On the Derivation of Geometric Surrogates of Abdominal Aortic Aneurysm Wall Stress

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Introduction

- Abdominal aortic aneurysm (AAA) is a vascular disease caused by the weakening of the aortic wall leading to the enlargement of the infrarenal aorta by more than 50%.
- Typically, an aortic diameter of 3 cm or greater is considered aneurysmal and a diameter greater than 5.0 cm is considered at high rupture risk. However, small AAA are also prone to rupture, an event that carries a mortality rate of 80%.
- In contrast to the use of maximum diameter to assess rupture risk, alternative strategies such as a biomechanical based rupture risk assessment have been proposed [1-3].
- An estimation of wall stress requires complex finite element modeling; however, wall stress can also be predicted using geometric surrogates.
- In this work, we identify geometric markers that correlate strongly with wall stress using a cohort of 160 patient-specific AAA models derived from 62 symptomatic/ruptured and 98 asymptomatic/unruptured AAA.

Methodology

CT Images: The abdominal computed tomography angiography (CTA) scans of 160 patients who were diagnosed with an AAA were obtained from an existing database in the Department of Radiology at Allegheny General Hospital (Pittsburgh, PA).

Point Cloud and Binary Mask: For each AAA, a point cloud was created with the three segmented boundaries (lumen, inner wall, and outer wall), which was used to create volumetric binary masks representing the three regions of interest (lumen, wall, and thrombus) [1].

Volume Mesh: Volumetric meshes were generated from the masks using the in-house meshing code AAAMesh.

Finite Element Analysis: Using the aforementioned volume meshes, finite element analysis (FEA) was performed with ADINA (Adina R&D Inc., Watertown, MA). A Mooney-Rivlin constitutive model [2] was used to represent the AAA wall material properties, while the AAA sac was subject to an intraluminal pressure of 120 mmHg in at least 24 time steps.

Biomechanical Parameters: The results of the simulations were post-processed and visualized using Ansys EnSight (Ansys Inc., Canonsburg, PA) to generate the first principal stress distributions, from which three biomechanical parameters (peak wall stress: PWS, 99th percentile wall stress: 99thWS, and spatially averaged wall stress: SAWS) were computed.

Screening: For both groups (ruptured and unruptured AAA), an initial screening of variables was conducted using stepwise regression. This was done to remove geometric markers that do not contribute toward the prediction of the biomechanical parameters.

Stepwise Regression: The resulting geometric markers with a correlation coefficient greater or equal to 0.3 and less or equal to -0.3 (i.e. markers that exhibit a moderate correlation with the biomechanical parameters) were used for subsequent stepwise regression analysis to find the most accurate geometric surrogates.

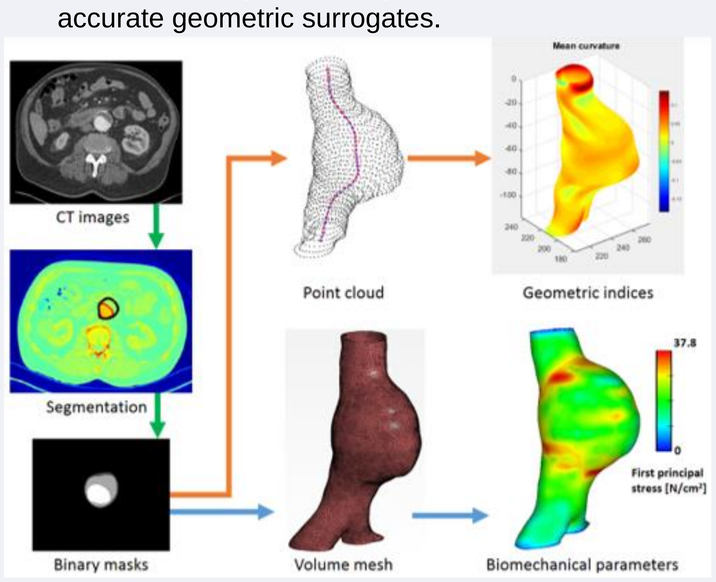

Fig. 1: Protocol followed for segmenting (AAAVasc), meshing (AAAMesh), and calculating geometric indices. Meshes are exported to ADINA for finite element analysis to compute biomechanical stresses. [1]

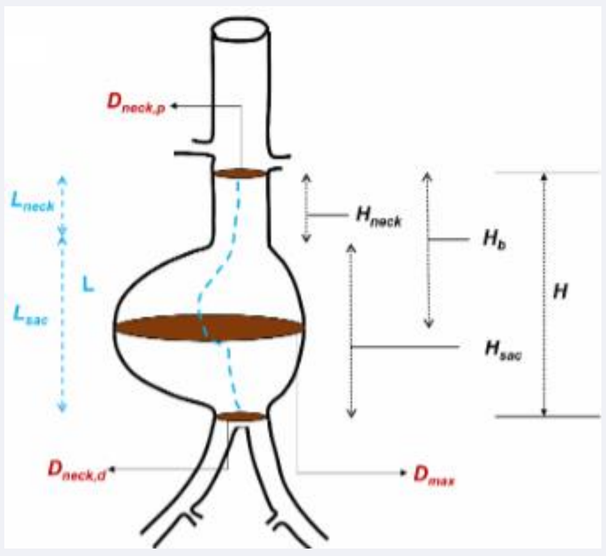

Fig. 2: Schematic of calculation of one-dimensional geometric indices (1D).

Results

Table 1: ***Maximum and mean PWS, SAWS, and 99thWS for the unruptured and ruptured AAA groups.***

Biomechanical Parameter	Unruptured		Ruptured	
	Maximum	Mean	Maximum	Mean
PWS	290.6	97.5 ± 43.4	339.0	128.2 ± 53.2
99thWS	112.0	50.1 ± 16.7	98.6	56.0 ± 29.3
SAWS	46.3	22.0 ± 7.5	52.6	29.3 ± 10.5

The first principal stress distributions for two exemplary AAA models are shown in Figure 3. The mean and maximum PWS, SAWS and 99thWS are shown in Table 1.

- The maximum and mean PWS of the ruptured AAA group were greater than the maximum and mean PWS of the unruptured AAA groups.
- The maximum 99thWS of the unruptured AAA was higher than for the ruptured AAA, but the mean 99thWS of the ruptured AAA was higher than for the unruptured AAA.
- The maximum and mean SAWS for the ruptured AAA was higher than the SAWS for the unruptured AAA.
- The outcome of the stepwise regression analysis is shown in Table 2, along with the corresponding correlation coefficients (r) and p-values.

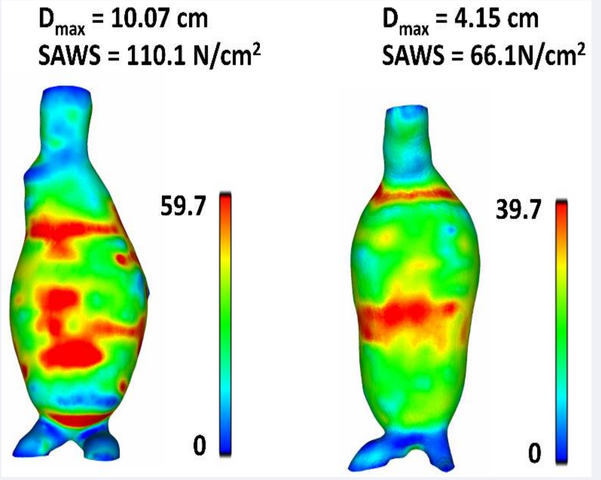

Fig. 3: First principal stress map for two exemplary AAA models with (A) large and (B) small maximum diameter (D_{max}). D_{max} and SAWS for each model are also indicated (note: stress maps were not created with the same length scale).

Table 2: Geometric surrogates of SAWS with their p-values and correlation coefficients, for the unruptured and ruptured AAA groups.

Biomechanical Parameter	Unruptured		Ruptured	
	p-value	r	p-value	r
TH_{median}	2.77e-08	-0.33	2.77e-08	-0.55
S	1.05e-08	0.67	1.05e-08	0.52
L	4.12e-05	0.40	n.s.	-
THD_{max}	6.77e-09	-0.39	n.s.	-
$D_{neck,d}$	n.s.	-	1.02e-02	0.31
TH_{minvar}	n.s.	-	1.40e-03	-0.33
TT_{max}	n.s.	-	1.10e-05	0.40

- The stepwise regression analysis for the unruptured AAA group had a goodness of fit of 69%, while the ruptured AAA group exhibited a goodness of fit of 65%.
- The outcome of the stepwise regression for the ruptured and unruptured AAA models revealed that wall thickness is an important predictor of SAWS.
  - Three of the five ruptured surrogates were thickness related, with two of them based on wall thickness and the other on thrombus thickness.
  - Notably, two of the four unruptured surrogates were wall thickness related.
- The surrogates of SAWS common to both AAA groups were surface area and the median of wall thickness. The surface area was found to be positively correlated to SAWS for both AAA groups while the median of wall thickness was found to be negatively correlated to SAWS for both groups.
- The surrogate with the highest predictive power for the ruptured AAA SAWS was TH_{median} (r = -0.55), while for the unruptured AAA SAWS, S had the highest predictive power (r = 0.67).

Acknowledgments

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