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CIRCUMFERENTIAL CYCLIC STRAIN IN PATIENTS WITH DESCENDING THORACIC AORTIC ANEURYSMS: IMPLICATIONS FOR ENDOVASCULAR DEVICE DESIGN

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INTRODUCTION

Endovascular graft (EVG) therapy has emerged as a promising alternative to open surgical repair of thoracic aortic aneurysms. However, the long-term durability of thoracic endovascular repair (TEVAR) remains uncertain due to complications such as incomplete aneurysm exclusion (endoleaks), migration, and stent fracture and collapse. These complications could likely be reduced if the biomechanical environment of the thoracic aorta was better understood. Currently, there are three FDA approved EVGs for treatment of descending thoracic aortic aneurysms (DTAA), but the range of bench-top testing mechanisms for these devices are limited.

Despite many advances in medical imaging and analysis techniques, relatively little is known about the wall dynamics of the thoracic aorta, particularly in patients with aneurysms. While one recent study reports diameter change before and after endovascular therapy [1], the data are preliminary and based on an Eulerian approach of a fixed spatial location in the image volume. We have previously described methods for quantifying cyclic strain based on the Lagrangian approach of tracking material points and applied these methods to quantify the circumferential and longitudinal strain of the normal thoracic aorta in young and older subjects [2]. In this study, we utilize this approach to compute cyclic deformation along the descending thoracic aorta (DTA) of patients with DTAA.

METHODS

Imaging Protocol

We selected six cardiac-gated CT data sets of patients with a DTAA from an existing library of scans at the Stanford Medical Center. We compared that group of diseased patients (age 77±3 yrs) to six older patients previously presented [2] (age 65±4 yrs); the ages ranged from 61-82. Two thoracic aortas, one from each group, are displayed in Figure 1. Each 4D-CT data set consisted of ten 3D volumes of the vasculature, each representing 1/10th of the cardiac cycle. We took measurements in the volumes where the aorta had the largest cross-sectional area (peak-systole) and the smallest (end-diastole). Those two frames were used for the subsequent analysis.

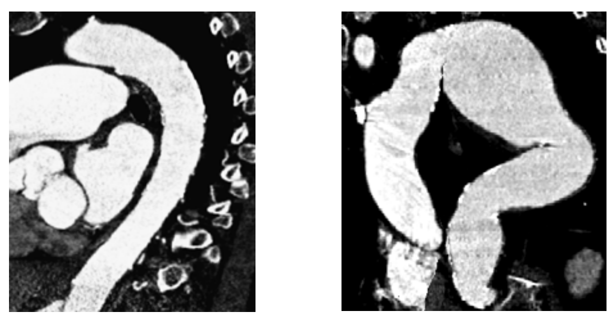

Figure 1. Sagittal view of a thoracic aortas of an older normal patient (left), and a patient with DTAA (right).

Using *SimVascular* [3], an initial center-path of the DTA was first constructed manually and then refined using the following process. Briefly, automatic segmentations were created at 2mm intervals along the initial path (those at ostia were excluded to avoid manual segmentation). The centroid of those segmentations were calculated and used to create a revised center-path followed by a Fourier-smoothing algorithm applied to create the final center-path [4].

Following the construction of the center-path in the systolic and diastolic frames, we created a group of segmentations along the thoracic aorta at eight locations: distal to the brachiocephalic (1), common carotid (2), and left subclavian (3) branch vessels, the proximal DTA (4), proximal DTAA (5), maximum diameter of DTAA

(6), distal DTAA (7), and distal DTA (8), important landmarks for endovascular device implantation (see Figure 2). The ostia of the inter-costal arteries (ICA) and branch vessels serve as a Lagrangian reference frame, which is fixed to the object of interest, versus previously used Eulerian frame, which is fixed in the image volume. We used a previously described method to "attach" the reference frame to the ostia to track the motion of the vessel's lumen by analyzing the *same* segment over the cardiac cycle [2]. Thus, we were not concerned with spurious results due to through-plane motion of the vessel, which is possible using an Eulerian frame.

Deformation Metrics

Circumferential cyclic strain was computed at 8 locations (sketched in Figure 2) by comparing the circumference of the lumen at peak-systole, C_S, and end-diastole, C_D, at those locations. Finding the ostia of the three branch vessels and the most proximal and distal ICA was straightforward for each patient group. However, the locations along the aneurysm (5-7) required some additional analysis.

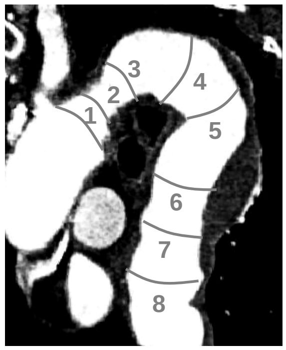

Figure 2. Eight locations of interest along the aorta

We measured the lumen circumference at the proximal, maximum and distal locations of the aneurysm in the DTAA patient group. Because the older patients did not have aneurysms, we used the vertebrae as markers. We used the vertebra locations near the proximal, maximum and distal locations of the aneurysm and averaged them to create a 'marker' for the patients without disease. For example, the vertebra near the proximal aneurysm location, for each DTAA patient, is: T5, T5, T3, T5, T3 and T3. These locations averaged to the T4 vertebra. Therefore, we used the ICA at that location to analyze the circumference of the lumen for the non-diseased patients. T6 and T7 vertebrae were used for the maximum and distal aneurysm locations, respectively.

The 2D-segmentation technique constructs a series of points in a closed curve, which enabled us to compute the circumference and thus, diameters from the measured circumferences ($C = \pi D$). The circumferential cyclic strain (CCS) was calculated from the Green-Lagrange strain tensor,

$$E_{\theta\theta} = \frac{1}{2}\left(\frac{C_S^2}{C_D^2} - 1\right) \quad (1)$$

RESULTS

The diameters in the aortic arch and the distal DTA are approximately 20-25% larger in the patients with DTAA when compared to the older patients; no aneurysms were present at those locations (top graph Figure 3). The non-aneurysm diameters in the DTAA group ranged from 33-42mm, whereas those same locations for the older patient group are 27-32mm. The largest diameters are greater than 60 mm in the patients with DTAA. A paired t-test results in $p < 0.05$ at each location when comparing older patient with DTAA diameters.

The average CCS of the DTA is 3.3% in the older patients and 1.6% in the DTAA patients (p=0.04). However, there is no statistical difference in the CCS when we include the three locations of the arch with the DTA between the older and DTAA patients. Additionally, the CCS at the distal two locations (7 and 8) are statistically different between the two patient groups (p=0.013 and p=0.007). The CCS in the older group is increasing distally (3 paired 8, p<0.005). In the DTAA group, the CCS at the LSC is 50% greater than the distal DTA (3 paired 7, p=0.028 and 3 paired 8, p=0.008), although the values are more varied in between those locations (bottom graph of Figure 3).

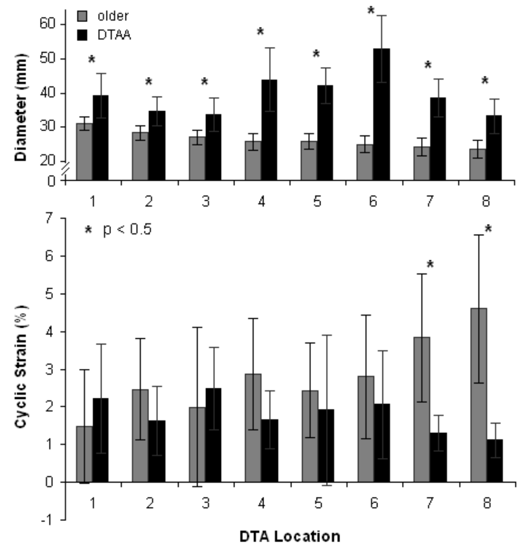

Figure 3. Diameters and cyclic strain along the DTA in patients with DTAA (■) and no visible thoracic disease (■).

DISCUSSION

We quantified the circumferential cyclic strain and diameters in a group of patients with DTAA at eight locations important in TEVAR. The diameters of the "non-diseased" portion of the thoracic aorta (locations 1-4 and 8) were significantly larger in patients with DTAA than in the older patients. The typical range for thoracic EVGs is 26 to 40 mm. Thus, with typical oversizing of 15% (even 20%), the graft would need to be at least 46mm (48mm).

The circumferential cyclic strain was the largest in the distal DTA for the older patients (4.6%) and the smallest for the DTAA patients (1.1%). Additionally, the CCS in the arch was similar for both patients groups (2.5%). Moreover, the magnitude of the CCS was consistently small in both groups, contrasting the results of van Prehn *et al.* [1]. We have commented on these differences before [2], particularly the diameter versus the circumference measurement, and the Eulerian versus Lagrangian reference frame. Additionally, we recognize this is a small study and would benefit from more data because these results may have implications for EVG design and long-term fatigue testing.

ACKNOWLEDGEMENTS

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