

Towards A Noninvasive Method for Determination of Patient-Specific Wall Strength Distribution in Abdominal Aortic Aneurysms

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Abstract—The spatial distributions of both wall stress and wall strength are required to accurately evaluate the rupture potential for an individual abdominal aortic aneurysm (AAA). The purpose of this study was to develop a statistical model to non-invasively estimate the distribution of AAA wall strength. Seven parameters—namely age, gender, family history of AAA, smoking status, AAA size, local diameter, and local intraluminal thrombus (ILT) thickness—were either directly measured or recorded from the patients hospital chart. Wall strength values corresponding to these predictor variables were calculated from the tensile testing of surgically procured AAA wall specimens. Backwards-stepwise regression techniques were used to identify and eliminate insignificant predictors for wall strength. Linear mixed-effects modeling was used to derive a final statistical model for AAA wall strength, from which 95% confidence intervals on the model parameters were formed. The final statistical model for AAA wall strength consisted of the following variables: sex, family history, ILT thickness, and normalized transverse diameter. Demonstrative application of the model revealed a unique, complex wall strength distribution, with strength values ranging from 56 N/cm² to 133 N/cm². A four-parameter statistical model for the noninvasive estimation of patient-specific AAA wall strength distribution has been successfully developed. The currently developed model represents a first attempt towards the noninvasive assessment of AAA wall strength. Coupling this model with our stress analysis technique may provide a more accurate means to estimate patient-specific rupture potential of AAA.

Keywords—Stress, Rupture, Statistical modeling, Aneurysm, Strength.

INTRODUCTION

Abdominal aortic aneurysm (AAA) rupture has a mortality rate of 95% and is ranked as the 13th leading cause of death in the US.¹ Current repair techniques for AAA are associated with nontrivial morbidity and mortality rates.

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Moreover, many AAA patients are elderly and may well live out the rest of their natural lives without their aneurysms rupturing. Therefore, it is important to determine when the risk of rupture of a particular aneurysm justifies the risks associated with repair. The ability to reliably evaluate the susceptibility of a particular AAA to rupture could vastly improve the clinical management of these patients.

For lack of a better approach, clinicians still predominantly use a size threshold to guide their decision on surgical intervention of AAA. The problem with this approach is that some aneurysms smaller than the selected threshold rupture, and other aneurysms larger than the threshold never rupture prior to the patient succumbing to other causes.^{11,13} The insufficiency of this criterion in predicting the risk of rupture of individual AAA is due to its empirical nature, as it is based on the aggregate population, and does not necessarily suit every individual.

From a biomechanical point of view, AAA rupture occurs when the stress in a region of the aneurysm wall exceeds the local strength of the tissue. We therefore believe that a patient-specific biomechanics-based approach that utilizes estimates of both wall stress and wall strength distributions would provide the most reliable assessment of the propensity for rupture of a particular AAA. Our laboratory and others have previously proposed the use of finite element analysis for the noninvasive prediction of patient-specific AAA wall stress distribution.^{15,16,19–21,28,29,32,38,39,42,45} This method was recently utilized to demonstrate that peak wall stresses for ruptured AAA are significantly higher than electively repaired aneurysms, even when controlled for size.²⁰ This study suggested that using peak wall stress to assess AAA rupture risk is an improvement over using AAA diameter. However, since local wall stress is only one of the two factors dictating mechanical failure of the AAA wall, the most accurate estimation of the rupture potential of individual AAA requires that the wall strength distribution be taken into account as well. That is, a certain value of peak wall stress might cause

rupture for one AAA but not for another depending on that individual AAA's wall strength distribution.

Despite this, AAA wall strength distribution has not been given the same amount of investigative attention as the wall stress distribution. Our laboratory first documented the failure strength of AAA wall as measured by *ex vivo* tensile testing of freshly obtained AAA samples.⁴¹ Subsequent work has shown that AAA wall strength differs from location to location within a given aneurysm, and is generally weaker in regions of increased thickness of adjacent intraluminal thrombus (ILT).⁴⁰ However, for the purpose of clinically assessing rupture potential of AAA, a noninvasive means to calculate *in vivo* wall strength distribution is necessary. To the best of our knowledge, there is no current technique available to accomplish this.

The goal of this study was to develop a noninvasive method to evaluate AAA wall strength distribution *in vivo*. To accomplish this, we constructed a statistical model relating the local strength of the AAA wall to certain carefully chosen noninvasively measurable variables using established regression techniques.

METHODS

Consenting patients undergoing traditional AAA repair surgery at the University of Pittsburgh Medical Center provided tissue samples and predictor variable information. All procedures were carried out in accordance with guidelines established by the NIH and the University of Pittsburgh biomedical Institutional Review Board. Following the removal of X and Y-space outliers, the entire dataset was *randomly* separated into construction and validation datasets. The construction dataset was kept larger than the validation dataset in order to increase the power and applicability of the resulting statistical model of AAA wall strength.

To develop a statistical model for the estimation of AAA wall strength distribution, it was first necessary to carefully choose the potential predictor variables, followed by experimental data collection. Linear regression techniques were subsequently used with the collected data set to determine which parameters were significant predictors of local AAA wall strength. Linear mixed-effects modeling techniques were then used to identify each of the model parameters. The final statistical model was applied to four AAA for demonstration purposes.

Selection of Potential Local Wall Strength Predictors

Factors that influence AAA wall strength are poorly understood. However, some key variables have been shown to be associated with aortic wall strength and/or AAA rupture potential. Some of these were selected as potential predictors of local AAA wall strength, the rationale for which are discussed below.

Age

In healthy arteries, the synthesis and degradation of collagen and elastin are carefully regulated by a balance between the activation and inhibition of proteases and their antagonists.²³ In the process of aging, this balance is temporally destroyed through the induction of matrix metalloproteinase gene expression or the secretion of enzymes by inflammatory cells.²³ Indeed, epidemiologic studies have shown an increased prevalence of AAA with advancing age.^{5,25} These observations suggest that the aorta as a whole may become weaker with advancing age.⁶

Gender

Although the frequency of AAA among men is between two to four times higher than among women in the same age group,⁵ epidemiologic studies have shown a higher risk of rupture of AAA in women than in men.^{5,25} A recent study by Wilson *et al.* showed that women have a shorter time to AAA rupture from initial diagnosis compared with men.⁴⁸ These studies, as well as preliminary data from our laboratory,¹⁴ suggest that there may be a difference in AAA wall integrity between males and females.

Smoking Status

Ultrasound screening surveys and case-control studies have demonstrated a strong association between cigarette smoking and AAA.^{3,10} Smoking has also been associated with rapid AAA enlargement and rupture,^{31,37} as it was reported that there is a 5-fold increase in AAA rupture risk for cigarette smokers versus non-smokers.³⁷ While the strength of the association and the presence of a dose response suggest a causal relation, specific mechanisms are unclear.⁶ One possibility is that continued absorption of chemicals from smoking may have effects on the proteolytic and fibrinolytic activities of the AAA wall, and also on smooth muscle cell metabolism,³¹ each of which could have a direct affect on AAA wall strength.

Family History of AAA

Familial tendency of AAA has been demonstrated by several investigators, including our laboratory.^{9,47} In a large case-control study by Darling *et al.*,¹² 15 percent of AAA patients reported an AAA in at least one first degree relative as compared with 1.8 percent of controls (odds ratio = 9.7). Other studies have reported similar findings.^{9,22,24} To our knowledge, no studies exist that examine the influence of family history on AAA wall microstructure or biomechanical properties. However, because of the strong familial tendencies in AAA disease, we chose to include family history as a potential predictor of AAA wall strength.

AAA Size and Local Diameter

As a AAA develops and enlarges, medial lamellar units are destroyed, and the main structural proteins responsible for providing structural integrity to the aorta (namely elastin and collagen) are degraded.^{27,35} Our laboratory has shown that there is also a significant decrease in the tensile strength of the AAA compared to nonaneurysmal tissue.³³ This observation along with evidence that larger AAAs have a higher risk of rupture^{4,26} might also suggest that the failure strength of AAA wall reduces progressively as a AAA enlarges. Since maximum AAA diameter is used as an indicator of overall size, both maximum AAA diameter (AAA size) and normalized local diameter (NORD) were taken as potential predictors.

Intraluminal Thrombus (ILT) Thickness

The intima and subintimal media in the infrarenal aorta are not nourished by the vasa vasorum.¹⁷ Our laboratory has published data supporting the hypothesis that the ILT commonly found in AAA serves as a barrier to the oxygen supply from the lumen, possibly causing hypoxia of the aortic wall.^{40,43} Indeed, we have demonstrated a strong inverse correlation between the ILT thickness and adjacent wall strength within the same AAA.⁴⁰ Local ILT thickness was therefore taken as a potential predictor of AAA wall strength.

Experimental Wall Strength and Local Parameter Measurement

Values of “global” predictor variables (i.e., these that do not vary spatially within a given AAA) were obtained in the following way. A patient’s age (in years), sex (1/2 = male, -1/2 = female), smoking status (1/2 = smoker, -1/2 = nonsmoker), and family history (1/2 = with, -1/2 = without) were obtained from the patient’s hospital chart. The AAA size (in cm) was measured directly on CT or

recorded from the patient’s chart when CT scans were unavailable.

There were two methods for measuring the local ILT thickness and local diameter for a given AAA wall specimen. In the first method, a wedge of ILT with AAA wall attached (typical dimensions were 1.5 cm wide by 4 cm long) was cut and removed from the intact aneurysm. The aneurysm was then cut open and the remaining ILT was removed. The whole ILT specimen with a piece of the wall attached was then sliced perpendicular to its longitudinal axis. This resulted in circumferentially oriented uniaxial specimens (of typical dimensions 0.2 cm wide by 1.5 cm long) attached as small angular segments on the periphery of roughly circular ILT cross-sections. Measurements of two randomly chosen ILT cross sectional diameters at 90° of each other were taken and averaged to provide the local AAA wall diameter for each circumferentially-oriented wall sample. ILT thickness measurements were taken at each end of each circumferentially-oriented wall sample, and the average was taken as local ILT thickness for that specimen (Fig. 1A). These benchtop measurements of ILT thickness and local diameter were confirmed by measuring the ranges of these variables on CT scan when available.

In the second method, a prolene stitch was placed on the AAA wall specimen to mark the longitudinal level of the inferior mesenteric artery (IMA), which was then used as a marker to link the location of a particular uniaxial specimen (of typical dimensions 0.2 cm wide by 1.5 cm long) with the appropriate longitudinal slice on CT images (Fig. 1B). The local diameter and ILT thickness were then measured directly on the appropriate slice of the patient’s CT scan using the above definitions.

For both of the above methods for measuring local diameter, the normalized diameter (NORD) was calculated by normalizing the local diameter by the diameter of the infrarenal aorta as predicted from the patients’ age and sex using a relationship derived from the literature.³⁶ In addition, the binary variable METHOD (+1/2, -1/2)

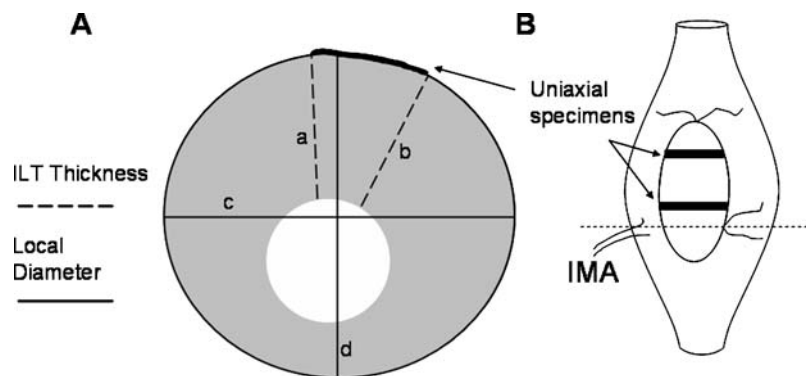


FIGURE 1. (A) Cross-section of a AAA displaying the measurement of local ILT thickness ($(a + b)/2$) and local diameter ($(c + d)/2$). (B) The correlation of the z location of uniaxial specimens with the inferior mesenteric artery (IMA) on CT scans to aid in the calculation of local ILT thickness and diameter. The dotted line corresponds to the longitudinal level of the IMA.

indicating the method of ILT thickness and local diameter measurement was also included in the regression analysis in order to ensure the validity of grouping these methods together in the regression analysis.

After the measurement of these local parameters, the circumferentially oriented wall samples were tested to failure in our uniaxial tensile testing device as described elsewhere.³³ The thickness of each specimen was measured using either digital calipers ($n = 55$) or a laser micrometer ($n = 28$). All thickness measurements were adjusted for differences between these measurement techniques. Specifically, the thickness values for the caliper-measured specimens ($n = 55$) were adjusted using a derived linear relationship between the average caliper and laser-measured values. All specimens were immersed in a container of PBS and tested immediately ($n = 68$) or stored at 4°C and tested within 24 h ($n = 15$). The peak value of stress attainable by each specimen (i.e., its failure strength) was recorded. Only specimens that failed at points remote from the clamps were analyzed and used in this study.

Variable Selection and Outlier Detection

The generalized statistical model used in variable selection and outlier detection is described as:

$$\begin{aligned} \text{STRENGTH} = & \beta_0 + \beta_1 \times \text{ILT} + \beta_2 \times \text{AGE} + \beta_3 \\ & \times \text{SIZE} + \beta_4 \times \text{NORD} + \beta_5 \times \text{HIST} \\ & + \beta_6 \times \text{SMK} + \beta_7 \times \text{SEX} + \beta_8 \\ & \times \text{METHOD} + \varepsilon \end{aligned} \quad (1)$$

where $\beta_0, \beta_1, \dots, \beta_8$ are regression coefficients. STRENGTH is the predicted strength of a point on the AAA wall in N/cm², ILT is local attached ILT thickness in cm, AGE is patient's age in years, SIZE is the maximum cross-sectional diameter of the AAA in cm, NORD is the local diameter normalized to the diameter of nonaneurysmal aorta estimated from the patient's age and sex,³⁶ HIST is family history (1/2 = with, -1/2 = without), SMK is patient's smoking status (1/2 = smoker, -1/2 = nonsmoker), SEX is patient's gender (1/2 = male, -1/2 = female), METHOD is the method used for local variable measurement described previously (1/2 = CT with IMA, -1/2 = bench top), and ε is the residual, i.e., the difference between the model predicted local wall strength and the measured local wall strength. The choice of 1/2 and -1/2 for the binary variables in the model were chosen in order to "center" these covariates, which reduces the chance of making an incorrect statistical inference regarding the estimates of model coefficients.^{2,8} Any continuous variables were also centered by subtracting each measurement by the mean of that variable in the construction group.

In order to use multiple linear regression techniques for variable selection (i.e., to determine which parameters are significant in predicting local AAA wall strength), care was

taken to ensure that no outliers were present in the collected data and that all assumptions relating to multiple linear regression (i.e., constant variance, linearity, normality, and multicollinearity) were met.^{18,44} The Hat diagonal and Studentized residual were used to detect outliers in X-space and Y-space, respectively. Any Studentized residual values $> t_{n-p-1, 0.025}$ (n = number of observations, p = number of parameters in the model) and any Hat diagonal $> 2 \times p/n$ were identified as outliers.

Backwards stepwise linear regression techniques were utilized to determine if individual predictor variables were significant.^{18,44} Briefly, if the associated p value for a certain variable was found to be greater than 0.10, that parameter was considered statistically insignificant and removed from the model.^{18,44} If more than one p value was greater than 0.10, the parameter with the highest p value was removed and regression analysis was repeated using the updated model until all remaining individual p values were less than or equal to 0.10.

Linear Mixed-effects Modeling

Once standard multiple linear regression techniques were used to isolate the significant predictors of wall strength, linear mixed-effects modeling was used to build the final statistical model of wall strength. The use of mixed-effects modeling allows the relaxation of the assumption of independence required in multiple linear regression. Mixed-effects models are primarily used to describe relationships between a response variable (strength) and some covariates in data that are grouped according to one or more classification factors.^{7,30} Since for the current study there are multiple specimens from an individual patient, the patient is considered to be one level of grouping. For a more detailed discussion of mixed-effects modeling the reader is referred elsewhere.^{7,30} Briefly, a mixed-effects model that is compromised of one level of grouping takes the form

$$\mathbf{y}_i = \mathbf{X}_i \boldsymbol{\beta} + \mathbf{Z}_i \mathbf{b}_i + \varepsilon_i, \quad i = 1, \dots, M \quad (2)$$

where $\boldsymbol{\beta}$ is the p -dimensional vector of fixed effects, \mathbf{b}_i is the q -dimensional vector of random effects, \mathbf{X}_i and \mathbf{Z}_i are the known fixed-effects and random-effects regressor matrices, ε_i is the within-group error vector with a Gaussian distribution, and M is the number of groups.³⁰ For the current statistical model of strength, we will have one random-effect that is the intercept term (β_0 in Eq. (1)), while the covariates (ILT, NORD, HIST, SEX, etc.) will be considered as fixed-effects. Therefore in our model p will be equal to the number of remaining significant predictor variables, q will be one since we have one level of grouping (patient), and M will equal the number of patients in the construction group. It is important to note that although the β_i may behave like parameters, formally they are just another level of random variation in the model so we do

not “estimate” them as such. The mixed-effects modeling was performed in the statistical software R, v. 1.9.1, which is freeware available on the world wide web (<http://www.r-project.org>).

Model Predictability and Application

The predictability of the statistical model for AAA wall strength can be performed by comparing the experimentally measured values of wall strength for the validation group of specimens to that calculated for the same specimens using the derived statistical model. The relative contribution and variability of each independent predictor variable’s affect on AAA wall strength will also be assessed by investigating the 95% confidence interval of the parameters in the final model for wall strength.

As a demonstration of the application of the developed model, the wall strength distribution was predicted for four separate AAA. Each global predictor variable (e.g., family history and AAA size) was obtained from each patient’s hospital chart, while spatially varying predictor variables (e.g., local diameter and ILT thickness) were measured from digitized computed tomography images.⁴⁴ The 3D wall strength and wall stress distributions were then calculated and plotted for each AAA for visualization.

RESULTS

Outlier Detection and Variable Selection

There were originally 83 specimens from 39 patients, of which 2 were removed as Y-space outliers. There were no X-space outliers detected in the entire dataset. This left 81 specimens from 38 patients to be randomly divided up into the construction and validation datasets. A summary of the 60 uniaxial specimens from 29 patients used in the construction group are summarized in Table 1. Of these 29 patients, 11 were female, 19 were smokers and 6 had family history. A summary of the 21 uniaxial specimens from 9 patients used in the validation group are summarized in Table 2. Of these 9 patients, 6 were male, 8 were smokers and 2 had family history.

Upon initial regression of Eq. (1), it was found that SIZE and NORD were collinear, indicating that they need

TABLE 1. Summary of the 60 specimens from 29 patients used in the construction group.

	Strength (N/cm ²)	ILT (cm)	NORD	Size (cm)	Age (yrs)
Mean	80.5	0.90	2.46	5.9	73.2
Standard Error	0.6	0.01	0.01	0.02	0.13
Minimum	21.2	0	1.06	5.0	57
Maximum	193.3	3.6	3.9	7.9	86
N	60	60	60	29	29

TABLE 2. Summary of the 21 specimens from 9 patients used in the validation group.

	Strength (N/cm ²)	ILT (cm)	NORD	Size (cm)	Age (yrs)
Mean	83.2	0.71	1.87	5.2	68.8
Standard Error	8.5	0.16	0.14	0.3	2.9
Minimum	20.5	0.07	1.06	3.9	56
Maximum	143.1	2.62	3.57	6.8	84
N	21	21	21	9	9

not both be included in the statistical model. NORD was chosen to remain in the model since it is a spatially-varying parameter and may therefore be used to model the spatially-varying strength known to be present in AAAs.⁴⁰ NORD was centered with respect to its mean value of 2.46. A plot of the residuals versus ILT thickness showed a non-constant variance, and transformation of the variable ILT into its square root ($ILT^{1/2}$) alleviated this problem. $ILT^{1/2}$ was centered with respect to its mean value of $0.81\text{ cm}^{1/2}$. Backwards stepwise linear regression of the model to the construction dataset revealed, sequentially that METHOD ($p = 0.75$), SMK ($p = 0.93$) and AGE ($p = 0.11$) were statistically insignificant predictors of AAA wall strength.

Mixed-Effects Modeling

The 95% confidence intervals for the mixed-effect model parameters for the construction group are displayed in Fig. 2. The mixed-effect model parameter values and their associated p -values for the fit to the construction group are summarized in Table 3. This final statistical model for AAA wall strength is then

$$\begin{aligned} \text{STRENGTH} = & 71.9 - 37.9 \times (ILT^{1/2} - 0.81) - 15.6 \\ & \times (\text{NORD} - 2.46) - 21.3 \times \text{HIST} \\ & + 19.3 \times \text{SEX} \end{aligned} \quad (3)$$

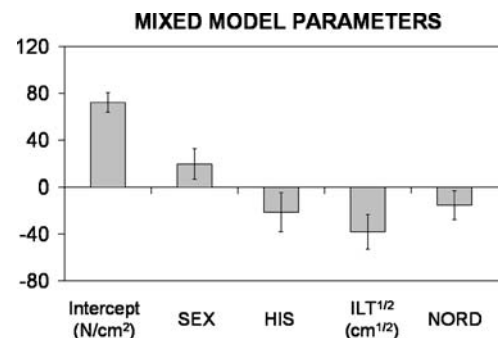


FIGURE 2. The mean and 95% confidence intervals for the parameters in the statistical wall strength model (Eq. (3)) when fit to the construction dataset. The p -value for these linear correlations were both less than 0.001.

TABLE 3. Linear mixed-effects regression report for the final model fit to group C.

Independent Variable	Lower 95% CI	Coefficient	Upper 95% CI	p value
Intercept	63.5	71.9	80.4	<0.001
ILT ^{1/2}	-52.8	-37.9	-23.2	<0.001
NORD	-27.9	-15.6	-3.3	0.01
HIST	-38.1	-21.3	-4.4	0.09
SEX	3.1	19.3	35.5	0.003

Inspection of Eq. (3) provides several insights as to its physical meaning:

- For two patients with the same gender and identical AAAs, the one with family history has a AAA that is globally weaker by 21.3 N/cm² compared to the one without family history.
- For two patients with the same family history and identical AAAs, a female will have a AAA that is globally weaker by 19.3 N/cm² compared to a male.
- For any two points within any given AAA with the same NORD, an increase in ILT^{1/2} of 1.0 results in a corresponding decrease in strength of 37.9 N/cm²
- For any two points within any given AAA with the same ILT^{1/2}, an increase in NORD of 1.0 results in a corresponding decrease in strength of 15.6 N/cm²

Model Predictability

Using this model to predict the strength as measured in the validation group resulted in reasonable predictability (Fig. 3). While the correlation coefficient between measured and predicted values is only 0.6, the trend of increasing predicted strength with increasing measured strength is visible. The fact that the 95% confidence intervals for the

material parameters of the model (Fig. 2) do not include zero confirms that each respective independent variable is positively or negatively correlated with AAA wall strength. It should be noted that the application of this model can only be used within the range of covariates used in its construction. For our construction group, the ranges of NORD and ILT are (1.06, 3.9) and (0, 3.6), respectively.

Demonstrative Model Application

The characteristics of the four patients whose AAA wall strength distributions were evaluated for demonstration purposes are shown in Table 4. The 3D distribution of wall strength for each AAA reveals a unique, complex pattern (Fig. 4). Note also in this figure the differences in the spatial distribution of wall strength as compared to wall stress. In general, wall strength values are higher at both neck regions and lower in the bulge region. Note that AAA 3 did not include any ILT, which resulted in strength variations dependent only on the local diameter of the AAA. Local wall strength values predicted for the four AAA studied ranged from 54 N/cm² to 143 N/cm². Also plotted in this figure is the 3D distribution of rupture potential index (RPI), which is defined as the locally acting wall stress divided by the local wall strength. Since RPI includes noninvasive estimations of wall strength and wall stress, this parameter may better be able to predict the risk of rupture on a patient-specific basis than wall stress or maximum diameter alone.

DISCUSSION

Rupture of an individual AAA, like failure of any loaded structure, occurs when the local stress applied to the wall exceeds the local strength of the tissue. In order to evaluate the risk of rupture for a given AAA, information on *both* local stress and local strength are required. Our results demonstrate that local wall strength may be reasonably

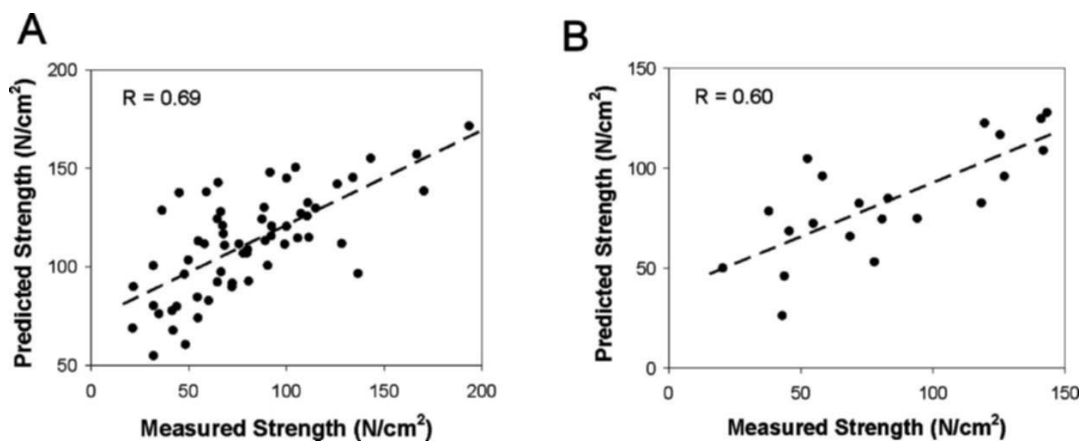


FIGURE 3. Predicted versus measured strength for the statistical model of wall strength (Eq (3)) for the construction (A) and validation (B) groups.

TABLE 4. Summary of the 4 patients used for demonstration of wall strength model application (Fig. 3).

Patient	Max. Calculated Strength (N/cm ²)	Min. Calculated Strength (N/cm ²)	Max. ILT Thickness (cm)	Gender	Size (cm)	Hist
1	143	60	2.3	M	6.0	No
2	126	54	3.0	M	6.1	No
3	94	58	0.7	F	6.4	No
4	125	71	1.8	M	6.4	No

predicted by certain clinical noninvasively-measurable parameters via Eq. (3). This model contains four, non-invasively measurable predictors: the square root of local ILT thickness, normalized local diameter, patient's sex, and the patient's family history of AAA.

The traditional approach of using AAA size to guide decisions for elective AAA repair has faced strong challenge because of its inability to accurately predict rupture for all AAA.^{11,13} Recent studies have been focused on studying *in vivo* stress levels in AAA, and it has been shown that aneurysms smaller than a certain size threshold can experience higher peak stress than larger aneurysms.^{21,32,39,44,45} While these studies have suggested that using peak wall stress to predict the rupture potential for individual AAA would be an improvement over using maximum diameter alone, stress is only one of two factors that dictate the failure of a material, including the AAA wall. For example, two aneurysms with the same peak stress levels but different

wall strength distributions might have a different rupture potential. In order to most accurately predict the rupture potential for each individual AAA, therefore, both the stress and strength distributions are necessary. By combining the technique reported here for predicting *in vivo* wall strength distribution with our companion method of 3D AAA wall stress analysis,^{32,45} a new and improved means to predict the rupture potential for individual AAA may be possible.

Importantly, the strength prediction model is noninvasive in nature. Each of the predictor variables—patient's sex, normalized local AAA diameter, family history, and local ILT thickness—are noninvasively obtainable. Therefore, *in vivo* AAA wall strength distribution for any given patient is clinically feasible and cost effective.

As with any modeling technique, there are certain limitations that should be kept in mind regarding the statistical model derived here. Due to restrictions associated with open surgical procedures, we were limited to AAA wall samples

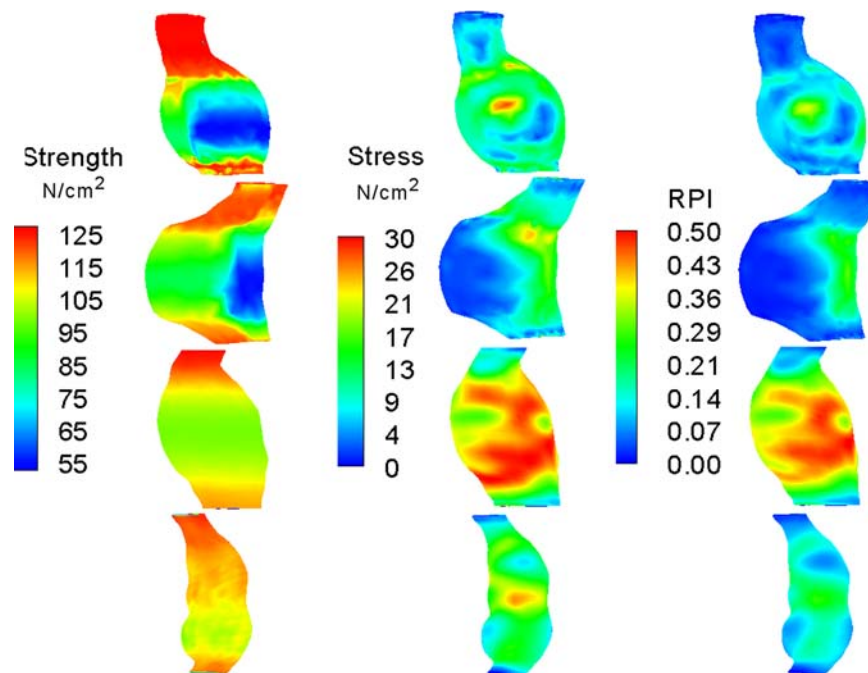


FIGURE 4. Demonstrative application of the statistical model of wall strength (Eq. (3), left), wall stress (middle), and rupture potential index (right) for four representative AAAs.

from the anterior region of AAA only. Ideally, samples would be obtained from the anterior, posterior and both lateral regions of AAA. This limitation should be kept in mind whenever utilizing the proposed statistical model. The use of an estimated nonaneurysmal diameter to normalize the local diameter was used for two reasons: CT scans were not available for all patients, and the authors believe that the proximal aorta of each AAA may not serve as an appropriate measure of the nonaneurysmal aorta, since this region can often times be dilated as well. It should also be noted that the local cross sectional diameter was measured as the average of two random, orthogonal diameter measurements. Therefore, this reflects only the average of circumferential radius of curvature when in reality the AAA wall also has a longitudinal radius of curvature and both radii can vary spatially.³⁴

An important constraint of the statistical model (Eq. (3)) is that the range of the original data from which it was constructed limits its application. For example, if one would like to predict the wall strength distribution for a AAA which contained an ILT thickness greater than 3.6 cm, the strength model derived here can not be used reliably since this ILT thickness is outside of the range listed in Table 1. In addition, using a “worst-case scenario” from the entire dataset (SEX = Female = -0.5 , HIS = Positive = 0.5 , $ILT^{1/2} = 1.9$, NORD = 3.9), the strength calculated is -12.0 N/cm². While negative wall strength is not physically reasonable, this occurs simply due a lack of a strength measurement with these worst-case scenario parameter values used in the derivation of the model. However, since for 38 patients and 81 specimens, no such combination exists, we would expect this occurrence to be of relatively low probability. In order to avoid this issue completely, a very large number of patients covering the entire range of possible predictor variables would be required, a task which lies outside the scope of the current study.

Finally, we have defined the mechanical failure of the AAA wall as the point in which its inherent mechanical strength is unable to withstand the forces being applied to it. The assumption that isolating and failing uniaxial strips of AAA tissue can adequately represent the true failure mechanisms of AAA has not been explored in the current work. In fact, the specific mechanisms involved in the mechanical failure of the in-vivo AAA wall have been given little attention and require further research.

All of the above limitations suggest that improvements in the model for noninvasive estimation of patient-specific AAA wall strength can be obtained. These improvements as well as investigations into additional factors affecting AAA wall strength may lead to a more robust and predictive model for predicting AAA wall strength and its contribution to the assessment of AAA rupture risk.

In summary, a four-parameter statistical model has been successfully developed to noninvasively estimate wall strength distribution of any AAA. Despite the noted limita-

tions, the current model represents a first attempt towards the noninvasive assessment of AAA wall strength. By combining this technique with the AAA wall stress calculation technique developed in our laboratory,^{32,46} a more accurate assessment for AAA rupture potential may be possible. The successful implementation of such a technique would likely benefit the management of patients with AAA.

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