneurysms.

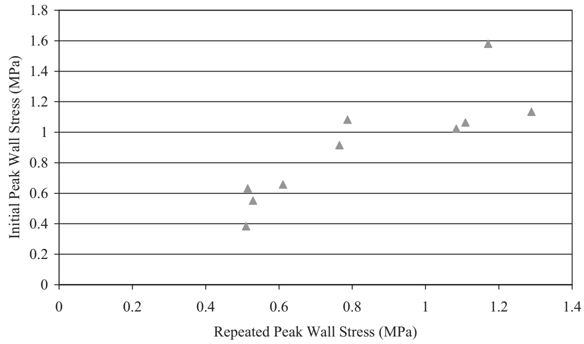

Fig 3. Intraoperator variability: peak wall stress from initial and repeat calculation plotted against each other.

Table I. Sample patient demographics

	AAA type		
*Demographics**	*Elective (n = 40)*	*Acute (n = 30)*	P
Age	76 (60-89)	74 (60-89)	.59†
Sex (male/female)	2.6:1	4:1	.47‡
Hypertension	66	46	.15‡
Ischemic heart disease	24	50	.049‡
Smoking	62	78	.40‡
COPD	23	37	.26‡

AAA, Abdominal aortic aneurysm; *COPD,* chronic obstructive pulmonary disease.

*Data presented as median (IQR), ratio, or percentage.

†Calculated by Mann-Whitney *U* test.

‡Calculated by χ^2 test.

reference to the initial attempt during repeat analysis. This was performed by operator 1, and reflects results obtained by an operator with clinical experience during an initial learning curve and beyond.

Loading and constraints. The finite element models were loaded with the patients' systolic blood pressure (SBP). In vivo, the renal arteries and the iliac arteries constrain an infrarenal AAA from deforming to some extent at the proximal and distal ends; hence to account for this, the finite element models were constrained at the proximal and distal ends.

Statistical analysis. Statistical analysis of interoperator and intraoperator reliability was done using the intraclass correlation coefficient on the calculated peak wall stress values.[16] Continuous data are presented as the mean (SD).

RESULTS

Interoperator reliability. Fig 1 shows the PWS calculated after aneurysm edge extraction on 10 different aneurysms by the four operators. The percentage average deviation from the mean varies from 5% (aneurysm 9) to 24% (aneurysm 6). The interoperator intraclass correlation coefficient was 0.71 (average, 0.91).

Intraoperator reliability. Fig 2 shows the PWS calculated after edge extraction done by operator 1 on two separate occasions to determine intraoperator variability. The graph in Fig 3 plots PWS values obtained for the same aneurysms against each other to determine R^2 values and the Pearson correlation coefficient. The R^2 value was 0.73, and the Pearson correlation coefficient was 0.86. The intraoperator intraclass correlation coefficient was 0.84 (average, 0.91).

Patient study. Full demographic details of the 70 study patients with infrarenal AAA (40 elective, 30 acute) are summarized in Table I. No statistically significant difference was found between the groups for age, sex, and comorbidities, including hypertension, chronic obstructive pulmonary disease, and the incidence of smoking. The incidence of ischemic heart disease was 24% in the elective group, which was significantly lower than the 50% in the acute group ($P = .049$).

The difference in the maximum diameter between elective AAAs (6.47 [1.30] cm) and acute AAAs (7.08 [1.39] cm) was not statistically significant (Table II). However, acute AAAs had a significantly higher PWS (1.11 [0.51]

Table II. Abdominal aortic aneurysm data results

	AAA type		
*Analysis result**	*Elective (n = 40)*	*Acute (n = 30)*	P†
Maximum diameter, cm	6.47 (1.30)	7.08 (1.39)	.073
BP, mm Hg	143 (25)	151 (23)	.181
Peak wall stress, MPa			
At recorded BP	0.67 (0.30)	1.11 (0.51)	.008
At constant BP	0.65 (0.25)	0.84 (0.31)	.009

AAA, Abdominal aortic aneurysm; *BP,* blood pressure.
*Results presented as mean (SD).
†Independent samples *t* test.

MPa) than elective AAAs (0.67 [0.30] MPa; $P = .008$). The difference in SBP between the groups was not significant (elective, 143 mm Hg; acute, 151 mm Hg; $P = .181$), but to examine the association of AAA geometry to risk of rupture without the effect of blood pressure, PWS was also calculated with SBP standardized at 120 mm Hg. With SBP standardized, acute AAAs had a significantly higher PWS (0.84 [0.31] MPa) than elective AAAs (0.65 [0.25] MPa; $P = .009$). Localization of PWS was anterior in 60% of patients and on the right in 52%.

DISCUSSION

Finite element analysis is a well-established engineering tool used to model complex structures and analyze stress distributions; however, problems can occur if geometry information and model characteristics are inaccurate. Aneurysm geometry is obtained by manual outlining of the external AAA wall. Manual input of the external wall is currently required owing to the difficulties in precisely identifying the AAA wall; indeed, this sometimes poses problems even for the expert clinician. Various techniques of automated image extraction of AAA geometry are available but are currently not sufficiently precise for PWS extrapolation. Manual extraction of geometry is subject to reliability problems, thus an assessment of the significance of this variability in reliability is crucial.

The various methods to examine variability, including the Pearson correlation, are based on regression analysis and the measure of the extent that two observations from a group of subjects can be fitted to a straight line. However, this seeks to identify agreement rather than *absolute* agreement, and a result of 1 can be obtained even where the intercept of the line is not through the origin of the graph and the slope is not 1. It also has the limitation of only being able to compare two observations at one time, with no recognized way to combine two or more Pearson correlation coefficients.

A more accepted form of reliability measurement is the intraclass correlation coefficient (ICC), identifying absolute agreement between two or more operators. An ICC of 70% in research and 90% in clinical work as been recommended as acceptable.[17] Interoperator reliability was 0.71 and intraoperator reliability was 0.84 in this study, suggesting that there is acceptable variation in our method for research, but further investigation is required before acceptance into clinical practice. Reliability can be most readily improved by operator training, and in our interoperator variability testing, minimal training and experience was given to two of the four operators.

Another approach to improve reliability would be to remove the human element. As previously stated, no reliable method for automated extraction of AAA external wall geometry from CT scans currently exists; however, our research group is investigating this problem. Automated systems with little or no manual input potentially improve the processing speed and reliability.

In the patient study, statistical significance in mean PWS is seen between the acute and elective AAA groups, but the difference in AAA diameter between the groups was not statistically significant. We believe PWS promises to provide individual rupture risk to patients with AAA, but this is very much work in progress, and further refinement of the process is on going. In addition, we recognize that AAA wall strength is as important as wall stresses in precipitating AAA rupture. Although invasive analysis of AAA wall tissue has demonstrated weaker wall in ruptured than nonruptured AAA,[18] the transition from this to estimation of rupture potential by using noninvasively calculated wall strength has proven to be more difficult.[19]

Potential limitations of this study include:

1. Blood pressure analysis. Peak blood pressure rather than normal resting blood pressure is important in PWS calculation because it only takes one instance when peak wall stress exceeds wall strength for AAA rupture to occur; however, the measurement of a patient's peak blood pressure is almost impossible. We used the highest recorded blood pressure in the patient's case notes during the current or previous admissions.
2. Wall thickness. According to standard engineering thin cylinder theory, wall stress should be inversely proportional to the wall thickness, and our previous study demonstrated that increasing or decreasing wall thickness by 25% led to a 20% decrease or increase in PWS values, respectively.[9] In the absence of improved methods of ascertaining aneurysm wall thickness, we used a uniform wall thickness of 2 mm (the standard reported wall thickness) in this study. Ideally however, wall thickness should be patient specific.[20] This may be averaged from several readings within a specific aneurysm or may be varied from location to location within the aneurysm. We are currently investigating methods of including this data within the model.
3. Intraluminal thrombus (ILT). This is seen in about 75% of AAAs, but opinion varies on the effect of ILT on wall stress and strength and, thus, on rupture potentials. A protective effect has been postulated whereby the ILT reduces[21] and redistributes[22] wall stress; however, the failure to reduce the transmission of pressure and pressure transmission by a different mechanism has also been demonstrated.[23] The effect of ILT on wall stress is, of

course, also influenced by AAA diameter, AAA length, wall thickness, luminal pressure, thrombus thickness, volume ratio, surface area ratio, elastic modulus, and homogenicity. A confounding factor is the effect of ILT on wall strength. It has been demonstrated that ILT reduces wall tensile strength, which is postulated to be due to a hypoxic environment, compensatory inflammation, and local proteolytic activity.[24] Recent work has provided a constitutive model for ILT derived from biaxial testing, but clearly, the impact of ILT rupture risk is complex and as stated by these authors, further work is required.[25] We began our modelling before the effect of ILT on wall stress was apparent, and thus chose not to incorporate ILT into our model. Subsequently, we wished to avoid major changes to the model mid study. It is now becoming clear that ILT probably has a role to play in rupture risk, although this role is not without ambiguity. We aim to investigate this role in future studies.

4. AAA tissue properties. We used a mathematic model for AAA tissue properties as developed by Raghaven et al, which was based on a United States population and was unvalidated on the local population.[10] Biomechanical analysis of local aneurysm tissue is being done to produce a tissue model specific for the local population. In addition, a number of approximations in the FEA model require further investigation and refinement if the accuracy and reliability of the predictions are to be improved. Most important, the material properties of the aneurysm wall are assumed to be isotropic and uniform throughout the aneurysm; however, recent research indicates that this may not be true.[26,27] A 7% difference has been demonstrated between PWS generated by constitutive models based on uniaxial (on which our model is based) vs biaxial testing methods, which may more accurately reflect the situation in vivo; however, this biaxial-based model, which assumes anisotropy, has produced erratic results within physiologic loading strains.[20] This assumed uniformity will have an indirect effect through its impact on the distortion and growth of the aneurysm through local changes in the nature of the wall material as reflected by a local reduction in the strength of the material. We are currently investigating variation in material properties of AAA wall in areas of different wall stress.
5. AAA decompression and site of rupture. In acute aneurysms, it is not known to what degree rupture may have decompressed the aneurysm resulting in a different geometry than before rupture and lower PWS values. This should be considered when comparing acute with elective aneurysms, because decompression must occur to some degree in all ruptures. The localization of PWS to the anterior segment in 60% of cases seems to be in direct opposition to perceived wisdom that most ruptures occur posteriorly. However, it may be that the patients whose AAA ruptures anteriorly present as free, uncontained intraperitoneal rupture and thus are more likely to die before arrival at the hospital.

CONCLUSION

The overall mortality rate associated with ruptured AAA has changed little in recent decades. The high perioperative mortality rate associated with ruptured AAA repair highlights the need to predict risk of rupture on an individual patient basis. Several attempts have been made in the past to identify risk factors associated with rupture, and several studies have analyzed the factors that influence the risk of rupture. However, only recently have studies focused on relating the risk of rupture on an individual patient basis. In this current study, we validate the earlier pilot work in a different population and demonstrate wall stress can be reliably calculated from routinely performed CT scans and may be valuable in predicting rupture risk.

Although this study has some limitations, the results are promising and support the case for a more detailed examination of the role of wall stress in assessing the risk of rupture on an individual patient basis. We also recognize that continuing advances in the estimation of wall strength are necessary to add more significance to a patient-specific peak wall stress and thus produce a meaningful estimate of individual AAA rupture. With the AAA population being generally elderly, the ability to evaluate individual, specific rupture risk, and thus perhaps offer early surgery to some patients, may significantly affect AAA-related mortality. These methods may also identify patients with a low risk of rupture who may avoid an unnecessary procedure, because not all patients with AAA die of rupture. Wall stress calculations are currently done manually, which is time consuming; however, further research is expected to culminate in a fully automated process that should significantly assist clinicians and patients in their decision making.

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AUTHOR CONTRIBUTIONS

Conception and design: IC, MF, MH, GD, PM
Analysis and interpretation: IC, MF, MH, JC, GD
Data collection: MH, JC, GD
Writing the article: IC, MF, MH, JC, GD
Critical revision of the article: IC, MF, MH, JC, GD
Final approval of the article: IC, MF, PM
Statistical analysis: MH, EG
Obtained funding: IC, MF, PM
Overall responsibility: IC, MF

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INVITED COMMENTARY

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Heng et al should be congratulated on a well-done study. In addition to validating earlier work by their laboratory and others using similar methods, they have presented important information about interobserver and intraobserver variability. Although one would like to see even lower interobserver variability, it should be emphasized that the authors have explored a "worst-case scenario" in which three of four observers had little training or experience in the method.

Two laboratories now have large clinical series including elective and ruptured abdominal aortic aneurysms (AAAs). Both laboratories have validated that peak wall stress is superior to maximum diameter for estimating rupture risk by a second patient cohort.[1-3] There are, of course, methodologic issues that can be improved. Thresholds for determining low and high risk of rupture differ in the laboratories performing these studies, most likely owing to differing methods of creating the mesh. This demonstrates the importance of consistency in the methods used to create the finite element mesh, and the importance of clinical control series to validate thresholds indicating elevated risk for rupture. Other ongoing areas of investigation include the relative importance of wall strength, calcification, thrombus, and fluid-structure interactions.

Large multi-institutional collaborative efforts are already under way to perform external validation cohorts for the method. A significant amount of work still remains to make these methods widely available to clinicians, but Heng et al should be congratulated on an important step along that pathway.

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