Effects of arterial blood flow on walls of the abdominal aorta: distributions of wall shear stress and oscillatory shear index determined by phase‑contrast magnetic resonance imaging

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Abstract Although abdominal aortic aneurysms (AAAs) occur mostly inferior to the renal artery, the mechanism of the development of AAA in relation to its specific location is not yet clearly understood. The objective of this study was to evaluate the hypothesis that even healthy volunteers may manifest specific flow characteristics of blood flow and alter wall shear or oscillatory shear stress in the areas where AAAs commonly develop. Eight healthy male volunteers were enrolled in this prospective study, aged from 24 to 27. Phase‑contrast magnetic resonance imaging (MRI) was performed with electrocardiographic triggering. Flow‑sensitive four‑dimensional MR imaging of the abdominal aorta, with three‑directional velocity encoding, including simple morphological image acquisition, was performed. Information on specific locations on the aortic wall was applied to the flow encodes to calculate wall shear stress (WSS) and oscillatory shear index (OSI). While time‑framed WSS showed the highest peak of 1.14 ± 0.25 Pa in the juxtaposition of the renal artery, the WSS plateaued to 0.61 Pa at the anterior wall of the abdominal aorta. The OSI peaked distal to the renal arteries at the posterior wall of the abdominal aorta of 0.249 ± 0.148, and was constantly elevated in the whole abdominal aorta at more than 0.14. All subjects were found to have elevated OSI in regions where AAAs commonly occur. These findings indicate that areas of constant peaked oscillatory shear stress in the infra‑renal aorta may be one of the factors that lead to morphological changes over time, even in healthy individuals.

Keywords Aneurysm · Aorta · Blood flow · Wall shear stress

Introduction Because of a rapidly aging population throughout the developed world, the number of patients developing aortic aneurysms has been increasing [1, 2]. Although most abdominal aortic aneurysms (AAAs) form inferior to the renal artery [3], the mechanism of the development of an aortic aneurysm associated with a specific location is not yet clearly understood. Some investigators believe that mechanical forces contribute to the development and enlargement of aortic aneurysms [4]; current explanations of these phenomena include the finite element model [5, 6], three‑dimensional (3D) reconstruction model [7], mechanical wall stress due to changing diameter of the vessel and asymmetry [8].

In addition, blood flow in the aorta intrinsically results in continual wall shear stress (WSS) or oscillatory shear stress (OSS) of the aortic wall, which may lead to dilatation of the aorta or development of aortic aneurysm. Magnetic
resonance imaging (MRI) used to determine WSS and OSS has recently shown an association between blood flow and cerebral artery aneurysms [9–12].

In contrast to assessments on cerebral aneurysms, which can be performed in the limited space of the cranium, it has been difficult to determine WSS or OSS using MRI in the aorta because of the large fields, the pulsatile aortic wall, and respiratory movement that interferes with precise and complicated calculations [13, 14].

For this study, a feasible method was developed to calculate time-framed WSS and oscillatory shear index (OSI) using phase contrast (pc)-MRI in consideration of the movement of the aorta in a cardiac cycle or in coordination with respiration. We focused on the impact of blood flow on the aortic wall in healthy volunteers.

**Objectives**

The objective of this study was to determine the impact of the blood flow by its mechanical forces such as wall shear stress and oscillatory shearstress on the aortic wall wherein the velocity is measured using pc-MRI and WSS is calculated from the measured velocity later. We anticipate that even healthy volunteers without aortic aneurysms may have specific blood flow characteristics in the infra-renal aorta and may alter WSS or OSS at locations that is associated with the development of AAAs.

**Methods**

Eight healthy male volunteers, aged 24 years old in 7 subjects and 27 years old in one, were enrolled in this study. None of the volunteers had aortic aneurysms, other cardiovascular disease, hypertension or under the treatment of medications. Their blood pressures were all in the normal range, their electrocardiograms (ECGs) were normal, and no arrhythmias were seen. The ethics committee of our institution approved the study and the written informed consent was obtained from each subject.

**MRI data acquisition**

MRI was performed using a Discovery MR750 3.0-T MR system (GE Healthcare, Milwaukee, Wisconsin), and image acquisition was performed using ECG triggering with respiratory synchronization method. Measuring parameters were as follows: 512 × 512 pixels, 28–32 slices, voxel size = 0.55 (anterior-posterior) × 0.55 (right-left) × 5.0 (superior-inferior) mm³, field of view = 280 mm, frame rate = 20 frames/systole (Fig. 1). To evaluate abdominal hemodynamics, flow-sensitive 4D MRI of the abdominal aorta with three-directional velocity encoding, including simple morphological image acquisition, was performed. Evaluation included the aorta from just proximal to the renal arteries down to the common iliac arteries.

**Off-line analysis**

Median filtering was performed to reduce noise. Regions of interest (ROIs) that included the abdominal aorta were extracted. A snake segmentation algorithm was used to identify the aortic wall in each time frame [15]. As aortic wall moves and changes its caliber about 10 % from the maximal in accordance with the stroke volume flow, we developed a newly scanning system to detect the aortic wall, to avoid such interference. The vector of the blood flow was reassessed in consideration of the distance from the true aortic wall in each time frame in accordance with the movement of the aortic wall (Fig. 2). Information on the specific location was applied to the flow encodes to calculate each parameter.

**Streamline flow**

To illustrate the behavior of blood flow in the abdominal aorta during a single cardiac cycle, 3D flow visualization...
using ParaView software 3.12.0 (Kitware Inc., Los Alamos, NM) to include time-resolved 3D streamline flow. Two individual initiating locations were defined to describe the streamlines.

### Calculation of WSS

The wall shear stress at position \( r \) and time \( t \) was calculated from the velocity field \( v(r, t) \) as:

\[
\tau(r, t) = \mu \frac{\partial}{\partial n}(v(r, t) - (v(r, t) \cdot n(r, t))n(r, t))
\]  

where \( \mu \) (0.0043)[Pa \cdot s] is the viscosity index, \( v(r, t) \) [cm/s] the flow velocity adjacent to the aortic wall and \( n(r, t) \) represents the normal vector of the aortic wall at \( r \). Terms inside parentheses \( {} \) means the flow velocity at \( r \) and \( t \) along the aortic wall. Equation 1 means the WSS is proportional to the radial derivative of the flow velocity along the aortic wall. Figure 3 shows a schematic illustration of variables used in the calculation of WSS.

As the WSS is defined as Eq. 1, WSS varies according to the time frame of one cardiac cycle.

### Calculation of OSI

Using the value calculated for WSS, the OSI at each point was calculated as:

\[
OSI(r) = \frac{1}{2} \left( 1 - \frac{\int_0^T \frac{1}{T} \| \tau(r, t) \| dt}{\int_0^T \| \tau(r, t) \| dt} \right)
\]

where \( T \) is the duration of a single cardiac cycle. Equation 2 represents the degree of variation of WSS during a single cardiac cycle. OSI ranges from 0 to 0.5, where 0 indicates that the flow is unidirectional, and 0.5 indicates that the flow is purely oscillatory.

With regard to Eq. 2, and the time integration of WSS at position \( r \), because the aortic wall pulsates, the aortic wall in each time frame was repositioned from the reference time-frame images (Fig. 2). The procedure of repositioning was as follows: the center of gravity of the extracted aorta for each slice was calculated for each time frame. The region of interest of the extracted aorta of each time frame was then shifted so that the center of gravity was matched to that of the reference time-frame image. Next, the azimuthal angle from the center of gravity of the extracted aorta was calculated for each pixel in the aortic wall. The distance of each pixel in the aortic wall from the center of gravity was adjusted to match that of the pixel with the same azimuthal angle of the reference time-frame image.

### Results

#### Streamline flows

The following were seen in all participants: when the ventricular ejection flow reached the ROI, first, a fast straight flow towards the anterior, mid part of the abdominal aortic wall was seen which disappeared rapidly, followed by a small, slow, constant vortex flow in a transverse direction towards the lateral wall around the renal arteries (Fig. 4, video).

The secondary peaked velocity was found at the anterior side of the inflection point in the abdominal aorta while the maximum velocity was found at the anterior side of the aorta superiorly adjacent to the renal arteries (Fig. 4; Table 1).
After the flow reached the secondarily peaked velocity, at the inflection point, the flow changed its direction toward the posterior wall of the aorta, resulting in rapid reduction in velocity. Although the flow reached maximum velocities $902 \pm 122$ (from 738 to 1119) mm/s just superior to the renal arteries, the velocity immediately decreased as a result of flow to the renal arteries. Therefore, vortex flows were generated distal to the renal arteries.

**Mean time-framed WSS**

Time-framed WSS was averaged in one cardiac cycle and further averaged among 8 subjects (Fig. 5a). The mean time-framed WSS peaked at the juxtaposition of the renal arteries at $0.30 \pm 0.053$ Pa and gradually decreased toward the distal abdominal aorta and plateaued at around 0.17 Pa (Figs. 4, 6).

**Peak WSS**

While WSS was calculated in all cardiac cycle, the WSS had the peak value when the peak blood flow passes at the specific location, which occurred at 120–140 ms after the start of ejection. In all cases, the peak WSS was observed in the anterior area of the abdominal aorta in the juxtaposition of the renal arteries (Fig. 5b; Table 1). The peak value of WSS peaked adjacent to the renal arteries was $1.14 \pm 0.25$ Pa, gradually decreased and plateaued in the middle and lower abdominal aorta to around 0.61 Pa.

**OSI**

The peak value of OSI was seen at locations where vortex flows were most frequently seen. The main flow was directed toward the posterior wall slightly after the renal arteries. Since vortex flows were seen distal to the ostia of the renal arteries at the lateral and posterior wall, the OSI rapidly increased across the renal artery and then the OSI peaked at $0.248 \pm 0.148$. In the whole abdominal aorta, the OSI was kept elevated between 0.14 and 0.22. (Figs. 6, 7; Table 1). However, the pattern of the OSI distribution varied according to the subjects.

**Discussion**

AAAs have become increasingly common [1, 2, 16], and ruptured AAAs have serious consequences. Therefore, determining the mechanism of aneurysm development is very important. Although AAAs occur in the infra-renal aorta in more than 80 % of cases [1–3, 17], the reason AAAs most frequently occur at this location has not been

<table>
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<th>Subjects</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<td>24</td>
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<td>1.30</td>
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<td>1.18</td>
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<td>Location of peak WSS</td>
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<td>Above renal arteries</td>
<td>Above renal arteries</td>
<td>Above renal arteries</td>
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<td>Above renal arteries</td>
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<tr>
<td>Location of second peak WSS</td>
<td>Anterior wall of the infra-renal aorta at the point of inflection</td>
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<td>Peak OSI</td>
<td>0.46</td>
<td>0.25</td>
<td>0.46</td>
<td>0.47</td>
<td>0.36</td>
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<td>Location of max OSI</td>
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<td>Distal to renal arteries on the posterior wall</td>
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<td>126/70</td>
<td>124/73</td>
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<td>(94)</td>
<td>(109)</td>
<td>(89)</td>
<td>(90)</td>
<td>(95)</td>
<td>(93)</td>
<td>(81)</td>
<td>(82)</td>
<td>(92 ± 8.7)</td>
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</table>

*BP* cuffed blood pressure, *OSI* oscillatory shear index, *WSS* wall shear stress
fully explained. It may be associated with pathological changes in the wall of the aorta extending from the thorax into the abdomen [18], elevated plasma matrix metalloproteinase concentration (MMP) [19, 20], hypertension and aging [2], and morphological heterogeneity [21]. Currently, investigations of the risk for rupture include evaluating wall stress or wall tension [22], the finite element model [5, 6], or geometric analysis using models of 3D reconstruction [7]. In addition, mechanical force applied to the aortic wall or asymmetrical shape [4] may be associated with dilatation of the aorta. However, assessment of the risk of enlargement or rupture requires comprehensive consideration of all relevant factors [23–30].

Aortic blood flow may also contribute to formation of aneurysms [31]. There have been several studies of cerebral aneurysms indicating that arterial blood flow leading to increased values of WSS and OSI was associated with the development of aneurysms and formation of thrombi [9–11, 32]. However, determining WSS and OSI in large arteries has been difficult for the following reasons: (1) evaluating a broad region of interest is time consuming; (2) the region being assessed by MRI may not be stable because of body or respiratory movements; and (3) as the aorta moves along the cardiac cycles, it is technically difficult to calculate

![Fig. 5](image-url) a Mean (time-averaged) wall shear stress in the whole abdominal aorta, indicated with standard deviation. b Peak wall shear stress in the whole abdominal aorta. RA renal arteries, WSS wall shear stress

![Fig. 6](image-url) Wall shear stress (a, e) at the peak phase and oscillatory shear stress (b, d) distribution. Elevated WSS were observed on the anterior part of the abdominal aorta above the renal arteries, while the high OSI were seen on the posterior part of the abdominal aorta below the renal arteries. View from left (a, b), front (c), and back (d). OSI oscillatory shear index, WSS wall shear stress, A anterior, L left, R right, P posterior

![Fig. 7](image-url) Oscillatory shear index in the whole aorta, indicated with standard deviation. OSI oscillatory shear index, RA renal arteries
WSS and OSI, which require precise distance from the aortic wall [11, 32]. In our study, aortic walls were traced semi-automatically [15] and the pulsating movements of aortic wall were precisely depicted. Although four-dimensional streamlines of the flow in the aorta have been previously described [13, 33], to the best of our knowledge, this is the first report where time-framed WSS and OSI values were determined for a large part of the aorta in a whole cardiac cycle. We were able to successfully reduce the amount of time needed to obtain MRI images; the procedure for evaluating a 15 cm segment of abdominal aorta took approximately 15–20 min. An examination period of around 20 min may be tolerable to patients and also reduce stress. During the next phase of this research, this protocol will be applied to patients who are diagnosed with abdominal aortic aneurysm. As McGloughlin et al. have indicated [34], patients with aortic aneurysms less than 5 cm in size may be suitable candidates for study.

The common findings included the streamline flows; there was smooth uniform flow above the renal arteries that rapidly fluctuated immediately below the renal arteries. Time-framed WSS values were highest at this location where the direction of the streamline changed rapidly, which occurred mainly at the anterior side of the abdominal aorta. Slightly distal to the location with highest WSS value, the streamline changed direction and reversed flow directed toward the posterior wall. About 5 cm distal to the renal arteries, the OSI had its peak, and kept the elevated value in the whole abdominal aorta. This elevated OSI in the abdominal aorta means that in this area, the blood flows in fluctuation and the vortex flow retains. Furthermore, the streamlines at the juxtaposition of the renal arteries demonstrated interesting behavior over 1 cardiac cycle: while fast flow with the maximum velocity was in an anterior–posterior direction and as this fast flow passed, it was rapidly attenuated. However, the vortex flows around the renal arteries remained in the cranial direction parallel to the renal arteries and this flow was constant even after fast flow had passed. This phenomenon would be attributed to the anatomical structure of the renal arteries that give rise in the transverse direction from the aorta which leads to a persistent inertial flow. The fast strong flow would be attenuated by the collision to the reflex wave that originated at the bifurcation of the common iliac arteries.

The evidence provided by studies of cerebral arteries [11, 32, 34] that there is an association between values for WSS and OSI and the development of aortic dilatation and aneurysms, indicates that elevated values for WSS apply transient, strong force to the aortic wall, and may be directly associated with aortic dilatation. In our study, the transient elevation of WSS was observed of $1.14 \pm 0.25 \text{ Pa}$ in the juxtaposition of the renal arteries. Likewise, with regard to the mean time-framed WSS, it had the highest value adjacent to the renal arteries with the value of $0.30 \pm 0.053 \text{ Pa}$ that was consistent with the previous reports [35, 36]. In contrast, in all our study subjects, the peak values for OSI occurred at the posterior wall distal to the renal arteries of $0.248 \pm 0.148$ and kept constantly high at around 0.14 in the middle and lower abdominal aorta. These findings were also consistent with the previous report by Pedersen et al. [37]. An autopsy study by Darling et al. found that 82 % of ruptures of AAAs occur along the posterior and postero-lateral walls of the abdominal aorta [17]. As Pedersen and his colleagues described [37], intimal thickness was seen in the infra-renal aorta and at the distal posterior vessel wall and this intimal thickness was significantly correlated with OSI at rest. Our findings of an elevated OSI value in these locations support their results and may explain some clinical relevance.

Furthermore, WSS and OSI were elevated in the area of the aorta where AAAs are common. It is noteworthy that these findings occurred even in healthy subjects. Although shear stress has a rather small magnitude compared to blood pressure, shear stress exerts a significant influence on the endothelial layer modifying its function and consequently the expression of many factors playing a role in the homeostasis of the arterial wall. It can be speculated that continual high wall shear stress or oscillatory shear stress in the infra-renal aorta over 3–4 decades may eventually lead to the development of aortic aneurysm, even in healthy individuals [38].

The largest difference of the result of this study from the previous researches [39–42] was, we calculated the time-framed WSS in every location of the abdominal aorta in consideration of the aortic wall movement. Although the previous research provided the mean WSS on the aortic wall over one cardiac cycle and indicated that lower mean WSS was observed in the abdominal aorta, as was seen in the current study, the time-framed WSS changes according to the flow; at the peak systole, the WSS showed the maximal value. In terms of the time-averaged WSS from the previous report [39–41], our result of the peak of time-framed WSS of $1.14 \pm 0.25$ was consistent with the previous reports (1.0 Pa).

Similarly, the maximal OSI was $0.248 \pm 0.148$ about 5 cm distal to the renal artery branches that is almost same as previous studies. Suh et al. reported [43] that OSI was 0.29 at rest in the infra-renal abdominal aorta that decreased to 0.15 during the mild degree of exercise.

In the current study, WSS, OSI and streamline flows were determined and MRI flow velocities were captured in a reasonable amount of time. The results have provided information on how aortic flow inherently contributes to aortic dilatation or formation of aneurysm. Previous research has demonstrated [43] that high flow recirculations and high shear stress followed by low shear stress are
correlated with platelet aggregation and activation, which in turn promotes the formation of thrombin. Furthermore, WSS and OSI are thought to be associated with thrombus formation and an intramural thrombus may also be associated with development and rupture of an aortic aneurysm [23, 34]. The effects of local inflammation of the aorta or inflammatory factors such as MMP-2 and -9 [19, 20] should also be related.

In future research, the methods used in this study will be used in studies enrolling patients with aortic aneurysms. Comparisons with normal control subjects and observation of changes in WSS and OSI over time may provide additional information on how aortic flow inherently affects aortic dilatation. In addition, because MRI provides actual measured velocity and forces of blood to the aortic wall, the pharmacological effects of antihypertensive can be evaluated with regard to changes in WSS and OSI values and the association between these changes and the rate of aortic dilatation. Eventually, the evaluation method used in our study may play an important role in patient-specific models [45] that have been recently introduced to predict risk of aneurysm rupture [25–30, 34, 38, 44, 46, 47]. However, additional clinical validation of the methods used in this study is warranted.

**Limitations of the study**

The limitations of this study include the fact that sensitivity of the 3D velocity mapping acquisition during low flow may be decreased because of low signals from pc-MRI. In addition, anisotropic (non-cubic) voxels may limit resolution of the flow in the longitudinal direction.

**Conclusions**

All subjects were found to have elevated OSI in the infra-renal artery of the abdominal aorta where AAAs commonly occur. These findings indicate that areas of constant peaked oscillatory shear stress in the infra-renal aorta may be one of the factors that lead to morphological changes over time, even in healthy individuals.

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**Compliance with ethical standards**

**Conflict of interest** The authors have no conflicts of interest to declare.

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