AGE-RELATED CHANGES IN THE BIOMECHANICAL CYCLIC STRAIN OF THE HUMAN THORACIC AORTA

Tina M. Morrison, Ph.D. (1), Gilwoo Choi, M.S. (2), Polina A. Segalova (2),
Christopher K. Zarins, M.D. (3), and Charles A. Taylor, Ph.D. (1)
(1) Bioengineering, and (2) Mechanical Engineering, Stanford University
(3) Department of Surgery, Stanford Medical Center

INTRODUCTION

Large vessels in the vascular system undergo progressive degeneration with aging. The widely accepted theory is the aorta enlarges and stiffens with age and vascular compliance decreases, which increases systolic pressure, decreases diastolic pressure, and greatly affects cardiovascular health and function. Quantifying the dynamics of an aging human aorta yields insight into changes in the vascular compliance and is vital in understanding pathogenesis and progression of disease, such as atherosclerosis and aneurysm formation, along with medical device implantation and design.

Despite many advances in medical imaging and analysis techniques, relatively little is known about the wall dynamics of the thoracic aorta. In this study, we employ simple, yet novel techniques to compute the cyclic deformation of the descending thoracic aorta (DTA) using ECG-gated CT data. Previous studies have reported circumferential strain using an Eulerian frame, which does not detect through-plane motion, but no studies heretofore have implemented a Lagrangian frame, which is 'attached' to the vessel, nor have any quantified longitudinal cyclic deformation. The aim of this study is to **quantify the age-related changes in the biomechanical cyclic strain of the human thoracic aorta**.

METHODS AND MATERIALS

PATIENT POPULATION

- 14 pre-existing ECG-gated CT image data sets
  - each without visible vascular pathology, aneurysms, atherosclerosis, devices, etc.
- 7 young patients: 2 females, 5 males
  - Ages 43 ± 6 years, range 36-51 years
- 7 old patients: 2 females, 5 males
  - Ages 69 ± 9 years, range 57-83 years

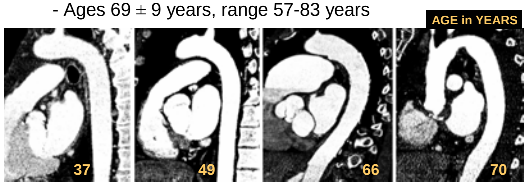
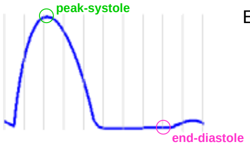


FIGURE 1. Four thoracic aortas (a sub-sample) from the medical archives at the Stanford Medical Center. Note the difference in age and vessel curvature.

ECG-GATED COMPUTED TOMOGRAPHY (CT)

The cardiac-gated CT data sets contain 10 3D-volumes, each representing 1/10th of the cardiac cycle, averaged over time.



Each 3D volume is an average of a 20-30 second breath hold. To ensure accurate measurements of cyclic strain, we analyzed the cardiac frames of peak-systole and end-diastole.

CT IMAGE PROCESSING

1. Created **center-path** lines to represent the thoracic aorta spanning from the left coronary artery (LCA) to distal descending aorta (DTA)
2. Generated 2D threshold segmentations at the ostia of branch vessels, used the **distal location** of the ostium (see Figure 2)
   - Ostia provided a Lagrangian frame because it was "fixed" to the aorta
   - Therefore, we eliminated through-plane motion
3. Calculated luminal cross-sectional area and luminal circumference of the 2D segmentations at each time frame (see Figure 3)

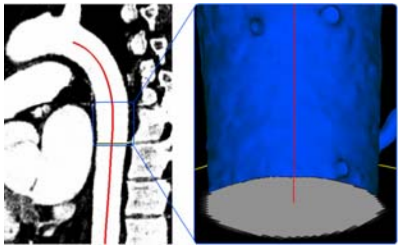


FIGURE 2. The **center-path** of the DTA of a young patient is displayed on the left. The segmentation window is placed at the **distal part of the ostium** shown on the right.

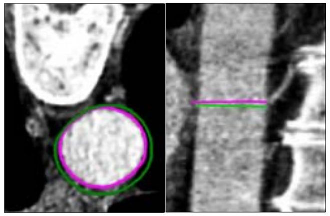


FIGURE 4. Over-lay of the luminal boundaries from **peak-systole** and **end-diastole** in the axial view (left) and in a sagittal view (right).

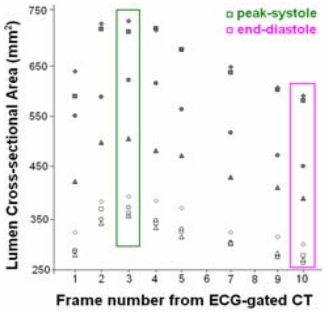


FIGURE 3. The lumen cross-sectional area of 4 proximal and 4 distal segmentations along the descending thoracic aorta (DTA) were computed in 8 of the 10 cardiac frames. The area peaked in frame 3 (**peak-systole**) and its nadir occurred in frame 10 (**end-diastole**).

DEFORMATION METRICS

Age-related changes were quantified along the thoracic aorta. The selected locations are shown in Figure 5

1. **ARCH LENTH**: the center-path arc length from the left coronary artery (LCA) to the left subclavian artery (LSC)
2. **PROXIMAL AND DISTAL DIAMETERS**: luminal circumferences (C) were measured at the first and seventh intercostal arteries (ICA) → $D = C / \pi$
3. CIRCUMFERENTIAL STRAIN: $(C_{sys} - C_{dias}) / C_{dias}$
4. **LONGITUDNAL STRAIN**: $(L_{sys} - L_{dias}) / L_{dias}$, where L is the length of the DTA
5. **RELATIVE MOTION**: 3D Cartesian length from the centroid of the segmentation created at the LCA to the centroid of the segmentation created at the 3rd ICA. NOTE: The statistical p-values were computed from a paired, two-tailed t-Test.

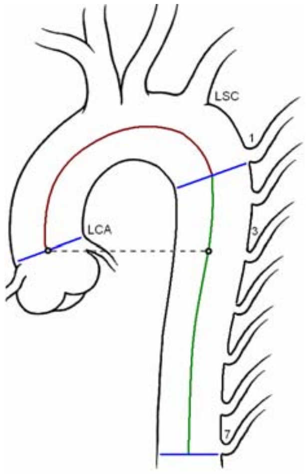


FIGURE 5. Schematic of the human thoracic aorta, where the deformation metrics are colored: **arch length**, **DTA length**, **proximal and distal diameter locations**, and the **relative motion** of the ascending aorta with respect to the DTA. LCA: Left Coronary Artery, LSC: Left Subclavian Artery, DTA: descending thoracic aorta, (1, 3, 7): Intercostal Arteries.

RESULTS

The arch length increased 14% with age from the young (mean age 43 years) to old (mean age 69 years) group. There was a similar increase in the proximal diameter and a 10% increase in the distal diameter. The circumferential cyclic strain in the proximal aorta decreased 74% with age, while in the distal aorta it decreased 64%. The longitudinal cyclic strain decreased with age by 55%, while the relative strain decreased by 68% between the ascending and descending thoracic aorta. Measurements and p-values are listed in Table 1.

Deformation Metrics	Young - 43yrs	Old - 69yrs	p-value
arch length [mm]	133 ± 18	152 ± 10	0.02
proximal diameter [mm]	23.3 ± 1	26.7 ± 4	0.002
distal diameter [mm]	21.6 ± 1	23.6 ± 3	0.006
proximal circumferential strain [%]	9.1 ± 3	3.0 ± 1	0.001
distal circumferential strain [%]	9.0 ± 3	2.1 ± 1	0.002
longitudinal strain [%]	2.1 ± 1	0.9 ± 1	0.03
relative motion [%]	7.1 ± 3	1.9 ± 2	0.01

TABLE 1. Deformation metrics measured from the images of young and old patients.

DISCUSSION

We quantified the longitudinal and circumferential bio-mechanical cyclic strain in young and old patients with no signs of aortic pathology, along with length changes in the arch and diameter changes in the proximal and distal descending thoracic aorta. From this analysis we learned that the aorta not only enlarges in the circumferential direction (≈10-15%), but the aortic arch also lengthens by a similar amount. We assume the lengthening will have minimal affect on devices in the short term. However, it is unclear how this will affect thoracic aortic devices in the long-term. We speculate this could have an adverse affect on stent-graft migration.

We also discovered that the circumferential strain is constant down the length of the aorta. A constant cyclic strain implies volumetric compliance is larger in the proximal than the distal aorta because diameters are statistically larger in the former. The compliance decreases with age even though the diameter of the aorta was statistically larger because the strain was three times smaller in the old group. This affects cardiovascular health and function, and may contribute to the pathogenesis and progression of vascular disease.

CONCLUSION

Age-related changes of the thoracic aorta include a significant increase in length and diameter, and a decrease in longitudinal and circumferential strain. This represents the first quantitative description of *in vivo* longitudinal strain and length changes for the human thoracic aorta and may have significant implications in long-term endo-aortic device stability.

ACKNOWLEDGEMENTS

Research was partially funded by the Dean's Postdoctoral Fellowship (2007)