CIRCUMFERENTIALLY NONUNIFORM WALL THICKNESS AND LAMELLAR STRUCTURE CORRELATES WITH CYCLIC STRAIN IN THE PORCINE DESCENDING THORACIC AORTA

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INTRODUCTION

Although wall structure and thickness variations have been noted along the length of the aorta [1], the aortic wall is generally assumed to deform concentrically and to have a uniform thickness and lamellar structure [2]. Circumferentially nonuniform wall motion has been observed, *in vivo*, in the normal human aorta [3] and the normal porcine aorta [4,5]. The current study was undertaken to investigate whether nonuniform wall strain is related to wall thickness and medial lamellar structure. The circumferential component of Green-Lagrange cyclic strain in cylindrical coordinates was calculated from magnetic resonance image data at one level in the descending thoracic aorta of six pigs, and was then correlated to medial thickness and lamellar structure, quantified *ex vivo*, at the same level.

METHODS

Quantification of Wall Motion

Motion of the mid-descending thoracic aorta was imaged, using a 2D cine phase contrast sequence, in six anesthetized Yorkshire cross pigs (45-53 kg). All imaging was performed with a 1.5 T MRI system (Signa CV/i, GE Medical Systems, Waukesha, WI) and an implanted, custom-built, receive-only coil. In-plane resolution of 0.3125 mm was achieved using a 16 cm field of view and a 512x256 acquisition matrix. RF spoiling was used to minimize motion artifacts and spatial saturation pulses were used to minimize flow effects and to enhance visualization of the vessel wall (Figure 1, left). Respiratory compensation and oversampling to prevent spatial aliasing (no phase wrap) options were also used. Twenty-four time frames through the cardiac cycle were reconstructed. True temporal resolution of the acquisition (four-times the repetition time) was 110-120ms. The vessel wall in each time frame was segmented using both magnitude and velocity images [3-5]. The circumferential component of Green-Lagrange cyclic strain was calculated from

$$E_{\theta\theta} = \tfrac{1}{2}\left(\tfrac{r^2}{R^2} - 1\right),$$

where R and r are the radii at time points of minimum and maximum luminal area as shown in Figure 1, right.

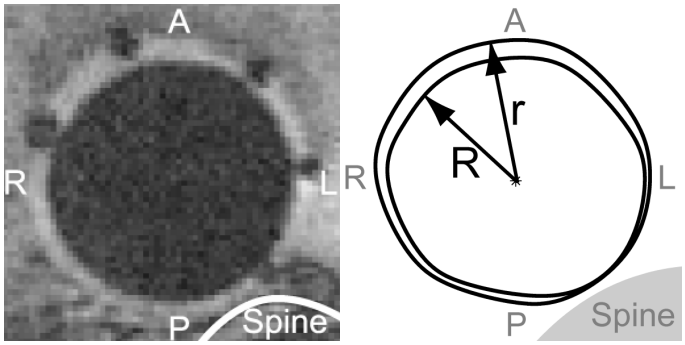

Figure 1. A close up of the vessel wall imaged with MRI (left; black dots were for a separate validation study) and an illustration of the vessel radii used in the strain calculations, at times of minimum (R) and maximum (r) luminal area (right).

Wall Histomorphometry

The thoracic aorta was harvested from seven pigs following sacrifice (animals were from both the wall strain protocol and another ongoing imaging study using the same size and variety of pig). Each aorta was immediately perfusion fixed in formalin at 120 mmHg for 30 minutes, followed by further fixation overnight in an effort to preserve the physiological configuration of the aortic wall. A segment of aorta, corresponding to the level of the imaging plane, was then dissected and marked for anterior, posterior, left, and right orientation; posterior was defined by take-off points of the neighboring intercostal arteries. Histological sections, 5 μM thick, were stained with Mason's trichrome, and then the stained sections were digitized around the circumference at 2x and 10x magnification. Multiple images were combined to form complete reproductions of the aortic wall at both magnifications. Medial wall thickness and the number of medial lamellar units was quantified at 8 points, 45° apart, relative to the posterior aspect of the aorta.

RESULTS

As seen previously, wall motion was not uniform around the vessel circumference. In this study, the left-posterior aspect of the wall, immediately adjacent to the spine in some animals (Figure 1), but not in all, strained the least and the right-anterior aspect strained the most (Figure 2, left). The wall media thickness and the number of medial lamellae also varied around the circumference, with the anterior wall being thickest and having the most lamellar units. The trichrome-stained section from one animal (Figure 2, right), illustrates the circumferential thickness variation. The lamellar structure in the avascular zone of the media (bordering the lumen) was observed to be more loosely organized than the vascular zone (bordering the adventitia), which contains vasa vasorum and more closely spaced, parallel lamellae. A close-up comparison of the anterior and posterior media thickness and structure is shown in Figure 3.

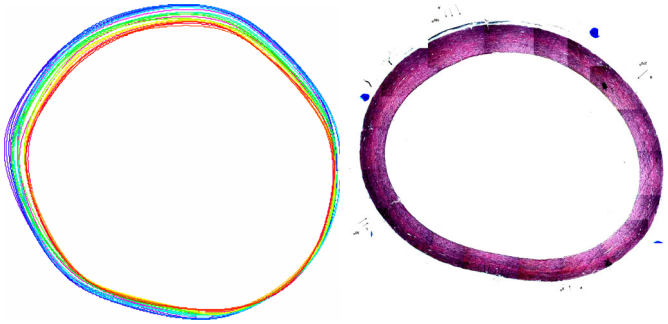

Figure 2. Qualitative comparison of wall motion (left, shown as the wall centerlines at 24 points in the cardiac cycle) and wall thickness (right, trichrome stained section).

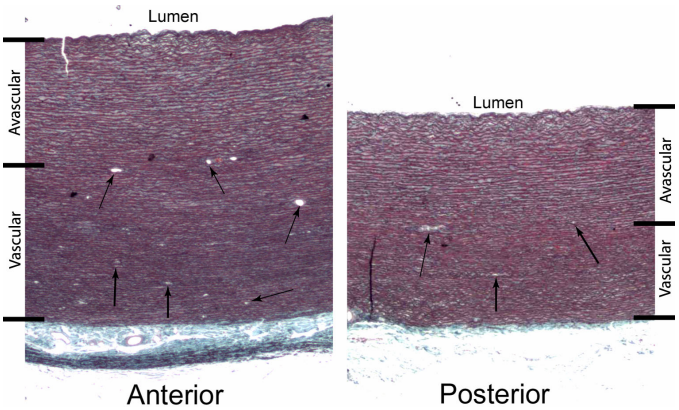

Figure 3. Comparison of medial thickness and structure in the anterior and posterior walls of the porcine descending thoracic aorta. Black arrows indicate examples of vasa vasorum in the vascular zone of the media. The difference in the lamellar structure between the vascular and avascular zones is evident at both locations.

A comparison of wall strain, wall thickness, and number of medial lamellae at eight measured points around the circumference is shown in Figure 4. All three quantities in the anterior wall were significantly different from the values in the posterior, left-posterior, left, and right-posterior locations ($p<0.05$, Fisher's PSLD test). Results from this comparison demonstrate that increased wall strain correlates with both increased wall thickness ($r^2=0.62$) and an increased number of medial lamellar units ($r^2=0.58$).

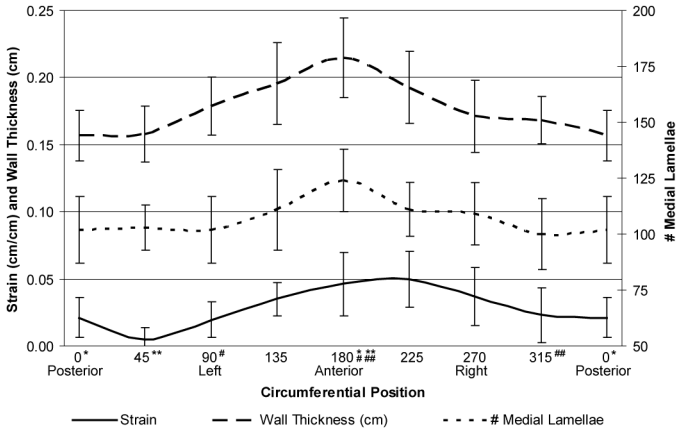

Figure 4. Quantitative comparison of cyclic strain, wall thickness, and number of medial lamellae.

DISCUSSION

This study demonstrates a circumferential variation in aortic wall structure and a direct relationship between circumferential wall structure and wall strain at one level of the thoracic aorta in the pig. Although the deformation pattern, which resembles that observed in the human thoracic aorta, creates the visual appearance of simple one-point tethering, complete analysis of the velocity data suggest that the wall is straining non-concentrically. It has previously been hypothesized [2] that the vessel wall remodels so that each lamellar unit bears a constant tensile load; the results presented herein thus suggest that the area of increased wall strain, which has more medial lamellae, corresponds to a region of greater tensile load.

Note that the strain measure reported is not the principal strain as would be calculated from the MR velocity data [5]. This quantity was calculated, but strain variations around the circumference could not be statistically resolved due to the small amount of wall motion observed; wall motion in these anesthetized animals was much smaller than that previously observed in humans. Noninvasive studies of the human aorta are in progress to quantify the relationship between wall structure and strain, calculated using local trajectories determined from MR velocity data.

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