Introduction

Rupture of an abdominal aortic aneurysm (AAA) is fatal.\(^\text{1}\) Although the current gold standard for predicting AAA rupture is the diameter,\(^\text{2,3}\) hemodynamic factors such as aortic wall stress or strain have been recently associated with the mechanisms of the rupture.\(^\text{4,5}\)

Finite element analysis based on three-dimensional (3-D) computed tomography (CT) angiography is the mathematical technique quite often used in analyzing AAA wall stress. However, CT itself involves the attendant risks of irradiation and contrast medium-induced nephropathy. In addition, the analysis requires exclusive knowledge and a method using several kinds of software and is time-consuming in clinical practice.

Strain analysis with a speckle-tracking method (STM) using ultrasonography, one of the least invasive modalities, was originally introduced for analyzing left ventricular function in ischemic heart diseases.\(^\text{6,7}\)

Here, we report an exploratory study that analyzed the behavior of AAAs with the STM using a commercially available ultrasonography apparatus.\(^\text{8}\)

Strain Analysis of Wall Motion in Abdominal Aortic Aneurysms

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**Objective:** In this exploratory study, we used ultrasound speckle-tracking methods, originally used for analyzing cardiac wall motion, to evaluate aortic wall motion.

**Materials and Methods:** We compared 19 abdominal aortic aneurysm (AAA) patients with 10 healthy volunteers (diameter, 48 mm vs. 15 mm). Motion pictures of the axial view of the aneurysm using ultrasonography were analyzed. Circumferential strain and strain rate at 6 equally divided segments of the aorta were semiautomatically calculated. We termed ‘peak’ strain and strain rate as the maximum of strain and strain rate in a cardiac cycle for each segment. We also evaluated the coefficient of variation of peak strain rate for the six segments.

**Results:** In the aneurysm and control groups, the mean values of peak strain along the 6 segments were 1.5% ± 0.6% vs. 4.7% ± 1.6% (\(p<0.0001\)), respectively. The coefficient of variation of the peak strain rate was higher in the AAA group (0.74 ± 0.20) than in the control group (0.56 ± 0.12; \(p<0.05\)).

**Conclusions:** Aortic wall compliance decreased in the more atherosclerotic AAA group. The higher relative dispersion of strain rates in the AAA group is indicative of the inhomogeneous movement of the aortic wall.

**Keywords:** strain, abdominal aortic aneurysm, inhomogeneity
Only a few studies have used this method for AAAs; however, their procedures and analysis methodology were rather complicated and time-consuming for clinical routine surveillance.\textsuperscript{39} We utilized software that can automatically divide the circumference into six segments and simplified the methodology of the measurement. We focused on the inhomogeneity of aortic wall movement by comparing the strain or strain rate of these different segments and sought in finding possibilities of clinical application for this simple method.

**Materials and Methods**

This study conformed to the guidelines established by the Declaration on Human Rights, Helsinki, and was approved by the ethics committee of the Graduate School of Medicine, The University of Tokyo, and all participating subjects gave informed consent.

**Definition of strain and strain rate**

A strain is a normalized measure of deformation representing the displacement between particles in the body relative to a reference length. Linear strain is defined as:

\[
\varepsilon(t) = \frac{L(t) - L_0}{L_0}
\]

where \(L(t)\) is the distance between the two endpoints of a segment and \(t\) is the time instance corresponding to each frame through the cardiac cycle. It is a dimensionless quantity.

A strain rate is the derivative of a strain with respect to time. It is defined as:

\[
\dot{\varepsilon}(t) = \frac{d\varepsilon}{dt} = \frac{d}{dt} \left( \frac{L(t) - L_0}{L_0} \right) = \frac{v(t)}{L_0}
\]

where \(v(t)\) is the speed at which the two endpoints are moving away from each other. It is dimensionally the reciprocal of time (s\(^{-1}\)).

**Patient population**

Patients with fusiform-type AAAs who visited the outpatient clinic for routine observation or were admitted for elective repair at our tertiary hospital from February 2012 to September 2012 were included in this study \((n = 19)\). For the control group, healthy volunteers aged <40 years without any cardiovascular medical history were selected \((n = 10)\).

**Measurements**

Blood pressure and pulse rates were measured just before ultrasonography. The abdominal aorta was then examined using ultrasonography (Apio 300; Toshiba Medical Systems, Otawara, Tochigi, Japan) under electrocardiographic synchronism. The maximal length of the minor axis of the aneurysm was measured under the axial view, and motion pictures were also recorded for at least three cardiac cycles at the same site. As for the control group without aneurysms, the same measurement was performed at the site where the inferior mesenteric artery branched. Normal convex probes for abdominal ultrasonography (PVT-375BT, 1.5 to 6 MHz phased convex array transducer, Toshiba Medical Systems, Japan) were used, and motion pictures were recorded under ‘Stain-PS’ mode. The default frame rate was 48 frames/s (fps), but this rate was altered according to adjustments in scan range width and depth. Data obtained from the examination were transferred to an external computer installed with 2-D speckle-tracking offline software.

For each patient, a motion picture of the axial view of the aorta at the site of the largest diameter pulsating for one cardiac cycle was obtained. The picture started from the end-diastolic phase (point of the R-wave) where the aorta is most contracted. Here, we manually plotted six points along the inner rim of the aortic intima starting at the 9 o’clock position. The computer then recognized the aorta, and the circumferential strain and strain rates for six equally divided segments were automatically calculated as shown in Fig. 1. Manual plotting was performed three times, and the mean values were analyzed.

**Analysis**

Based on the given figure, we defined the ‘peak’ strain or strain rate as the maximal absolute value of strain or strain rate in each segment. If there was >1 extremum, the one closest to the time when the global strain marked the highest was considered the ‘peak’ value.

We also calculated the coefficient of variation (CV) of the peak strain and strain rate for the six segments. The CV is defined as the ratio of the standard deviation (SD) to the mean and is used to compare the variability of ≥2 series with different means.

**Statistical analysis**

All statistical evaluations were performed with standard software programs (JMP Pro 10.0.2; SAS...
Strain Analysis of AAA

Patterns of time-strain and strain rate graphs

There were 2 major differences in the patterns of strain and strain rate graphs between the 2 groups (Fig. 1). First, the curves in the AAA group showed lesser dynamic movements than those in the control group. The mean peak strain along the 6 segments (MPS) in the AAA group and the control group was 1.5% ± 0.6% and 4.7% ± 1.6%, respectively ($p < 0.0001$), and the mean peak strain rate (MPSR) was 0.24% ± 0.07%/s and 0.70% ± 0.20%/s, respectively ($p < 0.0001$).

Secondly, the curves of strain rate in the AAA group showed higher dispersion in mean peak values than those in the control group. In other words, the curves in the control group were uniform. The CV of the peak strain rate for the 6 segments (CVPSR) was higher in the AAA group (0.74 ± 0.20) than in the control group (0.56 ± 0.12, $p < 0.05$; Table 2). The CV of the peak strain for the 6 segments (CVPS) in the AAA group was also higher than that in the control group but with no statistical significance.
images, the quality of the scanned image is dependent on the operators’ skills, which might lack objectivity. However, manufacturers are constantly improving these devices and upgrading the accuracy and reproducibility of tracing images. In the current study, even in cases with severe aortic calcification, the tracking seemed to work without apparent errors and with sufficient reproducibility. After lowering the learning curve, the procedures of scanning with ultrasonography required no more than 5 min and could be performed within our routine practice.

There were two main results in this study. First, strain and strain rate values decreased in the AAA group. We assumed that the result indicated the loss of wall compliance of the atherosclerotic aortic walls in the AAA group. Our finding was supported by a report from Sonesson, et al.12) who evaluated stiffness of the AAA and carotid artery with an ultrasonic echo-tracking system and demonstrated altered mechanical properties of the AAA wall. Second, the strain rates in the AAA group showed higher relative dispersion than those in the control group. One or two segments tended to have higher peak strain rate values than the other segments, suggesting an inhomogeneous movement of the aortic wall. To express the inhomogeneity of the aortic wall motion in AAAs, Brekken, et al.9) compared the range of strain values to the mean strain. We measured the CV of

### Discussion

If an aneurysmal sac is morphologically compared to a balloon, it is easy to understand that larger AAAs have more rupture risks in accordance with Laplace’s law.10) However, in reality, the behavior of the AAA should be influenced by various factors such as the distribution of calcification, blood pressure, morphology such as angulation, concomitant diseases, and biological factors.11) The most important dynamic parameter of rupture is the maximal principal wall stress. For predicting the AAA rupture site, it is important to know the distribution of the principal stress, which depends on the morphology—spindle or saccular—and the mechanical properties of the AAA wall. Li, et al.3) performed structural analysis by reconstructing 3-D stress contours showing von Mises stress distribution and demonstrated the high aneurysm shoulder stress in rapidly expanding AAAs in their longitudinal follow-up study. The visualized 3-D image of wall stress distribution should be a strong predictor for the rupture; however, their methods have the following problems: CT, which was necessary for the analysis, might expose patients to unnecessary irradiation, the analysis requires expert knowledge and skills, and above all, the procedure is time-consuming.

Although ultrasonography is a beneficial method that is less invasive and can obtain real-time dynamic

<table>
<thead>
<tr>
<th>Variable</th>
<th>AAA (n = 19)</th>
<th>Control (n = 10)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>76 ± 8</td>
<td>33 ± 2</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Men (n)</td>
<td>17</td>
<td>10</td>
<td>ns</td>
</tr>
<tr>
<td>Systolic blood pressure (mmHg)</td>
<td>125 ± 23</td>
<td>120 ± 15</td>
<td>ns</td>
</tr>
<tr>
<td>Pulse rate (bpm)</td>
<td>68 ± 7</td>
<td>72 ± 13</td>
<td>ns</td>
</tr>
<tr>
<td>Maximum aortic diameter (mm)</td>
<td>48 ± 10</td>
<td>15 ± 1</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Frame rate of measurement (frame/s)</td>
<td>40 ± 5</td>
<td>61 ± 10</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Depth of posterior wall (mm)</td>
<td>69 ± 11</td>
<td>44 ± 13</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

AAA: abdominal aortic aneurysm; ns: not significant

<table>
<thead>
<tr>
<th>Measured value</th>
<th>AAA (n = 19)</th>
<th>Control (n = 10)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPS (%)</td>
<td>1.5 ± 0.6</td>
<td>4.7 ± 1.6</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>MPSR (%/s)</td>
<td>0.24 ± 0.07</td>
<td>0.70 ± 0.20</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>CVPS</td>
<td>0.76 ± 0.23</td>
<td>0.66 ± 0.16</td>
<td>ns</td>
</tr>
<tr>
<td>CVPSR</td>
<td>0.74 ± 0.20</td>
<td>0.56 ± 0.12</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>

AAA: abdominal aortic aneurysm; MPS: mean of peak strain along the six segments; MPSR: mean of peak strain rate along the six segments; CVPS: coefficient of variation of peak strain of the six segments; CVPSR: coefficient of variation of peak strain rate of the six segments; ns: not significant

### Table 1 Patient demographics

### Table 2 Major measurements
the peak strain rate to show the inhomogeneity. Karatolios, et al.\textsuperscript{13} also quantified the inhomogeneity by using the CV of systolic strain like in our present study; however, they could not show the statistical difference between the AAA group and the healthy volunteers, possibly because of the small sample size. CVPSR should be one of the most useful and easily applied methods to show inhomogeneity and would be helpful in selecting patients at high risk of rupture. Wilson, et al.\textsuperscript{14} defined the distensibility with pressure strain elastic modules and stiffness and revealed that the decreased distensibility was significantly correlated to reduced time to rupture. Accordingly, the segment with conspicuously high peak strain rate among other AAA segments with low strain rate should be considered a candidate for future rupture.

Recently, Bihari, et al.\textsuperscript{13,15} applied the 3-D ultrasound STM to AAA and analyzed the whole aortic aneurysm using a commercially available apparatus. Measurement was semiautomatically performed at 36 points circumferentially and 24 points longitudinally. The method seems ideal for visualizing the whole image of the aneurysm; however, there is a limitation in scanning. As the sector probe was set at 1 point in their procedure, the scanning range will sometimes be too small to cover the whole aneurysm contour, such as in lean patients with large aneurysms. The advantage of our study is that a normal convex probe can scan aneurysms of any anatomy and in any condition. The disadvantage of our method is that the data of the wall properties might be too simplified: however, it might be useful enough, because we assumed that all surgeons need merely the rough information of the fragile site of the AAA wall for predicting rupture.

This technique may be clinically used in some situations. If a limited portion of the aortic wall showed massive inhomogeneous movements, we could predict that the site was at risk for rupture. In the follow-up of patients who have undergone stent graft implantation, development of abnormal strain and strain rate might indicate late adverse events such as type 1 or 3 endoleak. Close observation in such cases could improve outcomes in AAA patients.

There are some limitations to our present study. First, it included only a small number of patients, which may be insufficient for revealing the average features of AAA. Second, strain values were sometimes negative in the raw data, which is possibly caused by the timing of aortic contraction. As the range of strain rate itself is considered to represent the degree of stress on the aortic wall, we adopted the absolute values for the analysis. Further studies with large samples should be performed for evaluating such values. In addition, we used a healthy and young cohort as the control to evaluate the normal values of our measurement. An age-matched study with a larger population should be conducted.

Since this is a preliminary study, we measured only the axial view of the most dilated area to ensure the reproducibility of the measurement. Measuring the areas of the aneurysmal neck, shoulder, and bifurcation should be performed for elucidating the nature of the whole aneurysm in future studies.

**Conclusions**

Strain analysis using our STM and the software that automatically divided the aortic wall into six segments was a simple and feasible method for revealing the mechanical properties and segmental inhomogeneity of the AAA.

**Disclosure Statement**

All authors have no conflict of interest.

**References**