ABDOMINAL AORTIC ANEURYSM RUPTURE RISK ASSESSMENT EXPLOITING DYNAMIC (4D) CT BASED WALL MOTION DATA AND FINITE ELEMENT ANALYSIS

Eleni Metaxa,1 Vasileios Vavourakis,1 Nikolaos Kontopodis,1,2 Konstantinos Pagonidis,2 Christos V. Ioannou,2 Yannis Papaharilaou1

(1) Institute of Applied and Computational Mathematics
Foundation for Research and Technology–Hellas
Heraklion, Crete, 71110, Greece

(2) Medical School
University of Crete
Heraklion, Crete, 71003, Greece

INTRODUCTION
Abdominal aortic aneurysm (AAA) disease is primarily a degenerative process, where rupture occurs when stress exerted on the aortic wall exceeds its failure strength. Therefore, evaluating the wall stress distribution, along with its material properties, is essential for a biomechanically sound rupture risk estimation.

Previous studies have shown that AAA wall is stiffer than normal aortic wall.1 However, an increase in distensibility has been suggested to associate with a higher rupture risk profile.2,3 We therefore postulate that the relative distensibility of the AAA wall as compared to the upper healthy abdominal aortic wall, would provide insight in predicting rupture risk.

The purpose of the study was twofold: a) to measure the distribution of wall and intraluminal thrombus (ILT) distensibility in vivo along the abdominal aorta and AAA utilizing ECG-gated 4D CT wall motion data, in order to detect changes that potentially accompany AAA formation and evolution, and b) to investigate whether this information can be exploited to improve computational models used in AAA wall stress analysis.

MATERIALS AND METHODS
CT scan Acquisition
Abdominal aorta of 12 patients with known AAA was scanned with a 128 Multi-Detector ECG-gated CT (Siemens Medical Solutions). The time series at peak systole and end diastole were obtained.

Image post processing
Segmentation and 3D surface reconstruction of aortic lumen at systole and diastole, as well as external wall during diastole was performed manually with the ITK-SNAP. After mild smoothing of the surfaces, the centerline of the lumen at systole was extracted, and normal cross-sections 1 mm apart along the centerline were obtained.

Aortic distensibility evaluation
The relative area change (RAC) between systole and diastole was calculated for each cross-section for both wall and lumen regions with reference to their cross-sectional area at diastole. Assuming ILT to be incompressible, the area change of the lumen is used to approximate that of the wall region, thus:

\[ \text{RAC}_{\text{wall}} = \frac{W_s - W_d}{W_s} = \frac{L_s - L_d}{W_d}, \text{ and } \text{RAC}_{\text{lumen}} = \frac{L_s - L_d}{L_d} \]

where \( W \): wall area, \( L \): lumen area, \( s \): systole, and \( d \): diastole

Assuming that the lower abdominal aorta is subject to the same pulse pressure, recordings of RAC provide a map of aortic distensibility along the healthy and aneurysmal regions. Changes of AAA volume between systole and diastole were also recorded. Furthermore, the normalized distensibility (\( D_{\text{norm}} \)), defined as the ratio of distensibility between AAA and normal aorta, provides a measure of the degeneration process with reference to the upper healthy aortic wall

\[ D_{\text{norm}} = \frac{\Delta V_{\text{lumen}}}{V_s \cdot \Delta P} = \frac{\Delta V_{\text{lumen}}}{V_s \cdot \Delta P} = \frac{\Delta V_{\text{wall}}}{V_s \cdot \Delta P} \]

AAA Wall \( D_{\text{norm}} \) and AAA Lumen \( D_{\text{norm}} \) were calculated based on the volumes enclosed by wall and lumen boundaries respectively. These parameters are not sensitive to pressure pulse measurement errors.

Statistical analysis
Linear correlations between AAA Wall \( D_{\text{norm}} \) or AAA Lumen \( D_{\text{norm}} \) with maximum AAA diameter or mean ILT area calculated on the cross section were performed for all cases with the coefficient of determination \( R^2 \) providing a measure of their correlation.
Finite element analysis

For five out of the 12 patients, the aortic pulse pressure produced deformation was estimated computationally using as input data the diastolic aortic geometry and the diastolic and systolic pressure. A nonlinear inverse formulation was implemented in the FEA to recover the zero-pressure state configuration of the artery which significantly improves wall displacement accuracy of FEA.3 The 3D mesh was generated using ANSYS ICEM CFD, and an in house developed FEA solver,3 based on the open-source C++ libMesh library, was used. A neo-Hookean hyperelastic material model was adopted for the wall and ILT, with the following strain-energy functions respectively:

\[ W = a(I - 3) + \beta(I - 3)^{\frac{3}{2}}(\ln J)^2 \]

\[ W = c_1((I - 3) + c_2((I - 3)^{\frac{3}{2}}(\ln J)^2 \]

where \( a = 0.174 \) MPa and \( \beta = 1.88 \) MPa, \( c_1, c_2 = 0.026 \) MPa, \( c \) are material parameters, \( I, II \) are the first and second invariants of the Left Cauchy-Green tensor \( \mathbf{C} \), \( J^2 = \text{det}\mathbf{C} \), and \( k = 10^7 \) MPa a bulk modulus used as a volumetric penalty parameter for enforcing the quasi-incompressibility constraint. Two of the five cases included ILT allowing the investigation of its effect on AAA wall deformation.

RESULTS

Distensibility distribution along the aorta from 4D CT data

![Graph of RACwall and RAClumen](image)

Figure 1 Graph of RACwall (blue line) and RAClumen (red line) for a representative case, with distance along the centerline (start point above the renal arteries and end point at the aortic bifurcation apex). Maximum diameter (black, continuous line), as well as ILT area (green, dotted line) are shown.

For all cases, a marked reduction of aneurismal RACwall was found when compared to that of normal vessel. A representative example (Case #2) is shown in Fig. 1, where the normal upper infra-renal aorta has higher values of RACwall compared to the aneurismal wall region, (Diameter>30 mm). RAClumen had the same values with RACwall at the normal aorta but presented a wide variability in the aneurysm region, with some AAs showing segments of high distensibility (Fig. 1), while others were found to be relatively stiff along their entire length. To quantify distensibility of AAA as a whole and compare it to that of normal aorta, we calculated AAA \( D_{\text{norm}} \), for both wall and lumen. Values for AAA Wall \( D_{\text{norm}} \) varied between 0.99-1.01 with a mean of 0.42 and an interobserver difference of 0.16. No correlation between AAA Wall \( D_{\text{norm}} \) and aneurysm maximum diameter or ILT content, as represented by the mean ILT area of all sections, could be identified. The wall plus ILT composite was in general stiffer (except for 3 cases) than the normal vessel, as indicated by the AAA lumen \( D_{\text{norm}} \) which had a mean value of 0.76 with a range of 0.10-2.22, and an interobserver difference of 0.24. There was a positive correlation between AAA Lumen \( D_{\text{norm}} \) and aneurysm diameter (\( R^2=0.50 \)) as well as average ILT cross-sectional area (\( R^2=0.65 \)).

Comparison of AAA deformation between 4D CT and FEA

The AAA volume change between systole and diastole computed using FEA was larger than that obtained from 4D CT data for all five cases (Table 1). When ILT was excluded in the FEA, the volume change was 7.3% (Case #2) and 3.3% (Case #4) times larger.

Discussion

An important aspect of any computational model based rupture risk assessment is the incorporation of accurate material properties. Although there is currently no technique to non-invasively measure AAA wall material properties in vivo, the distribution of distensibility along the lower abdominal aorta can potentially reveal regions with altered elastic behavior associated with increased rupture risk. Our results show that AAA wall is less distensible than normal aortic wall, irrespective of aneurysm size, indicating that this reduction occurs at the early stage of AAA evolution. If decreased distensibility precedes clinical manifestation of AAA, \( D_{\text{norm}} \) could be a useful marker for the identification of increased risk of AAA development. Furthermore, the wide range of AAA Wall \( D_{\text{norm}} \) values between cases may be indicative of differences in the extent of wall structural degeneration and subsequently in rupture risk. Ongoing prospective studies examine if \( D_{\text{norm}} \) can be a useful adjunct to the diagnosis of risk.

In addition to the clinical value of a rupture risk marker that describes the degeneration state of AAA wall, the potential improvement in wall stress estimation, will benefit model based rupture risk stratification. By comparing wall deformation obtained from 4D CT data with that of FEA it was found that the inclusion of ILT in FEA drastically improves accuracy of computed wall displacement. Additionally, the in vivo deformation in all five cases was found less than that estimated by FEA, indicating a stiffer wall, and suggesting that the mean values of material properties used in FEA cannot always, as expected, accurately represent the actual values. However, differences between CT measured and FEA computed deformations were relatively small which probably translates to a similar influence of this discrepancy to computed wall stress. We are currently using a larger sample to evaluate if this indirect estimation of wall mechanical properties can have a stronger impact on wall stress estimation by fitting the model material parameters through an optimization algorithm.

ACKNOWLEDGMENTS

This work is partially supported by the Action «Supporting Postdoctoral Researchers» of the GSRT of Greece.

REFERENCES

1. Tierney et al., J Endovasc Ther. 2012; 100-114

Table 1 Comparison of AAA volume change between systole and diastole measured from 4D CT data (± interobserver difference) and computed by FEA.