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Technical Note

Longitudinal differences in the mechanical properties of the thoracic aorta depend on circumferential regions

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Abstract: Understanding the mechanical behavior of the arterial wall and its spatial variations is essential for the study of vascular physiopathology and the design of biomedical devices that interact with the arterial wall. Although it is generally accepted that the aortic wall gets stiffer along its length, the spatial variations in the mechanical behavior of the thoracic aorta are not well understood. In this study, therefore, we investigate both longitudinal and circumferential variations in the mechanical properties of the porcine descending thoracic aorta. Using a previously developed experimental method and stress–strain analysis, the stress, stretch, tangent modulus (TM), and pressure–strain elastic modulus (PSEM) are estimated in the range of *in vivo* pressure. The results show that the longitudinal differences of both TM and PSEM are statistically significant in the posterior region but not in the anterior region. Both moduli are greater in the posterior distal region when compared with the other test regions. The findings of this study meet a need for clarifying the region investigated, especially in circumferential region, to study the regional variations in biomechanics of blood vessels. © 2012 Wiley Periodicals, Inc. J Biomed Mater Res Part A: 00A:000–000, 2012.

Key Words: vascular stiffness, heterogeneity, aortic dissection, stent design

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INTRODUCTION

With the increased understanding of the role of biomechanics in vascular physiopathology, there is a pressing need for a better characterization of the spatial variation in the biomechanical properties of the arterial wall under various physiological and pathological conditions.[1] The descending thoracic aorta is a relatively straight segment containing several small intercostal arteries and a frequent site for dissections and aneurysms.

Previous experimental studies of the aorta have reported that its mechanical properties vary along the aortic tree,[2,3] which in general agrees that the aortic stiffness increases with increasing distance from the heart. Recent studies using *in vivo* imaging[4] and *ex vivo* optical measurement[5] found variations in the mechanical behavior of the aortic wall around the circumference. Successively, our previous study[6] used local strain analysis and showed that a significant variation in the stiffness of the descending thoracic aorta exists among four circumferential regions. Nevertheless, the study is limited to one longitudinal location, and the longitudinal variations of the thoracic aorta are not yet clearly elucidated in association with the circumferential regions.

In our previous study,[6] an extension-inflation experimental apparatus with a stereo-vision system was developed to characterize the mechanical properties of the local aortic wall. The strain measurement technique is similar to that of Filas et al.,[7] but a surface with a convected coordinate system[8] was approximated for a given test region instead of creating a new curvilinear coordinate system for each point. The distributions of stress and strain from the approximated 3D surface and the displacement field were estimated and then averaged over the local region studied. Statistical analysis of the mechanical states (e.g., stress, stretch, and modulus) finally showed that the posterior region of the proximal thoracic aorta is significantly stiffer

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than the anterior region. This finding raises two questions: is the trend of circumferential variations consistent in the distal thoracic aorta, and do the longitudinal variations exist in both anterior and posterior sides? In this study, therefore, we additionally characterize the mechanical properties of the distal descending thoracic aorta in two circumferential regions (the anterior and the posterior), using the experimental approach and stress–strain analysis of our previous study.[6] We then perform statistical analysis to examine possible variations between two longitudinal portions (the proximal and the distal) as well as two circumferential regions of the descending thoracic aorta.

METHOD

To characterize the regional mechanical behavior of the descending thoracic aorta, we classify test regions of the aortic wall into four groups: (1) the anterior region of the proximal thoracic aorta (AP), (2) the posterior region of the proximal thoracic aorta (PP), (3) the anterior region of the distal thoracic aorta (AD), and (4) the posterior region of the distal thoracic aorta (PD). Here, the proximal portion of the descending thoracic aorta covers the end of the aortic arch to the fourth intercostal artery, and the rest along its length is the distal portion.

This study adopts the experimental procedures and stress–strain analysis we developed[6] and investigates the mechanical behavior of the distal descending thoracic aorta. In short, the stereo-vision system obtains pairs of images on markers attached to the aorta during the inflation test [Fig. 1(A,B)]. Once the test for one circumferential region is completed, the other circumferential region is tested after 180° rotation of the specimen under the same experimental condition. The inflation test is repeated at three axial stretch ratios of 1.35, 1.40, and 1.45. Through the image data process, the 3D positions of markers are reconstructed and used in stress–strain analysis [Fig. 1(C)].

For comparison of local mechanical properties, two different moduli are defined as the measure of intrinsic and structural mechanical properties. One is the tangent modulus (TM) approximated by piecewise linear regression of the stress and stretch response at a given transmural pressure of P_i, that is

$$E_t(P_i) = \left.\frac{\partial\sigma}{\partial\lambda}\right|_{P=P_i} \tag{1}$$

where σ is the circumferential Cauchy stress and λ is the circumferential stretch. Another measure is the pressure–strain elastic modulus[9] (PSEM), which represents the structural stiffness during the cardiac cycle, calculated by

$$E_P = \frac{P_{sys} - P_{dia}}{(\lambda_{sys} - \lambda_{dia})/\lambda_{dia}} \tag{2}$$

where subscripts sys and dia denote the systolic and diastolic conditions, respectively. We assume $P_{sys} = 114$ mmHg (15.20 kPa) and $P_{dia} = 76$ mmHg (10.13 kPa), as the radial perivascular compression caused by surrounding tissue onto

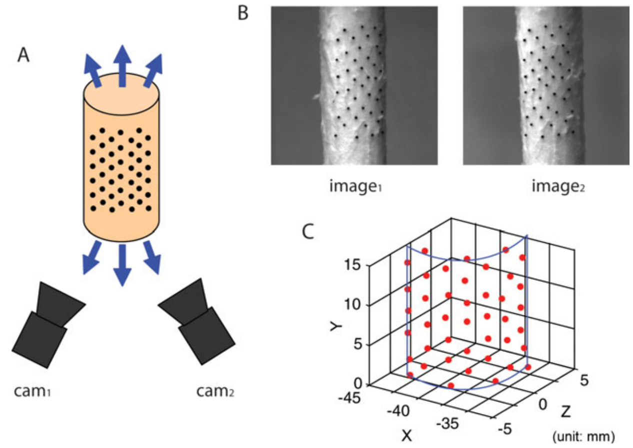

FIGURE 1. (A) Schematic setup of the stereo-vision system to focus on a specimen, (B) specimen images taken by each camera, and (C) the reconstructed positions of markers affixed to the specimen in the 3D coordinate system. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the aorta is assumed to be 5% of internal pressure.[10] In this study, the axial stretch ratio of 1.35–1.45 (buckling was observed during inflation at less than or equal to 1.30 stretch ratios) and the transmural pressure ranging from 76 to 114 mmHg are assumed to be physiological ranges.

The statistical significance of the differences between two circumferential regions and between two longitudinal portions is evaluated using the *t*-test. The difference between two regions is considered significant if the *p*-value is less than 0.05.

RESULTS

The experimental data from seven proximal descending thoracic aortas, which were adopted from our previous study[6] (for a stretch ratio of 1.35) and the unpublished data (for stretch ratios of 1.40 and 1.45), and new experimental data from seven distal descending thoracic aortas were used for analysis.

The anterior wall of the descending thoracic aorta was significantly thicker than the posterior wall (AP: 2.2 ± 0.3 mm, PP: 1.5 ± 0.2 mm, AD: 2.0 ± 0.3 mm, and PD: 1.3 ± 0.2 mm), and the ratio of the maximum to minimum thickness of the wall for each specimen was found to be 1.5 ± 0.2.

The circumferential stretch and Cauchy stress increased with respect to the increase of internal pressure applied during inflation. At the transmural pressure of 90 mmHg (12 kPa), mean circumferential stretches of the test regions ranged from 1.16 to 1.22 and their differences were not significant [Fig. 2(A)]. However, the circumferential stress of the posterior region was significantly greater than that of the anterior region for both proximal and distal portions [Fig. 2(B)]. This trend was consistent for three axial stretch ratios.

All aortic tissues exhibited a similar nonlinear stress–stretch response regardless of the regions studied [Fig. 3(A,B)]. The TM showed a nearly linear increase at the

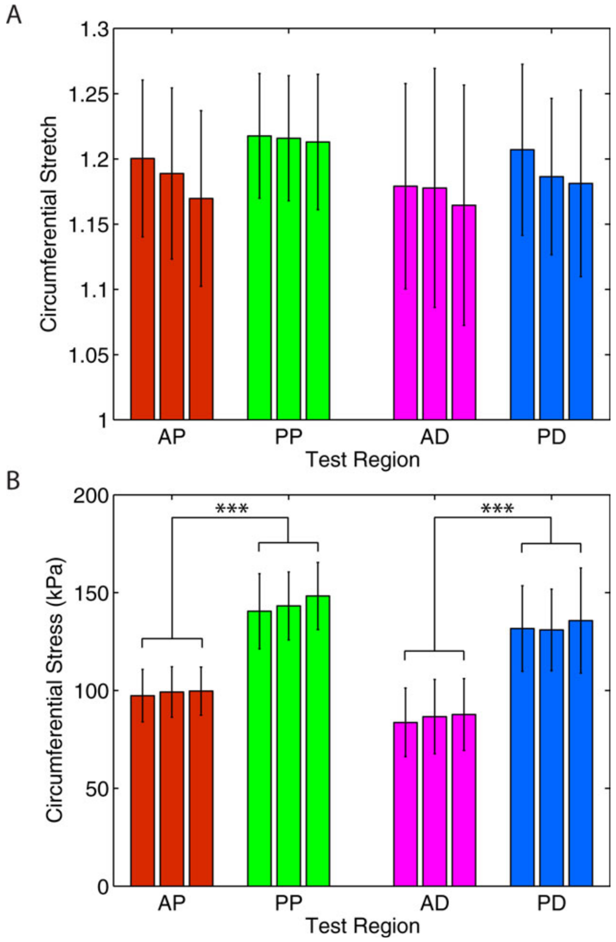

FIGURE 2. The circumferential stretch (A) and the circumferential stress (B) of the four test regions at a transmural pressure of 90 mmHg and axial stretch ratios of 1.35 (left), 1.40 (middle), and 1.45 (right) for each test region. Bars and error bars represent mean ± SD. AP: anterior proximal region, PP: posterior proximal region, AD: anterior distal region, and PD: posterior distal region. Asterisks represent significant differences (*: $p < 0.05$, **: $p < 0.01$, and ***: $p < 0.001$). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

low pressure but sharply increased at the high pressure over approximately 76 mmHg [Fig. 3(C,D)]. Note that high noise was observed in the distal portion due to a relatively larger fluctuation in the estimated strain. The difference of TM between the anterior and posterior regions was noticeable for all axial stretch ratios.

To quantitatively compare the moduli in both longitudinal and circumferential locations, their means and standard deviations were calculated at each axial stretch ratio. For the TM, the posterior region was significantly stiffer than the anterior region for both proximal and distal portions at all axial stretch ratios. In addition, the posterior region was significantly stiffer in the distal portion than the proximal at an axial stretch ratio of 1.35 with pressure ranging from 90 to 110 mmHg [Fig. 4(A)]. A similar trend was observed in the longitudinal difference of the posterior region at axial stretch ratios of 1.40 and 1.45, although the difference did not reach statistical significance level. Conversely, interestingly, the PSEM had relatively uniform values except in the posterior distal region, which had significantly higher mean values of PSEM than the posterior proximal region as well as the anterior distal region for all axial stretch ratios [Fig. 4(B) for an axial stretch ratio of 1.35]. For both TM and PSEM, the posterior distal region was the stiffest region where both longitudinal and circumferential differences were found statistically significant.

DISSCUSSION

The primary finding of this study is that the trend of longitudinal differences in the mechanical properties of the porcine descending thoracic aorta varies depending on the circumferential regions. To the best of our knowledge, it is the first study to present the regional variations associated with combined longitudinal and circumferential locations of the descending thoracic aorta. For comparison, we estimated two different moduli, TM and PSEM. The TM calculated from a stress–stretch plot represents material stiffness, whereas the PSEM represents physiological, structural stiffness during the cardiac cycle. In a presumably physiological condition, we specifically found that (1) in the posterior region, both values of TM and PSEM were significantly higher in the distal portion than the proximal, while the longitudinal difference of the anterior region was not significant for both moduli; (2) the TM was significantly greater in the posterior region than the anterior for both longitudinal portions; and (3) the PSEM was significantly greater in the posterior distal region when compared with the other regions.

Overall, this study showed that the material stiffness of the descending thoracic aorta was significantly greater in the posterior region than the anterior regardless of the longitudinal locations. Furthermore, the material stiffness in the posterior region was significantly greater in the distal portion than the proximal, although that in the anterior region did not show significant difference between two longitudinal portions. Conversely, the structural stiffness (i.e., the combination of the material stiffness and thickness) was similar in all test regions except the posterior distal region, even though the posterior region was thinner than the anterior. Therefore, it implies that these longitudinal differences of the descending thoracic aorta depend on the circumferential regions.

Although it is not clearly understood why the mechanical properties vary along the descending thoracic aorta, it has long been speculated that the mechanical behavior is related to the arterial wall constituents. Indeed, elastin bears the majority of aortic wall stress in the low stretch region,[11–13] and collagen contributes mainly to the stiff behavior of the wall in the high stretch region.[12,14] Possible reasons for the regional variations include the microstructural characteristics of elastin in the media of the aortic wall, although this is still controversial. The medial elastin composed of approximately 71% lamellar sheets[15] is a key determinant of arterial distensibility.[16] The number of elastic lamellar units[17,18] and the thickness of elastic membranes of the lamellar units[19] are greater in the proximal portion of the descending aorta than in the distal portion.

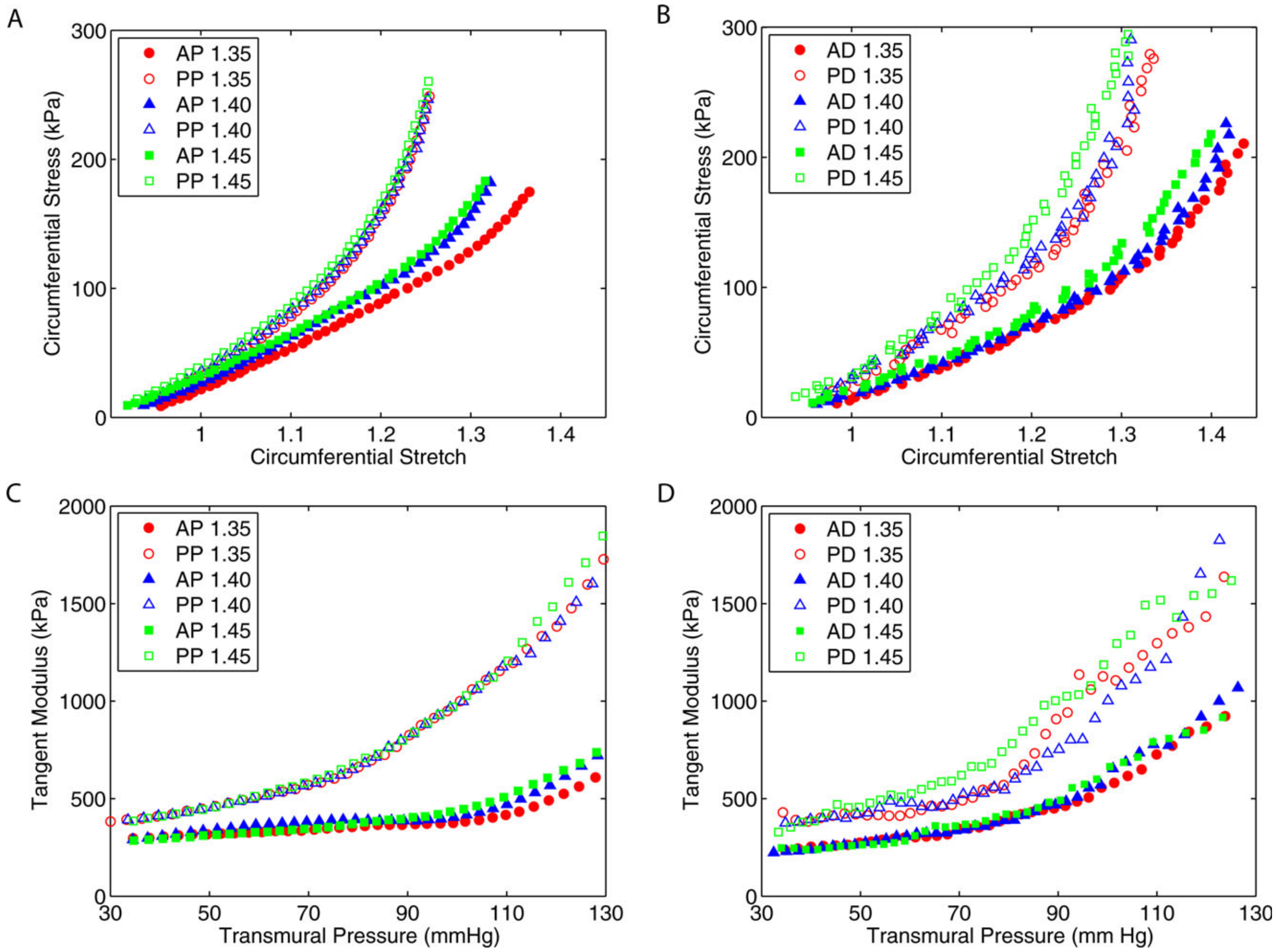

FIGURE 3. Representative stress–stretch responses in the proximal portion (A) and the distal portion (B) of the descending thoracic aorta, and their corresponding TM–transmural pressure responses in the proximal portion (C) and the distal portion (D) in reduced range of pressure, respectively. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

In addition, the number of elastic lamellae is greater in the anterior region than the posterior.[15] Contrary to these regional variations of the aortic elastin, it was reported that the isolated elastin has nearly uniform content along the length of the bovine thoracic aorta, although the isolated elastin network is stiffer in the distal portion than the proximal.[20] However, there have been neither histological nor microstructural studies to observe the elastin in combined longitudinal and circumferential locations. Thus, more investigation is needed for a better understanding of the microstructure of the aortic histology and the spatial variations in the mechanical properties of the thoracic aorta.

The *in vivo* axial stretch is one important piece of information needed to estimate the *in vivo* stress and strain. Han and Fung[2] reported that the *in situ* axial stretch ratios of the porcine descending thoracic aorta vary along its length (1.20–1.45). The perivascular force of the descending thoracic aorta, which has not been comprehensively elucidated, may be different between its proximal and distal portions.[10,21] In this study, we compared moduli of four different regions by assuming that they were subjected to the same axial stretch in the same transmural pressure range. Nevertheless, accurate estimations of *in vivo* axial stretch and perivascular force for each test region will greatly increase our understanding of the regionally varying mechanical states of the descending thoracic aorta.

Various animal models have been used to understand the biomechanics of blood vessels, albeit the ultimate target is human arteries. Typically, the allometric scaling law[22] is used to interpret the results from specific animal models based on their body mass. For the aortic biomechanics, Goergen et al.[23] tested five species including humans and reported that the displacement of abdominal aortic wall increases linearly with aortic diameter but increases on an allometric scale with body mass across species (allometric scaling exponent of the anterior wall: 0.377 ± 0.032 and that of the posterior wall: 0.378 ± 0.037). Although it is not clear whether the relationship between aortic wall motion and diameter is applicable to the regional strain distribution, this study motivates further investigation of the regional aortic wall properties across species.

In conclusion, this study shows that the longitudinal difference in the mechanical properties of the descending thoracic aortic wall is greater in the posterior region

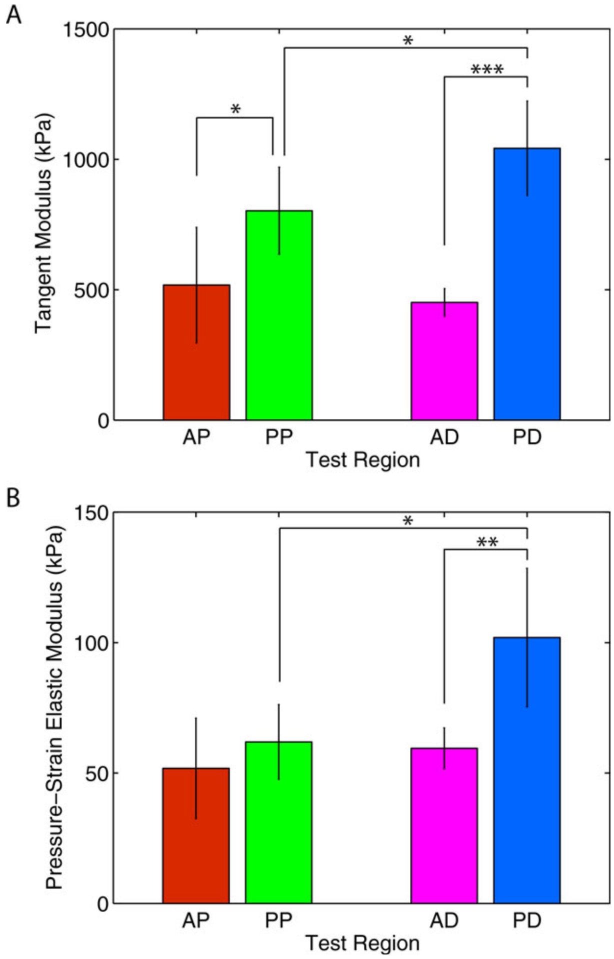

FIGURE 4. (A) The tangent moduli in the four test regions at a transmural pressure of 90 mmHg and an axial stretch ratio of 1.35, and (B) the pressure–strain elastic moduli in the four test regions at an axial stretch ratio of 1.35. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

compared to the anterior. The heterogeneous nature of the descending thoracic aorta meets an important need for clarifying the region investigated, particularly its circumferential region, in vascular mechanics. The findings of this study will be helpful to understand the physiopathology of life-threatening thoracic aortic diseases, such as thoracic and thoracoabdominal aortic aneurysms and aortic dissections, and to design biomedical devices or clinical interventions for such vascular diseases.

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