Mechanical properties of abdominal aortic aneurysm wall†

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There is a need to understand why and where the abdominal aortic aneurysm may rupture. Our goal therefore is to investigate whether the mechanical properties are different in different regions of the aneurysm. Aortas samples from five freshly excised whole aneurysms, 5 cm in diameter, from five patients, average age 71 ± 10 years, were subjected to uniaxial testing. We report the wall thickness, yield stress and strain, and parameters that describe nonlinear stress–strain curves for the anterior, lateral and posterior regions of the aneurysm. The posterior region was thicker than the anterior region (2.73 ± 0.46 mm versus 2.09 ± 0.31 mm). The stress–strain curves were described by $\sigma = \sigma_0 + \sigma_1 \varepsilon$, where $\sigma$ is true stress and $\varepsilon$ is engineering strain. In the circumferential direction, the wall stiffness increased from posterior to anterior to lateral. In the longitudinal direction, the lateral and anterior regions showed greater wall stiffness than the posterior region. The wall stiffness was greater in the circumferential than longitudinal direction. The anterior region was the weakest, especially in the longitudinal direction (yield stress $\sigma_0 = 0.38 \pm 0.18$ N mm$^{-2}$). For a less complex model the aneurysmal wall could be considered orthotropic with $\sigma = 12.89 \varepsilon^{2.95}$ and $4.95 \varepsilon^{2.93}$ in the circumferential and longitudinal directions. For the isotropic model, $\sigma = 7.89 \varepsilon^{2.95}$. In conclusion, different regions of the aneurysm have different yield stress, yield strain, and other mechanical properties, and this must be considered in understanding where the rupture might occur.

Introduction

In a clinical setting there exists a pressing need to be able to predict the rupture of the abdominal aortic aneurysm (AAA). Towards this goal we start with a basic question: are the mechanical properties of the aneurysmal tissue, such as yield stress and yield strain, different in different regions of the aneurysm? Understanding the material properties along with the stress distribution in the whole aneurysm is the essential step towards predicting the rupture of the AAA. In the present study we investigate the mechanical properties in various regions of the aneurysm.

An abdominal aortic aneurysm is considered present when the diameter of the aorta exceeds 3 cm. A typical aneurysm represents over 50% dilation in the aorta. If left untreated, an aneurysm will grow and eventually rupture. Between 60% and 75% of patients with ruptured aneurysms die before reaching the hospital [1, 2]. Also, surgical repair performed in an emergency is associated with a very high mortality rate close to 50% [3]. Thus, elective repair is the best mode of treatment with a mortality rate of only 3% [1, 2]. In 1988, in the United States alone, 40 000 aortic reconstructions were carried out for aneurysms, and nearly 15 000 people, mostly men over age 55, died from the rupture of AAA [1, 3].

Several factors are important in the development of an aneurysm. Heredity may be one of them. Also, mechanical factors related to blood pressure and flow may play a role in aneurysm formation [1]. Repair is recommended for all aneurysms 7 cm or more. Elective operation of AAA 4 to 6 cm diameter is controversial because of the risk associated with surgery. It has been reported that 9% of aneurysms of 4 cm diameter rupture over a period of three years [1] and 10% of ruptured AAA are 5.5 cm or smaller [4]. A higher expansion rate, from 0.5 cm per year and up is also associated with a high risk of rupture [5, 6].

An AAA ruptures when the aortic wall cannot sustain the load of pulsatile blood pressure and flow. In recent years, various models of aneurysms, with or without intraluminal thrombus, have been presented [7–10]. These models use a finite element analysis to determine stress in the aneurysm and take into account the complex geometry. The data on the mechanical properties of the aneurysm wall, especially from different regions of the aneurysm (e.g., anterior, posterior, lateral) is still not known. The thickness, yield stress and yield strain may be different in different regions of the aneurysm, and these properties may be different in the circumferential and longitudinal directions, particularly since the normal aorta is orthotropic [11]. Although He and Roach [12] and Raghavan et al. [13] reported some data, sufficient experimental data is still lacking because of the unavailability of whole aneurysms for experiments, since in most surgical repairs only the anterior part of the aneurysm is removed. The increasing use of endovascular grafts for treatment of aneurysm makes the availability of the aneurysm tissue even more unlikely in the future [14]. Therefore, the experimental data presented here on the whole aneurysm is of great significance in understanding AAA ruptures. We studied the aorta samples from freshly excised whole aneurysms from patients by subjecting them to uniaxial testing.
Experimental method

Five aneurysms, 5 cm or greater in diameter, were obtained from five patients undergoing elective surgical repair. The patients were 60 to 87 years of age, with an average of 71 ± 10 years. The aneurysms were stored in saline at 4°C immediately after excision. Forty-seven test specimens were prepared by cutting the aneurysms into small rectangular pieces. Twenty-one specimens were longitudinally oriented, and twenty-six were circumferentially oriented. The typical sample size was 16 × 4.3 mm. The thickness of the specimens was measured as follows. A customized micrometer was coupled with a resistivity meter so that when the two tips of the micrometer came in contact with the tissue sample, a resistance circuit was established and the thickness could be directly read at this time. This technique was developed and used by us previously [15]. The average thickness was determined from the measurements at three different locations, with an accuracy of 0.05 mm.

The uniaxial tensile tests were run on an Instron Mini 44 load frame, controlled by a personal computer through the Instron Series IX software for Windows. The force accuracy of the load cell was 0.02 N, and the extension accuracy of the crosshead was 0.05 mm. Output ASCII files were generated for further analysis.

The specimens were held between the load cell and the crosshead using specially designed grips made from surgical clamps so as to prevent slippage. The initial length of the samples under zero load was recorded (typically 10 mm). In order to make sure that no slippage was present, as well as to obtain reproducible data, each specimen was preconditioned by three successive loadings to 5% strain and unloadings at a constant strain rate of 10% min⁻¹. Then, the sample was stretched at the same strain rate until rupture.

The force and displacement data were transformed into true stress σ and engineering strain Є. The true stress (or Cauchy stress) is defined as the ratio of the force f applied to the current cross-sectional area a of the sample. Using the assumption that the volume of the specimen was conserved, the current cross-sectional area was

\[
a = \frac{I_0 \Delta t}{I_0 + \Delta t}.
\]

where \( I_0 \) is the initial length, \( w \) is the initial width, \( t \) is the initial thickness and \( \Delta t \) is the elongation of the specimen. The true stress was calculated as

\[
\sigma = \frac{f}{a} = \frac{f}{wd}(1 - \varepsilon).
\]

where the engineering strain \( \varepsilon \) is defined as

\[
\varepsilon = \frac{\Delta l}{l_0}.
\]

The curve of true stress \( \sigma \) versus engineering strain \( \varepsilon \) was plotted for each specimen. This type of curve typically exhibits a strong nonlinearity. Different forms of curve fit can be used. We used a power equation with two parameters \( a \) and \( b \) shown below:

\[
\sigma = ax^b.
\]

with \( a > 0, b > 1 \) and \( 0 \leq \varepsilon \leq 1 \), and that provided an excellent fit. The best-fit parameters \( a \) and \( b \) were determined for each curve by using a linear least squares regression after rewriting the above equation as

\[
\ln \sigma = b \ln \varepsilon - \ln a.
\]

When several samples from different aneurysms, regions or directions were considered for averaging, the data from these samples were pooled into a single data set. The least squares regression was then used to produce the best-fit parameters \( a \) and \( b \) describing the average curve.

For any two curves with parameters \( a_2, b_2 \) and \( a_1, b_1 \) respectively, and for a given strain, the difference between the corresponding two stresses is

\[
\sigma_2 - \sigma_1 = a_2 \varepsilon^{b_2} - a_1 \varepsilon^{b_1}.
\]

Then, \( \sigma_2 \) is greater than \( \sigma_1 \) if \( a_2 = a_1 \) and \( b_2 < b_1 \), or \( a_2 > a_1 \) and \( b_2 = b_1 \), or \( a_2 = a_1 \) and \( b_2 > b_1 \).

The incremental modulus \( E \) at any point of the stress-strain curve is equal to the value of the slope. Thus, we get

\[
E = \frac{d\sigma}{d\varepsilon} = ab\varepsilon^{b-1} = \frac{\sigma}{\varepsilon}.
\]

The parameters \( a \) and \( b \) for each specimen were determined from the stress-strain curve between zero load and the yield point. The yield point is defined here as the point of the stress-strain curve where the slope \( (d\sigma/d\varepsilon) \) begins to decrease with increasing strain. Since permanent damage could occur beyond the yield point, the yield stress \( \sigma_y \) and the yield strain \( \varepsilon_y \) of the specimens are considered important and are reported here instead of the ultimate stress and strain. The mean yield stress and yield strain were determined as the arithmetic average.

The aneurysm aorta specimens were separated into six groups according to (i) the region-anterior, posterior or lateral and (ii) the direction-circumferential or longitudinal. Since only five whole aneurysms were available for the study, the sample size was too small to carry out a statistical analysis of the results. Also, samples from the same aneurysm are not statistically-independent. Nonetheless, significant trends indicated by the results are reported because they are interesting and important.

Finally, the material properties of the aneurysm wall were also assessed for the two following conditions: (1) assuming an orthotropic behaviour and averaging all regions and (2) assuming an isotropic behaviour. Which data should be used in the analysis will depend upon the complexity of the analytical model employed for determination of stress in the aneurysm.
Results

The results from five whole aneurysms, obtained from five patients, are presented. The thickness measurements of all samples were retained, but the stress–strain data from a few samples were discarded when tissue exhibited degenerative behaviour due to longer than 4 days of storage. The data from all of the specimens, including those that failed away from the grips or close to the grips, was used.

First, by examining the data on a single aneurysm, one can appreciate the variations in the material properties in different regions of the aneurysm. Figures 1 and 2 show the experimental stress–strain data obtained from multiple samples taken from the anterior, lateral and posterior regions of one aneurysm. The curves are plotted up to the rupture of the specimens. In both circumferential and longitudinal directions, the stress–strain curves are different in different regions of the aneurysm, suggesting that the stress–strain properties vary between different regions. Also, in any given region there is an appreciable variation in the stress–strain properties. Figure 3 presents the average best-fit curves for the anterior, lateral and posterior regions of the same aneurysm shown in figures 1 and 2. In both

![Circumferential Stress-Strain Curve](image1)

Figure 1. Experimental stress–strain curves in the circumferential direction obtained from multiple samples taken from the anterior, lateral and posterior regions of a single aneurysm. The material properties are different in different regions of the aneurysm. Also the variation in the material properties is appreciable in any given region.

![Longitudinal Stress-Strain Curve](image2)

Figure 2. Experimental stress–strain curves in longitudinal direction obtained from multiple samples taken from the anterior, lateral and posterior regions of the same aneurysm as in figure 1. The material properties are different in different regions of the aneurysm. Also, there is an appreciable variation in the material properties in any given region.
Figure 3. Average best-fit stress–strain curves in each of the three regions of the same aneurysm as in figures 1 and 2. Also, the stress–strain curve representing the grand average of the three regions is shown. L, A, P—lateral, anterior and posterior region, respectively, AV—grand average. Wall stiffness increases from posterior to anterior to lateral regions of the aneurysm. Also, the stiffness is greater in the circumferential direction than in the longitudinal direction.

circumferential and longitudinal directions, the stress–strain curves of the lateral region are above those of the anterior region, which are above those of the posterior region suggesting that the wall stiffness decreases from lateral to anterior to posterior regions. Furthermore, for each of the regions, the relative position of the curves suggests that the tissue is stiffer in the circumferential than in the longitudinal direction.

A similar analysis was carried out to include all five aneurysms. For each of the six groups the averages were determined for the parameters $a$, $b$, yield stress and yield strain.

The thickness of each specimen was also measured (table 1). In the five aneurysms, the thickness gradually decreased from posterior ($2.73 \pm 0.46 \text{ mm}$) to lateral ($2.52 \pm 0.57 \text{ mm}$) to anterior ($2.99 \pm 0.54 \text{ mm}$) region. The value of $n$ in table 1 is the number of tissue specimens available, regardless of their origin. This is also the case in tables 2 and 3 described below.

For the five aneurysms, the averages of the parameters $a$, $b$, yield stress and yield strain are shown in table 2. Figure 4 shows similar data in the form of an average stress–strain curve for each of the six groups. The coefficient of determination ($R^2$) of the curve fit for the model was greater than 0.95 for all specimens.

Comparing different regions
In the circumferential direction, the yield stress of the lateral region was greater than that of the anterior or posterior region ($0.73 \pm 0.22 \text{ N mm}^{-2}$ versus $0.52 \pm 0.20 \text{ N mm}^{-2}$ or $0.45 \pm 0.14 \text{ N mm}^{-2}$, respectively, table 2). For a given strain, stress in the lateral region was greater than that in the anterior region, which was greater than that in the posterior region (figure 4, and parameters $a$ and $b$ in table 2).

In the longitudinal direction, the yield stress in the posterior region was equal to that in the anterior or lateral region ($0.58 \pm 0.04$ versus $0.52 \pm 0.12$ or $0.38 \pm 0.02$, respectively, table 2). For a given strain, stress in the lateral or anterior regions was greater than that in the posterior region (figure 4, and parameters $a$ and $b$ in table 2).

It is noteworthy that this pattern of regional differences in stiffness (stress for a given strain) seen in five aneurysms was also evident in each one of them (figure 3).

Comparing different directions
For any given region, there was no marked difference between the yield stress in the circumferential direction and that in the longitudinal direction (table 2). However, in the posterior region, the yield strain was higher in the longitudinal direction than in the circumferential direction ($0.58 \pm 0.04$ versus $0.39 \pm 0.13$, table 2).

Also, in any region, the stress–strain curve in the circumferential direction ($L$, $A$, $P$) was above its
Five Aneurysms

Figure 4. Best-fit stress–strain curves averaged for all five aneurysms in each of the three regions. L, A, P represent, respectively, lateral, anterior and posterior regions, while subscripts c and l represent, respectively, circumferential and longitudinal directions. The different regions of the aneurysm clearly show different stress–strain properties including yield stress, yield strain, and stiffness at a given strain. Also, these properties are different in the circumferential and longitudinal directions.

Table 2. Material properties of the aneurysm wall, $\sigma = a\epsilon^c$ (five aneurysms).

<table>
<thead>
<tr>
<th>Region</th>
<th>Direction</th>
<th>$a$ (N mm$^{-2}$)</th>
<th>$b$</th>
<th>$\sigma_1$ (N mm$^{-2}$)</th>
<th>$\epsilon_1$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>Circ.</td>
<td>17.06 ± 1.14</td>
<td>3.01 ± 0.09</td>
<td>0.32 ± 0.20</td>
<td>0.38 ± 0.07</td>
<td>12</td>
</tr>
<tr>
<td>Lateral</td>
<td>Circ.</td>
<td>12.39 ± 1.17</td>
<td>2.21 ± 0.10</td>
<td>0.73 ± 0.22</td>
<td>0.28 ± 0.11</td>
<td>5</td>
</tr>
<tr>
<td>Posterior</td>
<td>Circ.</td>
<td>10.14 ± 1.57</td>
<td>3.54 ± 0.30</td>
<td>0.45 ± 0.14</td>
<td>0.39 ± 0.13</td>
<td>5</td>
</tr>
<tr>
<td>Anterior</td>
<td>Long.</td>
<td>7.84 ± 1.25</td>
<td>2.97 ± 0.14</td>
<td>0.38 ± 0.18</td>
<td>0.32 ± 0.12</td>
<td>7</td>
</tr>
<tr>
<td>Lateral</td>
<td>Long.</td>
<td>7.43 ± 1.14</td>
<td>2.77 ± 0.09</td>
<td>0.31 ± 0.14</td>
<td>0.38 ± 0.02</td>
<td>3</td>
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<tr>
<td>Posterior</td>
<td>Long.</td>
<td>2.08 ± 1.45</td>
<td>2.80 ± 0.25</td>
<td>0.47 ± 0.30</td>
<td>0.58 ± 0.04</td>
<td>2</td>
</tr>
</tbody>
</table>

$\sigma_1$ = yield stress; $\epsilon_1$ = yield strain.

Table 3. Average material properties, $\sigma = a\epsilon^c$.

<table>
<thead>
<tr>
<th>Model</th>
<th>Direction</th>
<th>$a$ (N mm$^{-2}$)</th>
<th>$b$</th>
<th>$\sigma_1$ (N mm$^{-2}$)</th>
<th>$\epsilon_1$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orthotropic</td>
<td>Circ.</td>
<td>12.89 ± 1.38</td>
<td>2.92 ± 0.21</td>
<td>0.55 ± 0.21</td>
<td>0.38 ± 0.10</td>
<td>22</td>
</tr>
<tr>
<td>Orthotropic</td>
<td>Long.</td>
<td>4.95 ± 1.23</td>
<td>2.84 ± 0.14</td>
<td>0.42 ± 0.19</td>
<td>0.38 ± 0.13</td>
<td>12</td>
</tr>
<tr>
<td>Isotropic</td>
<td>All</td>
<td>7.89 ± 1.21</td>
<td>2.88 ± 0.13</td>
<td>0.50 ± 0.21</td>
<td>0.35 ± 0.11</td>
<td>34</td>
</tr>
</tbody>
</table>

$\sigma_1$ = yield stress; $\epsilon_1$ = yield strain.

counterpart in the longitudinal direction ($L$, $A$, $P$, respectively) (figure 4). Overall then, for a given strain, the stress was greater in the circumferential direction than in the longitudinal direction.

The yield stress in different regions and in different directions is shown also in figure 5. From these results (table 2, figures 4 and 5), the anterior region appears to be the weakest part of the aneurysm, especially in the longitudinal direction ($\sigma_1 = 0.38 ± 0.18$ N mm$^{-2}$, $\epsilon_1 = 0.32 ± 0.12$). It may be noted that the longitudinal direction curves belonging to the posterior region ($P$), shown in figures 2 to 4, may not be truly representative curves. However, they are shown for the sake of completeness and this will be discussed later.

The incremental modulus as a function of strain was also determined (figure 6). The modulus varies from $<1$ N mm$^{-2}$ to almost $6$ N mm$^{-2}$ in the aneurysm. It is
of interest to know which value of the modulus should be used when modelling the aneurysm for determination of stress under systemic pressure. For a 5 cm diameter aneurysm, modelled as a closed-end cylinder with a 2 mm thick wall, the law of Laplace yields about 0.33 N mm$^{-2}$ and 0.16 N mm$^{-2}$ for the circumferential and the longitudinal stresses, respectively, under 100 mm Hg. By reading the corresponding strains in figure 4 for the different regions and directions, one can determine from figure 6 that the incremental modulus at 100 mm Hg is about 4.0 N mm$^{-2}$ in the circumferential direction, and about 1.5 N mm$^{-2}$ in the longitudinal direction. These values may be used as a first order approximation when the aneurysm is modelled as having linear orthotropic material properties at systemic pressure.

It is apparent that in the aneurysm the stress–strain properties are different in different regions and in different directions (figure 4). However, for the stress analysis, it may not be possible to consider this degree of complexity given the available analytical software. Also, for practical reasons it may be necessary to carry out stress analysis with different levels of complexity. For these reasons we have extended the present study to further represent the material properties of the aneurysm in a couple of different ways. The material properties can be consolidated to represent orthotropic behaviour as well as isotropic behaviour for the entire aneurysm. The results are as follows (table 3, figure 7). When all of the regions are combined to represent the orthotropic model of the aneurysm, the stress–strain curve for the circumferential direction lies above that for the longitudinal direction indicating that the wall is stiffer circumferentially. The material properties of the wall may be described by equations $\sigma = 12.88 e^{0.92}$ in the circumferential direction and $\sigma = 4.95 e^{0.44}$ in the longitudinal direction. Also, the wall is stronger in the circumferential direction than in the longitudinal direction ($\sigma_{L} = 0.55 \pm 0.21$ N mm$^{-2}$ versus $\sigma_{C} = 0.42 \pm 0.19$ N mm$^{-2}$), whereas the yield strains are not significantly different ($\epsilon_{L} = 0.33 \pm 0.10$ versus $\epsilon_{C} = 0.38 \pm 0.13$). For a given strain $\epsilon_{L} > \epsilon_{C}$ and for a given stress $\sigma_{C} < \sigma_{L}$ (figure 7). For an isotropic model, the material properties may be described by $\sigma = 7.88 e^{0.55}$ and the yield stress and strain are respectively $\sigma_{Y} = 0.30 \pm 0.21$ N mm$^{-2}$ and $\epsilon_{Y} = 0.35 \pm 0.11$ (figure 7, table 3).

**Discussion**

The mechanical properties of whole aneurysms are being presented for the first time in this study. To our knowledge, the differences in the material properties in the anterior, posterior and lateral regions of an aneurysm have not been presented before. Also, the longitudinal and circumferential directions were explored thoroughly to understand the anisotropy of the aneurysmal wall.

In the five aneurysms studied, the wall thickness was highest in the posterior region and gradually decreased towards the anterior region (table 1). This is consistent with the clinical observation. The bulge of an AAA is most often located in the anterior and anterolateral regions, because the posterior region is supported by the spine. Assuming conservation of the wall volume, the dilation induces a simultaneous thinning of the aneurysm wall. In fact, the wall may undergo compensatory thickening so as to avoid severe thinning. It is interesting to note that the thickness distribution in AAA appears to be opposite of that in the normal abdominal aorta where the anterior wall is thicker than the posterior wall in 64% of cases [16].

**Comparing properties in the circumferential direction**

For comparison of the mechanical properties we consider observations on normal and aneurysmal abdominal aortas reported by Raghavan et al. [13] and Valenta [16] (figures 8 and 9). The results obtained by Raghavan et al. for the anterolateral region of AAA are similar to those obtained in the
Figure 6. Calculated incremental modulus versus strain averaged for all five aneurysms, in different regions. L, A, P represent, respectively, lateral, anterior and posterior regions, while subscripts c and l represent, respectively, circumferential and longitudinal directions. The modulus varies from <1 to 6 N:mm⁻².

Figure 7. Average stress–strain curves for all regions and all aneurysms. Orthotropic properties are represented by the curves for circumferential and longitudinal directions, while isotropic properties are determined by further averaging these two curves.

The present study for the lateral region (figure 8). They reported the aneurysm yield stress in the circumferential direction (anterolateral region) to be 0.71 ± 0.12 N mm⁻², mean ± SEM, which is similar to our findings (0.52 ± 0.20 N mm⁻² for the anterior region, and 0.73 ± 0.22 N mm⁻² for the lateral region, mean ± SD).

When compared with the stress–strain curve of a normal aorta in the circumferential direction, one of the few curves available for comparison [16], all of the curves of the aneurysmal wall are shifted to the left, which indicates an overall stiffening of the tissue. This phenomenon of circumferential stiffening was also described in different reports based on the measurement of the pressure modulus in AAA [17–19]. The relative positions of the stress–strain curves of the posterior, anterior and lateral regions in comparison to that of the normal aorta could be taken to suggest that the disease is perhaps
increasing from the posterior region to the anterolateral region. This would be consistent with the pattern of thinning of the aneurysm wall noted earlier (table 1).

*Comparing properties in the longitudinal direction*

The stress–strain curves obtained by us are compared with those by others [12,13,16] on normal and aneurysmal abdominal aortas (figure 9). The curve we obtained for the posterior region is outside the range of those obtained by others. Since this curve is based on only two samples from the same aneurysm, we believe that it may not be representative of most aneurysms, and therefore should not be considered. He and Roach [12] obtained stress–strain curves of the anterior region of aneurysms and compared them to those from the normal aortic tissue. All curves from the diseased aorta were shifted to the left, indicating a higher stiffness for the aneurysmal wall. Raghavan et al. [13] also noted that the aneurysmal tissue in the longitudinal direction (anterior region) is somewhat

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**Figure 8.** Comparison of stress–strain curves of AAA between the present study (L, A, P) and reference [13] in the circumferential direction. A curve for normal tissue [16] is also shown. L, A, P, A/L represent, respectively, lateral, anterior, posterior, and anterolateral regions. N represents normal tissue (dotted lines).

**Figure 9.** Comparison of stress–strain curves of AAA between the present study (L, A, P) and references [12,13] in the longitudinal direction. Curves for normal tissue [12,13,16] are also shown. L, A, P represent, respectively, lateral, anterior, and posterior regions. N represents normal tissue (dotted lines).
stiffer than the normal tissue. The curves obtained by us for the anterior and lateral regions of the aneurysm, however, seem to be clustered around the curves obtained by Raghavan et al. [13] and by Valenta [16] for the normal aorta (figure 9). Considering the variability in this type of experiments, the results of our study are comparable to those of the others. This variability in the results from various authors for both the normal and the aneurysm aortas [12,13,16] is also obvious in figure 9.

Raghavan et al. [13] reported that the yield stress is significantly lower for the aneurysmal group than for the normal group (0.65 ± 0.10 N/mm² versus 1.21 ± 0.33 N/mm², mean ± SEM). The yield stress they reported is somewhat higher than what we found for the same region (0.65 ± 0.10 N/mm², mean ± SEM versus 0.38 ± 0.18 N/mm², mean ± SD). Since the age group and aneurysm size in their study and ours are comparable, the reason for this difference is not clear, particularly since our results are similar to theirs in the circumferential direction.

To compare the modulus of elasticity with the results of others, the present model must be simplified since others used a simplified model. As mentioned in the Results section, if an orthotropic linear model is considered for the aneurysm above 80 mm Hg, the modulus of elasticity can be taken as 4.0 N/mm² in the circumferential direction and 1.5 N/mm² in the longitudinal direction. These values are in the same range as those calculated from Raghavan et al. [13]. Raghavan et al. pointed out that the mechanical properties of the aneurysm wall were essentially similar for both directions. We, however, reach a different conclusion even when all regions are averaged (figure 7).

Another approach to examine the mechanical properties of aneurysms has dealt with the influence of selective degradation of collagen or elastin. Using specific proteolytic enzymes, Dobrin and others showed that the destruction of elastin is the primary cause of the aneurysmal aortic dilation, whereas rupture is due to collagen failure [3,20–22]. From this standpoint, histological studies of the abdominal aortic tissue could be helpful in understanding why the mechanical properties are different in different regions of the aneurysm.

Conclusions

The present study describes the mechanical properties of the aortic wall in anterior, lateral and posterior regions of the aneurysm, in terms of wall thickness, yield stress and strain, and parameters of the nonlinear stress–strain relationship. It provides data for more accurate modelling of the aneurysm for stress analysis. The aneurysms’ anterior region was the location where the wall thickness and the material strength, especially in the longitudinal direction, were smallest. This suggests that if aneurysm rupture occurs in the anterior region, the tear is likely to be circumferential. The study also presents data on the yield stresses and strains in different regions of the aneurysm, which is essential in understanding why and where the aneurysms rupture.

References


