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Biomechanical analyses of the thoracic aorta: Could wall stress and 3D geometry help identify patients at risk of acute aortic dissection?

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SUMMARY

Aortic dissection is an often fatal clinical condition which is challenging to accurately diagnose and if untreated, further progression of the dissection is inevitable. The aim of this study was to biomechanically investigate a cohort of patient-specific thoracic aortas to determine potential factors that may contribute to aortic dissection. Fifty patients were included in the study. Patient-specific finite element analysis was performed to estimate the in vivo wall stresses. Geometric parameters were measured and statistical analysis was used to identify any significant correlations. Ascending aortic diameter, arch radius and tortuosity were all significantly related to wall stresses. Arch type, gender and smoking status had no significance influence on wall stresses. Maximum wall stress was located in the ascending aorta or the aortic arch in the majority of cases (>90%), which coincides with the locations of clinical intimal entry tears in acute Type A dissection. Geometry influences wall stress and regions of elevated wall stresses appear to coincide with the location of acute Type A aortic dissection intimal entry tears. Computational modeling and three dimensional geometric analyses may potentially improve the diagnosis of aortic dissection. However, this work needs to be extended to include a group of known aortic dissection cases to verify any clinically-relevant parameters.

Key Words: *aortic dissection, wall stress, geometry.*

1. INTRODUCTION

Aortic dissection is characterized by the separation of the layers of the aorta, usually the intima-media layers, causing blood to flow within. The flow of blood into this false lumen causes further propagation and dissection of the layers, resulting in a lethal condition. Aortic dissection is currently the most common cause of aortic emergency requiring surgical repair [1]. Incidence rate is approximately 2.9 - 3.5 per 100,000 person-years; however, reports suggest that this may be increasing, most likely due to improvements in medical imaging and an aging population. The condition has a very high mortality rate, with one study reporting that 68% of cases died within 48 hours of hospital admission. This high rate is partly attributed to the failure to accurately recognize aortic dissection. Nevertheless, even when properly diagnosed and treated, the in-hospital mortality is still 25%. Additionally, autopsy reports suggest thoracic aortic dissection and rupture accounts for twice the number of deaths per year as abdominal aortic aneurysm (AAA) rupture, even though AAA incidence rates are much higher. Over recent years, biomechanical modeling has been employed to better understand the role of in vivo stresses acting on the thoracic aortic wall. The aim of this present study is to examine the wall stress and geometry of the thoracic aorta, in a cohort of elderly patients, with the aim of identifying geometric parameters that correlate with wall stress, and thus, which may encourage acute aortic dissection.

2. METHODS

Study Group

Patients were selected from a recent clinical trial (NCT01358513) [2], whereby all cases were > 50 years with no known aortic dissection. Patients had varying levels of aortic valve disease which was not accounted for in this study. Ethical approval was granted by the local research ethics committee and all computed tomography (CT) was performed as part of Dweck et al. [2]. All patients underwent full clinical assessment at baseline which included recording of their blood pressure and routine clinical parameters at the time of imaging.

3D Reconstruction, Mesh and Stress Analysis

CT datasets were imported into Mimics v15 (Materialise, Belgium). Segmentation of the aorta began at the sinotubular junction (STJ) and ended at the diaphragm level of the descending thoracic aorta. The surface of each model was then conservatively smoothed. Each 3D model was then imported into 3-matic v6 (Materialise, Belgium) and as the exact wall thickness cannot be determined from conventional CT, a uniformly thick aortic wall (2.32 mm) was created.

The models were then discretized into 3D 10-node tetrahedral solid stress finite elements and exported for analyses with the non-linear large deformation solver in ABAQUS/Standard (Dassault Systemes, USA). Each model was simulated using three mesh densities, with each mesh size approximately doubling in number. Models were deemed independent of mesh size when the change in the 99th-percentile of peak von Mises wall stress was < 2%. The aortic wall was modeled as a hyperelastic isotropic material using data determined from non-aneurysmal thoracic aortas. Each model was rigidly constrained at the aortic root and the distal region of the descending aorta to simulate tethering to the heart and the abdominal aorta. We also examined the role of aortic root motion. For each analysis, the 99th-percentile of von Mises, circumferential and longitudinal stress was calculated, and the location of each maximum stress recorded. Location of peak stresses were compared to the clinical locations of intimal tearing in Type A aortic dissection [3].

Geometry Measurements

3D models were used to determine several geometric measurements within Mimics. Firstly, the centerline of the each model was created and the total tortuosity measured. The centerline was then divided into two sections using the apex of the aortic arch, with tortuosity of the ascending and descending aorta determined. The arch angle was measured from the right lateral view along the inner surface of the arch. The radius of the arch was measured by inscribing a circle to the inner curvature of the arch centerline and recording the maximum radius. Finally, the best-fit ascending aortic diameter was quantified using the centerline and the outer aortic wall. A schematic of these measurements is shown on an example geometry in Figure 1.

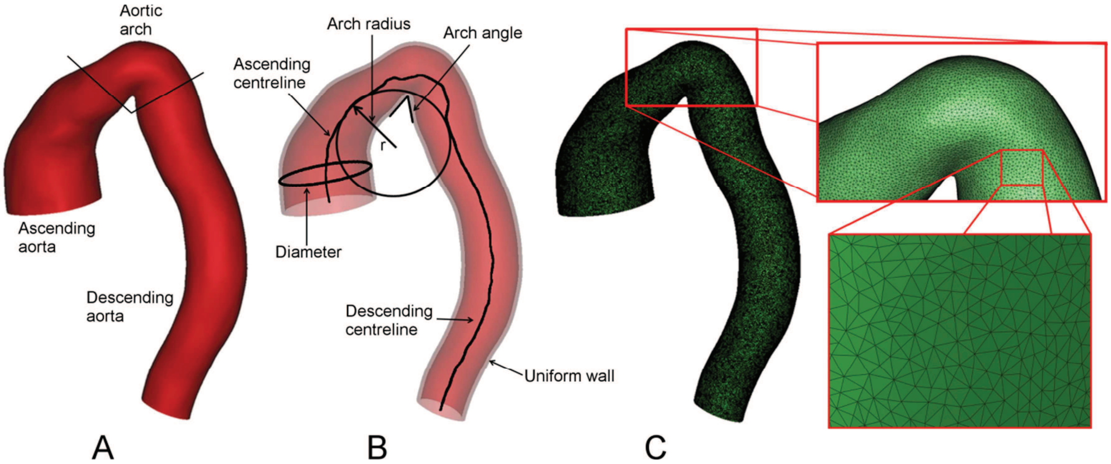

Figure 1: (A) Example 3D reconstruction. (B) Typical measurements for each case. (C) Discretized geometry showing typical mesh-independent element size (inserts).

3. RESULTS

Patient Characteristics and Geometries

The mean age of the cohort was 73.8 ± 8.2 (54 - 90) years, with an even gender distribution (male = 27, female = 23). Mean blood pressure was 146 ± 18 (109 - 193) mmHg and body mass index (BMI) was 26.8 ± 3.7 (19.9 - 40.0). The maximum best-fit ascending aortic diameter was 36.1 ± 4.8 (28.1 - 56.6) mm. Total centerline tortuosity was 0.53 ± 0.06 (0.43 - 0.67), ascending aortic tortuosity was 0.12 ± 0.04 (0.06 - 0.23) and descending aortic tortuosity was 0.15 ± 0.04 (0.07 - 0.27). The mean arch angle was 113 ± 16° (45 - 151°) and arch radius was 46.8 ± 6.3 (34.9 - 62.3) mm. The cohort consisted of 23 Type I and 27 Type II aortic arches.

Wall Stresses and Locations

Mesh size was dependent on diameter ($p<10e^{-5}$) and arch angle ($p<10e^{-6}$). The mean von Mises wall stress was 0.16 ± 0.02 (0.11 - 0.25) MPa, circumferential wall stress was 0.13 ± 0.02 (0.09 - 0.21) MPa and the longitudinal wall stress was 0.11 ± 0.01 (0.08 - 0.16) MPa. The ascending aorta experienced high von Mises, circumferential and longitudinal wall stress, in particular along the inner and outer curvatures. The location of maximum stresses for the entire cohort are presented in Figure 2 and compared to the location of clinical intimal tears in 17 patients detected with 64-slice CT [3]. Peak wall stress was observed in the ascending aorta or aortic arch in the majority of cases (94% of von Mises stress; 90% of circumferential stress; 96% of longitudinal stress).

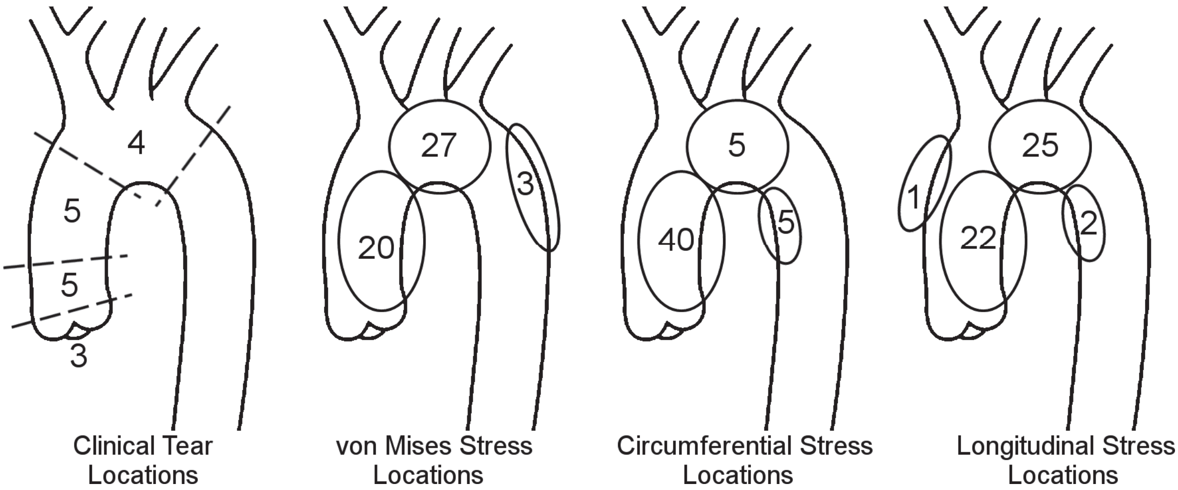

Figure 2: Illustration showing locations of maximum von Mises, circumferential and longitudinal stresses for the entire cohort, compared to the location of clinical intimal entry tears observed in 17 patients [3].

4. CONCLUSIONS

In this cohort of human thoracic aortas, peak wall stresses were found in the ascending aorta and aortic arch, which coincide with regions where the majority (>80%) of intimal entry tears occur in acute aortic dissection. The geometry of the aorta, but not necessarily the arch type (i.e. Type I or II), was observed to be a significant factor in wall stress. Ascending aorta best-fit diameter was the most influential on von Mises ($p<10e^{-7}$), circumferential ($p<10e^{-7}$) and longitudinal ($p<10e^{-7}$) wall stresses. It would appear that the diameter of the ascending aorta is a good indicator of potential pathologies that may develop as a result of elevated thoracic wall stresses. Arch radius also significantly correlated with von Mises ($p<10e^{-6}$), circumferential ($p<10e^{-5}$) and longitudinal ($p<10e^{-5}$) wall stresses. It was found that the total tortuosity of the aortic centerline influenced both von Mises (p=0.044) and circumferential (p=0.045) wall stresses, whereas the tortuosity of the descending aorta correlated with both the von Mises (p=0.011) and longitudinal (p=0.009) wall stresses. Best-fit diameter, arch radius and tortuosity can all be quantified from 3D reconstructions and may be useful clinical parameters in the risk assessment of aortic dissection, and potentially used independent of wall stress analysis. Next, we aim to extend this study to a group of pre and post aortic dissection cases to verify any clinically-relevant parameters. Future studies building on the data presented here may help establish the role of patient-specific modeling as a diagnostic tool in the assessment of aortic dissection.

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