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The Association between Geometry and Wall Stress in Emergently Repaired Abdominal Aortic Aneurysms

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Abstract

Abdominal aortic aneurysm (AAA) is a prevalent cardiovascular disease characterized by the focal dilation of the aorta, which supplies blood to all the organs and tissues in the systemic circulation. With the AAA increasing in diameter over time, the risk of aneurysm rupture is generally associated with the size of the aneurysm. If diagnosed on time, intervention is recommended to prevent AAA rupture. The criterion to decide on surgical intervention is determined by measuring the maximum diameter of the aneurysm relative to the critical value of 5.5 cm. However, a more reliable approach could be based on understanding the biomechanical behavior of the aneurysmal wall. In addition, geometric features that are proven to be significant predictors of the AAA wall mechanics could be used as surrogates of the AAA biomechanical behavior and, subsequently, of the aneurysm's risk of rupture. The aim of this work is to identify those geometric indices that have a high correlation with AAA wall stress in the population of patients who received an emergent repair of their aneurysm. In-house segmentation and meshing algorithms were used to model 75 AAAs followed by estimation of the spatially distributed wall stress by performing finite element analysis. Fifty-two shape and size geometric indices were calculated for the same models using MATLAB scripting. Hypotheses testing were carried out to identify the indices significantly correlated with wall stress by constructing a Pearson's correlation coefficient matrix. The analyses revealed that 12 indices displayed high correlation with the wall stress, amongst which wall thickness and curvature-based indices exhibited the highest correlations. Stepwise regression analysis of these correlated indices indicated that wall stress can be predicted by the following 4

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indices with an accuracy of 76%: maximum aneurysm diameter, aneurysm sac length, average wall thickness at the maximum diameter cross-section, and the median of the wall thickness variance. The primary outcome of this work emphasizes the use of global measures of size and wall thickness as geometric surrogates of wall stress for emergently repaired AAAs.

Key terms

finite element modeling; arterial biomechanics; geometric modeling

3. INTRODUCTION

An abdominal aortic aneurysm (AAA) is a major health risk-especially to senior citizens-originating from a loss of structural integrity of the infrarenal aorta, which leads to a balloon-shaped expansion of this artery called an aneurysm. An AAA is defined when the maximum transverse dimension of the abdominal aorta is at least 50% greater than its normal, healthy diameter. The current clinical standard of care for AAA repair is a maximum diameter of 5.5 cm or a growth rate of 1 cm/year, which are evidence-based criteria and not individual predictors of aneurysm rupture risk. Patients with an aneurysm measuring less than 5.5 cm are monitored periodically to assess the need for clinical intervention. If a patient becomes symptomatic or their aneurysm ruptures, an emergent repair is performed. However, this need could be accurately evaluated by biomechanical measures such as wall tension and wall stress, which are strongly dependent on the individual aneurysm geometry.

The current need for interventional treatment of AAAs based only on the maximum transverse diameter has its shortcomings, given that there are aneurysms measuring less than 5.5 cm that do rupture, and aneurysms that have been diagnosed while being larger than 5.5 cm, but had not ruptured. Autopsy analyses conducted by Darling et al.³ showed that nearly 13% of aneurysms measuring less than 5.5 cm ruptured and 60% of aneurysms measuring greater than 5 cm never ruptured, thus raising questions about the use of maximum diameter as the sole predictor of rupture risk. The latter came into practice based on both clinical experience of vascular surgeons treating AAA patients and the physical principles of the Law of Laplace. However, this law was formulated under the assumption of simple cylindrical or spherical geometries with a single radius of curvature, which is evidently not ideal for AAAs. On the contrary, AAAs have complex shapes and exhibit spatial variations in major and minor wall curvatures, essentially negating the assumptions underlying the applicability of the Law of Laplace. AAA rupture risk is also associated with the aneurysm expansion rate. Studies conducted by Lederle et al.⁹ and Brown et al.² have confirmed that ruptured aneurysms had a significantly larger mean expansion rate than unruptured AAAs. However, the use of expansion rates may be limited to aneurysms under surveillance, which can be monitored over an extended period of time.

From a purely biomechanical viewpoint, AAA rupture occurs when the aneurysmal wall stress exceeds its wall strength. It is important to understand the patient-specific AAA wall mechanics that influences the risk of rupture. Biomechanical parameters that can be used to

quantify the wall mechanics such as Peak Wall Stress (PWS), wall strength, rupture potential index, etc., have all been proposed as more accurate predictors of rupture risk compared to maximum diameter. Studies conducted by Fillinger et al.⁵ suggested that PWS was considerably higher in ruptured aneurysms compared to unruptured aneurysms, indicating that PWS can be used to assess rupture risk. This result was corroborated by the findings of Venkatasubramaniam et al.,²⁵ who modeled 27 AAA patients (12 ruptured and 15 unruptured) and found that PWS was considerably higher in ruptured aneurysms than in unruptured ones. Moreover, Khosla and colleagues⁸ performed a meta-analysis of 348 individuals concluding that PWS is greater in symptomatic or ruptured AAA than in asymptomatic intact AAA, even after adjustment for mean systolic blood pressure, which is typically standardized at 120 mmHg. A probabilistic rupture risk index (PRRI) was proposed by Polzer and Gasser¹⁴ to account for the uncertainties in AAA wall thickness and wall strength, and tested in a diameter-matched cohort of 7 ruptured and 7 intact AAAs. The results of the latter study support the use of a probabilistic approach for rupture risk prediction, combined with AAA biomechanical modeling, rather than solely using a deterministic approach. PWS shows a close association with maximum diameter, leading to the notion that PWS may not necessarily serve as a sole predictor of rupture risk, but that other factors such as size and wall strength should also be considered.⁶ To calculate biomechanical parameters such as PWS, scientists rely on computational tools and finite element analysis (FEA) solvers, which are complex, require training to operate, and are dependent on population-averaged constitutive material properties for the AAA wall. Hence, there arises a need to simplify the process and identify other metrics that may have a strong association with the AAA wall mechanics.

Geometric characteristics of aneurysms have been reported to be significant predictors of PWS and expansion rate. Quantification of geometric indices characteristic of the AAA shape are not solely based on aneurysm size, but also on shape, morphology, and wall thickness of the aneurysm. AAA biomechanics and rupture prediction with patient-specific models show that wall stress distributions are highly dependent on the aneurysmal geometry.¹ Complex AAA geometry is characterized by a complex wall stress distribution, as proposed by Sacks et al.¹⁸ Studies conducted by Tang et al.²⁴ showed that the inclusion of geometric indices can help in distinguishing ruptured from unruptured aneurysms. Giannoglou et al.⁷ reported a strong correlation of PWS with the mean and maximum centerline curvatures in AAA models. In addition, infrarenal aortic volume appears to predict growth rate and correlates stronger with an estimated biomechanical rupture risk, according to Lindquist and associates.¹¹ In a recent report by Georgakarakos et al.,⁶ they found a substantial correlation between PWS and tortuosity of AAAs measured along the centerline of the abdominal aorta. Therefore, geometric indices that correlate well with biomechanical parameters could be considered surrogates of wall mechanics for the accurate assessment of rupture risk.

The purpose of the present work is to perform quantitative wall mechanics and geometric analyses for patient-specific AAAs that were emergently repaired, to assess whether a substantial correlation exists between precise geometric indices and wall stress. Such correlation is foreseen as the foundation for a geometry-based computational tool for future assessment of AAA rupture risk on an individual basis, thereby contributing to the clinical

management of aneurysmal disease. To this end, the significance of this work is in the derivation of geometric measures that, when highly correlated to wall stress, can be used as surrogates of the most importance biomechanical determinant of rupture risk.

4. MATERIALS AND METHODS

4.1 3D image reconstruction

Following approval of a human subjects research protocol by the corresponding Institutional Review Committees, the abdominal computed tomography angiography (CTA) scans of 75 patients who underwent emergent repair of their AAA were obtained retrospectively from existing databases in the Departments of Radiology at Allegheny General Hospital (Pittsburgh, PA) and Northwestern Memorial Hospital (Chicago, IL). These images corresponded to the last surveillance follow up of the patients, which occurred no later than 1 month prior to the emergent intervention. An in-house MATLAB (Mathworks Inc., Natick, MA) code called AAASc (v1.0.3, The University of Texas at San Antonio, San Antonio, TX) was used to segment the lumen and wall of the abdominal aorta. The Standard Digital Imaging and Communications in Medicine (DICOM) images are input into the MATLAB code, which utilizes the contrast gradient of the image to identify the lumen, inner wall and outer wall contours, as there is significant difference in the intensity of the lumen compared to that of the surrounding soft tissues. Image segmentation is initiated when the user selects a seed point inside the lumen and the algorithm proceeds to identify the lumen boundary by detecting differential gradients for each image in the data set.²⁰ The automatic lumen segmentation algorithm is repeated for every subsequent slice. The outer wall segmentation is also performed automatically by generating a possible set of contours from which the user chooses the best to represent the outer wall boundary.²¹ Inner wall segmentation is challenging as it is limited by the inability to differentiate the vessel wall from the intraluminal thrombus (ILT) present in the AAA sac based on intensity differences. The algorithm uses a neural network to extract the inner wall boundary, where the user selects points in the wall and points not belonging to the wall to train the network and build the inner wall boundary based on intensity and image texture features.¹² Finally, AAASc generates a point cloud representing the AAA surface and volumetric binary masks that represent the three regions of interest of the AAA (namely, the lumen, ILT and wall). The protocol for image segmentation of contrast-enhanced abdominal CT images has been applied previously by our research group for generating patient-specific AAA models.^{10,22,23} The masks are used to generate surface and volume meshes using the in-house meshing code AAAMesh.¹⁷

4.2 Biomechanical characterization using FEA

AAAMesh generates a NASTRAN formatted mesh file, which is imported into the FEA solver ADINA (Adina R&D Inc., Watertown, MA) to run a structural analysis simulation. The FEA meshes consist of quadratic (27-noded) hexahedral elements across the AAA wall. A prior mesh sensitivity analysis indicated that meshes in the range of 100,000 to 300,000 elements with an aspect ratio of nearly 1.0 and two elements clustered across the wall thickness were sufficient to achieve convergence of the first principal stress distribution when the AAA is pressurized to the normal peak systolic pressure.¹⁷ The FEA simulations

were run subjecting the AAA to an intraluminal pressure of 120 mmHg in a minimum of 24 time steps. Fixity conditions were applied to the proximal and distal ends of the abdominal aorta to simulate anatomical tethering and prevent displacement and rotation at these locations. The AAA wall material properties are represented by a Mooney-Rivlin constitutive model derived from the work of Raghavan and Vorp,¹⁶ who performed uniaxial tensile tests of tissue specimens obtained from 69 AAA patients. The strain energy function of such a model is proportional to the first invariant of the left Cauchy-Green deformation tensor, as indicated by Eq. (1),

$$W = c_1(I_1 - 3) + c_2(I_1 - 3)^2 \quad (1)$$

where W is the strain energy density,

I_1 is the first invariant of the left Cauchy-Green tensor, and

c_1 and c_2 are material parameters evaluated experimentally.

This second order Mooney-Rivlin material model, with $c_1 = 17.4 \text{ N/cm}^2$ and $c_2 = 188.1 \text{ N/cm}^2$, was implemented with nearly incompressible material properties (Poisson's ratio $\nu = 0.499$). The outcome of the simulations was used to assess the first principal stress (PS1) distributions using the post-processing software EnSight (Computational Engineering International, Apex, NC). The spatially averaged PS1 was recorded as the biomechanical parameter representative of the AAA wall mechanics for subsequent data analyses. The rationale for spatially averaging PS1 rather than using PWS as the biomechanical parameter was based on the fact that many of the spatially distributed geometric indices are also averaged over the AAA wall surface. In addition, there are several other geometric indices (as described in the Supplementary Material) that provide a global assessment of the AAA geometry rather than a maximum located at a single location on the aneurysm.

4.3 AAA geometry quantification

In-house MATLAB codes previously developed by Shum et al.²² were used to calculate 52 patient-specific geometric indices that quantify the shape, size, curvature, and wall thickness of each aneurysm. The complete mathematical formulation of each of these metrics is described in the Supplementary Material. The point clouds generated from the image segmentation process were used to calculate the 1D and 2D indices, while the 3D indices are quantified from the surface and volume meshes. The biquintic Hermite finite element method (BQFE) was used to evaluate the curvature-based indices, as described by Lee et al.¹⁰ This method utilizes a high order interpolation scheme to estimate the global curvature indices derived from local curvature distributions. BQFE discretizes the aneurysm outer wall into 12 elements as opposed to the traditional method of biquadratic surface patching (BSP). Surfaces are fit to each of the elements, from which the local principal curvatures k_1 and k_2 are computed using Eqs. (2) and (3),

$$k_1 = a + c + \sqrt{(a - c)^2 + 4b^2} \quad (2)$$

$$k_2 = a + c - \sqrt{(a - c)^2 + 4b^2}, \quad (3)$$

where a , b , and c are best-fit constants determined for each surface node. The ten global curvature indices, described in the Supplementary Material, are then derived and defined for each AAA model: summation of Gaussian and Mean curvatures (KG , KM), area-averaged Gaussian, Mean, first principal and second principal curvatures (GAA , MLN , $K1AA$, $K2AA$), and the L2-norm of the above mentioned curvatures (GLN , MLN , $K1LN$, $K2LN$). Figure 1 provides a graphical representation of the protocol involved in the generation of meshes and the quantification of wall stress and geometric indices.

4.4 Data analysis

With the goal of identifying the geometric indices that have substantial correlation with wall stress, we carried out a series of test of hypotheses. Specifically, for each $j = 1, \dots, m = 52$ we tested the null hypothesis $H_0^{(j)}: \rho_j = 0$ against the alternative hypothesis $H_a^{(j)}: \rho_j \neq 0$ where ρ_j is the population correlation coefficient between the j^{th} geometric index and wall stress. The test rejects $H_0^{(j)}$ for large values of $|T_j|$, where

$$T_j = \frac{r_j \sqrt{n-2}}{\sqrt{1-r_j^2}}, \text{ for which } n \text{ is the sample size, and} \quad (4)$$

$$r_j = \frac{\sum_{i=1}^n (x_{ij} - \bar{x}_j)(y_i - \bar{y})}{(\sum_{i=1}^n (x_{ij} - \bar{x}_j)^2 \cdot \sum_{i=1}^n (y_i - \bar{y})^2)^{1/2}} \quad (5)$$

is the sample (Pearson's) correlation coefficient between the j^{th} geometric index and wall stress; x_{ij} is the value of the j^{th} geometric index from the i^{th} patient; $\bar{x}_j = \frac{1}{n} \sum_{i=1}^n x_{ij}$; y_i is the spatially averaged wall stress for the i^{th} patient; and $\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i$. The p-values of these tests are computed from the fact that, under $H_0^{(j)}$, T_j has an approximate t -distribution with $n - 2$ degrees of freedom.²⁶ A geometric index may be identified as having a substantial correlation with wall stress if the p-value of its corresponding test is smaller than a chosen level of significance.

Testing each individual hypothesis using the traditional level of significance $\alpha = 0.05$ would not be adequate because of the so-called multiple testing problem.¹⁹ Doing so results in a test with an overall type-I error, which implies a rejection of the null hypothesis while it is true. To correct for this, we use the Bonferroni correction, which consists of performing each individual test with the nominal significance level $\alpha^c = \alpha / \text{number of tests}$ where α is the desired significance level of the overall test. This reduces the probability of making a type-I

error. In this work, $\alpha^c = 0.05/52 = 0.00096$; therefore, when the geometric indices are tested for correlation with wall stress and return a p-value smaller than 0.00096, they are considered to have a substantial correlation with wall stress.

The sequence of aforementioned tests allow for the identification of the geometric indices that are substantially correlated with wall stress, but will not account for strong associations that may be present between some of the geometric indices. To remove redundancies in the information that geometric indices may have about wall stress, we carried out a stepwise regression analyses²⁶ to further reduce the number of selected indices. These result in the identification of a reduced set of geometric indices that are substantially correlated with wall stress and also provide a preliminary model to predict the latter from the former.

5. RESULTS

5.1 Wall mechanics

The results of the FEA simulations yielded the spatially averaged PS1 with a mean = $29.3 \pm 10.8 \text{ N/cm}^2$ and a maximum = 55.1 N/cm^2 among the 75 AAAs. In addition, the average maximum diameter among the 75 AAAs was $6.9 \pm 1.7 \text{ cm}$ with the largest aneurysm having a maximum diameter of 11.0 cm. Figure 2 illustrates the spatial distribution of PS1 over the wall of a representative aneurysm. We note that biomechanical and geometric data derived from one of the AAA models were excluded from the statistical analyses described in section 4.4. The rationale for this is that the wall stress for this model was observed to be an outlier relative to the aforementioned range; hence, the association of wall stress and geometric indices was based on a sample size of $n = 74$ patient-specific AAAs.

5.2 Association between spatially averaged wall stress and geometric indices

Pearson's correlation coefficients were calculated for the spatially averaged PS1 with respect to each of the geometric indices in the sample of AAAs. Histograms were used to assess the degree of symmetry in the distribution of wall thickness indices (as defined in the Supplementary Material), e.g. average wall thickness, median of the wall thickness, mode of the wall thickness, etc. In addition, as demonstrated in Fig. 3, the linear fit of the relationships between any two of these indices closely passes through the origin. Therefore, in building the correlation matrix of geometric indices and subsequent hypothesis testing, the median and mode of the wall thickness were not included, reducing the list of indices (from an initial 54) to 52. Similarly, the other wall thickness related indices (e.g., the minimum, maximum, mean, mode, and median of the wall thickness variance) were also analyzed by means of assessing their degree of symmetry, but it was found that the linear fits of their relationships did not pass through the origin. Hence, these indices were considered to have potential correlations with wall stress and included in the statistical analysis.

Average wall thickness ($t_{w,ave}$) and average wall thickness at D_{max} ($t_{w,Dmax}$) were highly correlated with wall stress as evident from their respective p-values being lower than the corrected level of significance after applying Bonferroni correction ($\alpha_c = 0.00096$). Table 1 lists the twelve geometric that were found to have a substantial association with wall stress, as well as their corresponding correlation coefficients and p-values. The Pearson's

correlation coefficients and p-values for the relationships of wall stress with all 52 geometric indices can be found in Table S1 in the Supplementary Material. The identified geometric indices that showed positive correlation with the spatially averaged PS1 were: 1D size-indices maximum diameter (D_{max}), AAA length (L), sac length (L_{sac}), and bulge height (H_b), 3D size indices vessel surface area (S) and vessel volume (V). The geometric indices that showed negative correlation with the spatially averaged PS1 were average wall thickness ($t_{w,ave}$), average wall thickness at D_{max} ($t_{w,Dmax}$), mean wall thickness variance ($t_{w,meanVar}$), and median wall thickness variance ($t_{w,MedianVar}$). Amongst the curvature indices, area averaged mean curvature (MAA) and area averaged major principal curvature ($K1AA$) were significantly correlated with wall stress. The relationships between wall stress and the significantly correlated geometric indices are illustrated in Fig. S1 in the Supplementary Material.

5.3 Stepwise regression analysis

A stepwise regression analysis was performed starting from the 12 geometric indices identified in Table 1. It resulted in the smaller number of geometric indices listed in Table 2, with coefficients and standard errors also listed there. The coefficient of determination for this model is 0.76, so the four geometric indices that were ultimately selected explain 76% of the variability of wall stress.

6. DISCUSSION

In this work we attempt to find if an underlying relationship exists between specific geometry measures and the spatially averaged first principal stress that characterize quantitatively emergently repaired AAAs. The clinical images representative of these emergent scenarios were acquired within 1 month prior to the intervention and are inclusive of both ruptured and symptomatic AAA. If such relationships exist, one can envision the highly correlated geometric indices to be reliable surrogates of AAA wall mechanics for emergently repaired aneurysms, which in turn can be used for rupture risk assessment in the clinic as part of a non-FEA modeling approach.

For the patient cohort, the largest spatially averaged first principal stress was 55.13 N/cm² while the largest maximum diameter was 10.98 cm; evidently large aneurysms subject to high average mechanical stresses. This led to 6 of the 12 highly correlated indices with wall stress being size-related geometric indices. Among the geometric indices that exhibited high correlations with wall stress were wall thickness type indices. The average wall thickness and average wall thickness at D_{max} bore the highest correlations with the wall stress, followed by the mean and median variances in the wall thickness. This underscores the importance of accurately estimating individual AAA wall thickness distributions from clinical images. In an autopsy study conducted by Raghavan et al.¹⁵ it was revealed that all aneurysms had a significant reduction in wall thickness near the site of rupture. Using a laser micrometer, Di Martino and colleagues⁴ measured wall thickness of AAA specimens that were freshly excised from patients who underwent surgical repair. They found a significant difference in the wall thickness of ruptured (3.6 ± 0.3 mm) vs. electively repaired (2.5 ± 0.1 mm) AAA. In a separate study, Mower et al.¹³ demonstrated that wall thickness represents a

major parameter influencing wall stress distribution compared to maximum aneurysm diameter alone.

The area averaged mean curvature and area averaged major principal curvature were also highly correlated with wall stress. Shape and curvature based indices have been identified as predictors of rupture risk, due to the high correlations obtained between the mean and maximum centerline curvatures with PWS, as reported by Giannoglou et al.⁷ Therefore, the outcome of the present study appears to indicate that wall thickness and surface curvature based geometric indices are reliable predictors of wall stress in addition to AAA size.

The stepwise regression analysis further reduced the number of geometric indices by eliminating redundancy in their predictability of wall stress. Such analysis suggests that maximum aneurysm diameter (D_{max}), AAA sac length (L), average wall thickness at D_{max} ($t_{w,D_{max}}$), and the median of the wall thickness variance ($t_{w,MedianVar}$) can be used to predict the spatially averaged wall stress with an accuracy of 76%. We infer from this outcome that the two size- and two wall thickness-related indices may play the role of reliable surrogates of wall stress for emergently repaired AAAs. As maximum diameter and sac length were the only size-related indices in the regression model, we interpret that the aspect ratio of an aneurysm (width and length) is sufficient to quantify its size and predict wall stress when combined with wall thickness. To assess the reliability of this regression model, the actual spatially averaged wall stress is shown as a function of the estimated spatially averaged wall stress in Fig. 4. The linear fit of the relationship closely passes through the origin and results in a mean error of 3.9%, indicating the suitability of the stepwise regression model in predicting the actual wall stress resulting from the FEA simulations. Since the clinically relevant maximum diameter was one of the four indices found as the outcome of the regression analysis, the predictability of wall stress using D_{max} alone was examined and is represented graphically in Fig. 5. The accuracy of using maximum diameter as the sole predictor of spatially averaged wall stress was 23%. We infer that the three additional geometric indices [AAA sac length (L), average wall thickness at D_{max} ($t_{w,D_{max}}$), and the median of the wall thickness variance ($t_{w,MedianVar}$)] results in the improved accuracy (76%) in predicting wall stress based on all four geometric surrogates.

The adjusted significance level used in the joint testing of the significance of the 52 possible correlations between geometric indices and wall stress was based on the Bonferroni correction. This adjustment could be overly conservative, leading to a potentially high rate of false negatives; this is considered a limitation of the statistical methodology applied for data analysis. Moreover, the zero-pressure state of stress and residual stresses of the AAA models were not calculated as part of the FEA modeling approach, which are also limitations of the study. The justification for this is that obtaining modified AAA finite element meshes as a result of estimating the zero-pressure geometries would have led to aneurysm shapes different than those from which the geometric indices were calculated.

Patient-specific models generated from CTA images of 75 emergently repaired AAAs were used to calculate the spatially averaged first principal stress and 52 geometric indices to quantify the biomechanics and geometry of the aneurysms, respectively. An assessment of the potential correlations between biomechanics and geometry using tests of hypotheses

revealed 12 geometric indices that are highly correlated with wall stress. Of these, four wall thickness indices (the average wall thickness, the average wall thickness at the maximum diameter, the mean of the wall thickness variance, and the median of the wall thickness variance) and two curvature based indices (area averaged mean curvature and area averaged major principal curvature) had the largest correlations with wall stress. Furthermore, stepwise regression analysis of the 12 highly correlated indices revealed that the spatially averaged wall stress can be reliably predicted using only 4 of these indices (maximum diameter, AAA sac length, average wall thickness at the maximum diameter, and the median of the wall thickness variance), with an accuracy of 76%. Therefore, the significance of this work is based on the finding that global measures of wall thickness and size can be used as the geometric surrogates of wall stress for emergently repaired AAAs.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Schematic of the protocol followed in segmenting (AAVasc), meshing (AAAMesh), and evaluating the wall stress and geometric indices.

Figure 2.
Exemplary spatial distribution of PS1 — first principal stress [N/cm^2].

(a)

(b)

Figure 3. Relationships of (a) mode vs. average wall thickness, (b) median vs. average wall thickness and (c) median vs. mode of the wall thickness, demonstrating the existence of nearly symmetric and linear distributions of these geometric indices.

Figure 4.

Representation of the *actual* spatially averaged first principal stress (obtained from the FE model) vs. the *estimated* spatially averaged first principal stress (obtained from the regressed geometric indices) [in N/cm²]. The former is the direct output from the FEA simulations while the latter is found from the stepwise regression model based on the four geometric indices listed in Table 2. The mean error of the regression model in predicting the actual wall stress was 3.9% with a standard deviation of 20.3 N/cm².

Figure 5.

Representation of spatially averaged first principal stress (PS1) vs. maximum diameter (D_{max}) using the correlation coefficient of the stepwise regression analysis. Maximum diameter alone is able to predict the spatially averaged wall stress with an accuracy of 22.7%.

Table 1

Pearson's correlation coefficients and p-values for the relationships of spatially averaged wall stress with each of the significantly correlated geometric indices.

Geometric Index	Correlation coefficient (r)	p-value
D_{max} (mm)	0.48	0.000018
L (mm)	0.53	<< 0.00096
L_{sac} (mm)	0.49	<< 0.00096
H_b (mm)	0.38	0.00086
V (cm ³)	0.47	<< 0.00096
S (cm ²)	0.52	<< 0.00096
$t_{w,ave}$ (mm)	-0.63	<< 0.00096
$t_{w,Dmax}$ (mm)	-0.62	<< 0.00096
$t_{w,meanVar}$ (mm)	-0.45	<< 0.00096
$t_{w,MedianVar}$ (mm)	-0.48	<< 0.00096
MAA (mm ⁻¹)	-0.61	<< 0.00096
$KIAA$ (mm ⁻¹)	-0.44	0.00011

Table 2

Coefficients of the stepwise regression predictive model with their respective standard errors for the 4 significantly correlated geometric indices with spatially averaged wall stress. The coefficient of determination of this model was 0.76.

Geometric Index	Coefficient of linear regression	Standard error
$D_{max} (mm)$	0.29	0.037
$L (mm)$	0.068	0.012
$t_{w,Dmax} (mm)$	-7.68	1.23
$t_{w,MedianVar} (mm)$	-17.55	9.53